OnArmQWERTY: An Empirical Evaluation of On-Arm Tap Typing for AR HMDs

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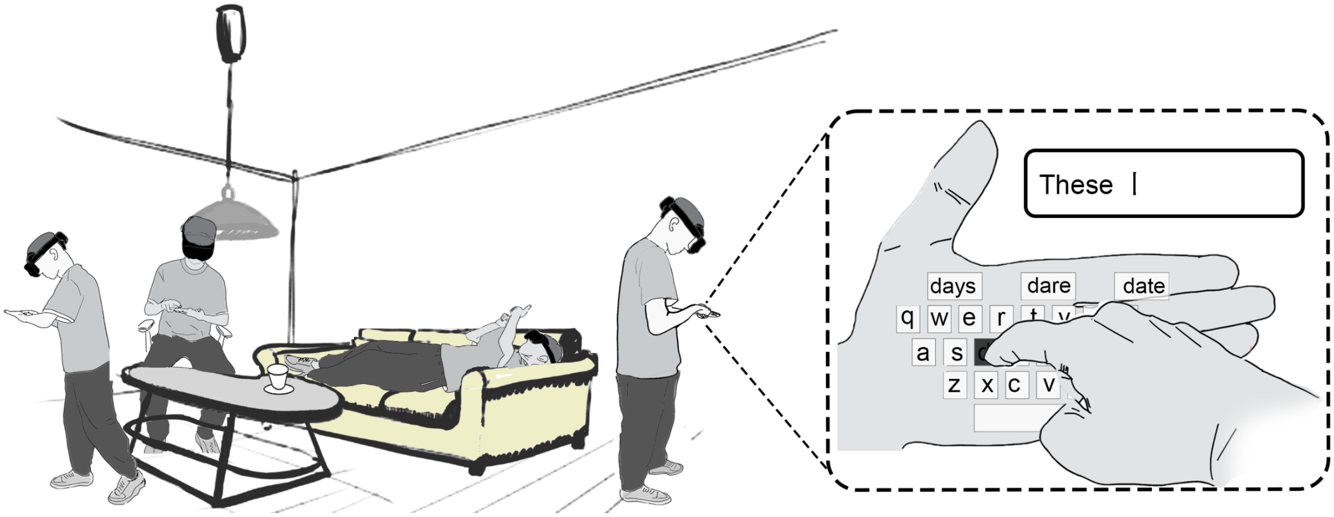

Figure 1: A user, wearing an AR head-mounted display, enters text in various postures—sitting, standing, lying down, and walking—using OnArmQWERTY, with a virtual keyboard projected directly onto the palm.

Abstract

Text entry is an essential and frequent task in Augmented Reality (AR) applications, yet developing an effective and user-friendly method remains a challenge. This paper introduces OnArmQWERTY, a text entry technique for AR HMDs that allows users to project a virtual QWERTY keyboard onto various locations on their non-dominant hand, including the palm, the back of the hand, and both the anterior and posterior sides of the forearm. Users interact with this overlaid keyboard on their skin by tapping with the index finger of the dominant hand, benefiting from the inherent self-haptic feedback of on-body interaction. A user study involving 13 participants evaluated the performance of OnArmQWERTY compared to a traditional mid-air virtual keyboard. The results demonstrate that OnArmQWERTY significantly improves typing speed and accuracy. Specifically, typing on the palm location outperforms all other on-arm locations, achieving a mean typing speed of 20.18 WPM and a mean error rate of 0.71%, which underscores the importance of comfortable, ergonomic typing postures and effective tactile feedback as key factors enhancing text entry performance.

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CCS Concepts

• **Human-centered computing → Text input**.

Keywords

Text Input, Virtual Keyboard, Augmented Reality (AR), Virtual Reality (VR), Head-Mounted Displays (HMDs), On-Body User Interface (UI), Input Interaction.

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1 Introduction

Recent progress in head-mounted displays (HMDs), such as Apple Vision Pro [30], Hololens [8], MagicLeap [41], and Meta Quest Pro [31], has created new possibilities for Augmented Reality (AR) applications in fields like remote work [22], healthcare [47], and education [64]. Despite this, finding an efficient, user-friendly method for text entry in AR settings remains a significant challenge.

Previous research has explored various text entry techniques in AR HMDs, including physical keyboard [9, 40], controller-based typing [6, 61], mid-air hand typing [16, 48, 75], head and eye-gaze based typing [11, 20, 38, 45, 76, 83], speech recognition [4, 55], finger taps on physical surfaces [23, 28, 63, 80], and fingertip tapping [72, 73]. Each method has its limitations. For instance, a physical keyboard requires flat surfaces and limits mobility, making it unsuitable for the versatile environments—both indoor and outdoor—where AR is typically used. Controller-based typing, while effective, can be cumbersome due to the need to constantly hold the controllers. Mid-air typing offers only audio-visual feedback and lacks haptic feedback [24]. This can lead to significant arm and hand fatigue [29, 34], which may reduce typing speed and accuracy [7]. Similarly, head and eye-gaze based typing can cause neck and eye fatigue [33, 39]. Speech recognition, although efficient, struggles with instability in noisy environments and raises privacy and social acceptability concerns, especially in public spaces. Techniques involving finger taps on physical surfaces and fingertip tapping differ greatly from traditional typing methods. They require users to adapt to new interaction paradigms and often depend on custom hardware, which complicates typing out-of-vocabulary (OOV) words. Among these methods, mid-air hand typing using a QWERTY virtual keyboard is the most commonly used text input technique in commercially available AR/VR HMDs. It is favored for its familiar layout, as most users already have extensive experience with it from using virtual and physical keyboards on smartphones, tablets, and PCs. Additionally, its simplicity and portability make it popular, despite its sub-optimal performance in terms of speed and accuracy.

In the past, researchers have investigated on-body user interfaces—particularly arm-anchored UI elements—to expand the AR/VR interaction space, thanks to advancements in body tracking technologies [1, 26, 43, 54, 81]. In general, arm-anchored on-body interactions offer various benefits, including quick and easy access, proprioception, and tactile feedback. With these advantages in mind, a few on-body interfaces have been specifically developed to enter text for head-mounted displays [10, 14, 26, 37, 66, 68]. For example, PalmType [66] transforms the user's palm and fingers into a keyboard for smart glasses, utilizing proprioception to precisely identify palm and finger regions without the need to look. A QWERTY layout is projected onto the non-dominant hand, while sensors on the wrist detect the finger positions of the dominant hand. The glasses display the virtual keyboard, highlighting keys to enable typing in a natural posture without the need for memorization. Similarly, DigiTouch [68], a glove-based input device, allows for text entry through thumb-to-finger touch interactions on a split-QWERTY keyboard layout mapped onto the user's fingers. Meanwhile, Shapeshifter [14] enables users to enter text in VR HMDs by gesturing on parts of the human body, such as the palm and back of the hand, using a digital thimble equipped with sensors that track finger movement and pressure. These techniques involve indirect on-body typing—where input and keyboard are decoupled—using touch and gesture recognition on the body itself. Other methods, such as OmniTouch [26], ARmKeypad [10], and STAR [37], enable direct interaction with the keyboard. For example, OmniTouch projects a simple number pad onto the palm for digit entry. ARmKeypad transforms the user's forearm into a virtual keyboard, allowing users to tap directly on their arm to enter text on a head-mounted display. Meanwhile, STAR involves two-thumb typing, similar to smartphone use, on a mini virtual QWERTY keyboard overlaid on the skin of the hands. Users must constantly adjust their hand position relative to the keyboard since it does not entirely fit within the surface available to the index fingers. While direct methods often require less mental effort, reduce the learning curve, and allow for more precision than indirect techniques [5, 74], there is limited empirical research evaluating the text entry performance of these on-body direct typing methods, except for the STAR technique. This gap in research raises the following question when considering the overlay of a full virtual QWERTY keyboard on the body: Which part of the arm on the user's non-dominant hand is best suited for on-body tap typing?

In this work, we introduce OnArmQWERTY, a text input method designed for AR HMDs. This system allows users to project a virtual QWERTY keyboard onto various locations on their non-dominant hand, including the palm, the back of the hand, and both the anterior and posterior sides of the forearm (see Figure 2). Through the headset, users can see the keyboard projected directly onto their skin and interact with it by tapping with the index finger of their dominant hand. While interacting with the keyboard, users also receive self-haptic feedback (i.e., the haptic feedback from touching one's own body), which is completely lacking in the default mid-air virtual keyboard-based text input technique available in AR HMDs. We conducted a user study with 13 participants in a standing posture to evaluate OnArmQWERTY. The study aimed to determine the most suitable arm location for on-body tap typing and to compare the typing performance on the arm with that of the default mid-air virtual keyboard.

The main contributions of this paper are:

- Introducing OnArmQWERTY, a text entry technique for AR HMDs that allows users to project a virtual QWERTY keyboard onto various arm locations on their non-dominant hand and interact with it by tapping directly with the dominant hand's index finger.

- Reporting the findings of an empirical study that identifies the optimal arm location for on-arm tap typing and compares its performance with mid-air virtual keyboard typing.

2 Related Work

Our work draws inspiration from the literature on virtual keyboard-based text input in AR/VR HMDs and the arm-anchored user interfaces, briefly reviewed in this section.

2.1 Virtual Keyboard-Based Text Input in AR/VR HMDs

The virtual keyboard is a promising alternative to physical keyboards and has been extensively studied in AR/VR text entry literature. Previous research has evaluated the performance and user experience of virtual keyboards in various layouts, including, but not limited to, circular layouts [35, 71, 77], invisible QWERTY [45], and invisible single line [42]. However, a virtual keyboard with a standard rectangular QWERTY layout is preferred due to its familiarity and minimal learning effort required in AR/VR settings [36]; therefore, we have also adopted this layout in our design.

Tap-based (also called selection-based) text entry is probably the most commonly implemented method in commercial headsets (e.g., HoloLens, Quest, and HTC VIVE series). Early work by Speicher et al. [61] evaluated six selection-based text input methods, finding that controller pointing (15.44 WPM) outperformed head-pointing (10.20 WPM), controller tapping (12.69 WPM), freehand input (9.77 WPM), and other methods. In ATK [75], Yi et al. utilized a Leap Motion sensor for ten-finger tap typing in mid-air, achieving a typing speed of 29.2 WPM and a 0.4% error rate after practicing with over 45 phrases. Findings from ThumbAir [21] demonstrated that two-thumb in-air typing could achieve a speed of 13.7 WPM with a 1.2% error rate after participants practiced with 140 words and 35 phrases. Extending the exploration of tap-based methods, Dudley et al. [15] used an OptiTrack system to track finger positions for tap-based text input, finding that two index fingers typing on a mid-air virtual keyboard reached 42.1 WPM after typing 160 sentences. They noted that aligning virtual keyboards with physical surfaces, like tables, increased speed up to 55.6 WPM with two index fingers. Additionally, they observed that ten-finger mid-air typing was less efficient, with higher error rates and slower speeds compared to using just two fingers. This two-index finger-based tap input, proposed by Dudley et al. [15], was described as PokeType in [19], which showed an increase in typing speed from 21.51 WPM after 10 training phrases to 25.42 WPM following 40 phrases. Meanwhile, PalmType [66] turns the user's palm into a virtual keyboard for smart glasses, resulting in a typing speed of 7.7 WPM and a 1.58% error rate after typing eight phrases, without the aid of word prediction or auto-correction features. Lastly, STAR [37] allows smartphone-analogous two-thumb typing on a mini virtual QWERTY keyboard overlaid on the skin of the hands, achieving 21.9 WPM with a 0.3% error rate after 50 phrases.

Similar to tap-based typing, gesture-based typing [79] has received significant attention in AR/VR settings. For example, Vulture [48] used finger pinch gestures, tracked by the Optitrack system, to enable mid-air swipe typing. Supporting only word-level input, the technique resulted in an average typing speed of 28.1 WPM and a 2% error rate after 48 practice phrases. Shen et al. [58] introduced a 3D trajectory decoding method that enabled novices to reach 18-21 WPM, potentially increasing to 35 WPM with more practice.

Research has also been conducted to compare users' performance with tap-based and gesture-based text entry. Xu et al. [70] investigated finger tap and gesture-based text entry on a mid-air virtual keyboard in AR, finding similar speeds but a lower uncorrected error rate for gesture-based input. Additionally, they observed that controller pointing, used for both tap typing (14.6 WPM) and gesture typing (13.68 WPM), outperformed techniques involving head or hand pointing, consistent with findings from [61]. Whereas, Dudley et al. [17] found that two-finger touch typing outperforms gesture typing, with mean entry rates of 25.6 WPM and 21.5 WPM, respectively, across 160 phrases.

While mid-air hand typing, including tap and gesture-based input, has been widely studied, its performance on an arm-anchored virtual keyboard remains unclear. In this work, we are particularly interested in evaluating the text input performance of on-arm tap typing compared to the default mid-air tap typing.

2.2 Arm-Anchored User Interfaces

Arm-anchored on-body interfaces utilize specific parts of the human body—the forearm, wrist, palm, back of the hand, and fingers—as both input and output spaces for various interactions, such as keyboards [26, 37, 66–68], menu navigation [1, 3, 43, 54], command selection [25, 59], color palettes [26, 81], 2D trackpads [2, 51, 57, 81], and TV remotes [12]. Unlike prior studies that viewed the on-body space solely as an input or output modality, Yu et al. integrated the on-body and mid-air interfaces to broaden the range of design possibilities for VR interactions [78]. Additionally, Pei et al. leveraged the dexterity of users' hands to simulate a broad array of virtual 3D objects for tasks such as object retrieval and interactive control in AR/VR environments [53]. Fang et al. developed a novel mobile VR haptics method that uses one hand as a surface or prop for the other to provide physical feedback [18].

In the past, a wide variety of approaches have been considered to enable on-skin touch input for on-body interactions, such as wearing a conventional trackpad on the body [65], acoustic sensing [27, 50], depth sensing camera [26, 59, 62], touch-enabled textile sleeve [57], an array of infrared sensors [51, 66, 67], RF and capacitive sensing [56, 81, 82, 84].

Overall, on-body interfaces provide a range of ergonomic benefits. These systems are always available for interaction, offering enhanced control through eyes-free targeting and proprioception [25, 66, 67]. They also offer robust haptic feedback [18], which improves precision while reducing the physical demands typically associated with mid-air interactions. On-body interfaces support both bimanual [2, 26, 43] and single-handed interactions [54, 59]. In bimanual configurations, UI elements are anchored to the non-dominant arm, facilitating interaction with the dominant hand. For single-handed operations, these interfaces utilize intuitive thumb-to-finger micro-gestures. Moreover, the interface elements can be either directly projected onto the body [26, 81] or displayed around it [43, 54], enhancing usability and accessibility.

Despite extensive exploration of arm-anchored user interfaces, empirical research evaluating text entry performance with a virtual QWERTY keyboard projected onto different locations of the user's non-dominant hand—including the palm, the back of the hand, and both the anterior and posterior sides of the forearm—remains absent. This work aims to address this gap.

3 Designing OnArmQWERTY

The primary goal of our proposed OnArmQWERTY text input method is to project a virtual QWERTY keyboard onto the user's non-dominant hand, allowing users to interact with it by tapping with the index finger of their dominant hand. To ensure a seamless and efficient typing experience, the input interaction space (i.e., the finger tap) and the virtual keyboard should remain coupled.

To design OnArmQWERTY, we initially surveyed the existing literature on various arm-anchored text input interfaces [10, 14, 26, 37, 66, 68]. PalmType [66] and ARmKeypad [10] each mapped a full QWERTY keyboard onto the palm (including the fingers) and the forearm area of the non-dominant hand, respectively. Meanwhile, DigiTouch [68] explored a split-QWERTY keyboard layout mapped across the fingers of both hands. STAR [37] overlaid a virtual keyboard on the skin of both hands, necessitating a knuckle posture. While these interfaces incorporated tap-based interaction with the keyboard, they did not comprehensively explore other potential areas of the arm where a full virtual QWERTY keyboard might be projected. To address this gap and further refine the design, we conducted an elicitation study followed by the development of a prototype, as described below.

3.1 Elicitation Study: Typing Locations on Arm

To explore potential locations on the arm for projecting a virtual keyboard, we conducted an elicitation study in the lab with nine participants (six males and three females), aged between 27 and 38 years (mean = 31.44, SD = 3.86). All participants were AR/VR researchers. Initially, they received a brief presentation on various arm-anchored text input interfaces proposed in the literature. They were then asked to envision different locations on their non-dominant hand where a full virtual QWERTY keyboard—comparable in size to a smartphone keyboard in portrait orientation—could be projected through an AR HMD without necessitating awkward body postures. Participants were instructed to use the index finger of their dominant hand for tap typing on the projected keyboard on their skin. They were encouraged to think about various on-the-go typing scenarios, such as sitting, standing, walking, and lying down as depicted in Figure 1. To facilitate brainstorming, participants were allowed to hold their phone on different parts of the arm, simulating access to its keyboard. The study coordinator assisted them in holding their phone at their preferred arm locations while they typed a few sentences using the phone's keyboard. The session lasted approximately 30 minutes, including introductory instructions and the completion of a demographic survey. This study was unpaid.

Our study identified four main locations for virtual keyboard projection based on participants' comments and observations during their interactions: the palm, the back of the hand, and both the anterior and posterior sides of the forearm. All participants agreed that the palm, with fingers held together, provides a compact and continuous surface ideal for projecting a virtual keyboard. However, they suggested avoiding the finger area as much as possible, as its uneven surface might hinder tap typing. It was also observed that the fingers, particularly at the tips, exhibited slight movements during fast tapping, which was found to be somewhat uncomfortable for typing. Five participants considered the back of the hand as another viable surface for keyboard projection, echoing concerns about the unevenness of the finger area. Additionally, the anterior part of the forearm, especially near the elbow, was recognized as well-suited for keyboard projection due to its relatively smooth surface and minimal curvature. Similarly, three participants further suggested exploring the posterior side of the forearm near the elbow. Although this area is not perfectly flat, its slight curvature is still deemed suitable for projecting a virtual keyboard.

3.2 Prototype Implementation

We used a Meta Quest 3 headset [32] and a Vicon tracking system [44] to prototype OnArmQWERTY, as shown in Figure 3(B) and (C). To track various on-arm locations, we relied on the Vicon system instead of the default hand and arm tracking provided by the Quest headset, ensuring robust, highly accurate, and low-latency tracking. Four Vicon Vero cameras were used for a 3m x 3m x 2.5m tracking volume. The incoming pose information from the Vicon coordinate system ($\overrightarrow{V}$) needs to be translated into the Quest internal coordinate system ($\overrightarrow{Q}$) to display the keyboard on respective on-arm locations. To facilitate calibration between the Quest and Vicon spaces, we created a Calibration Marker (M) by attaching four passive reflective markers to one of the Quest controllers, which can be tracked by both Vicon and Quest. With known equivalent points $\overrightarrow{M_V}$ in the Vicon space and $\overrightarrow{M_Q}$ in the Quest space, we can determine the calibration matrix $\overrightarrow{T_{QV}}$. This matrix facilitates the transformation of coordinates between the Vicon and Quest systems, ensuring accurate alignment and tracking across both spaces.

In our software framework, the OnArmQWERTY application, running on the Quest, was implemented using Unity3D. We tested different sizes of a rectangular QWERTY keyboard, starting with sizes similar to that of a typical smartphone's on-screen virtual keyboard. Through an informal typing test, we determined our proposed keyboard dimensions to be 94.3 mm x 54 mm, which are approximately 47.34% wider and 66.15% taller than the iPhone XR keyboard, as depicted in Figure 4. We used the same keyboard dimensions for all on-arm locations across all users. This size of the keyboard allowed users to confidently select each key with their index finger. To detect key presses, we attached a collider to each key and placed a small sphere collider on the user's fingertip. When the fingertip collider touched a key's collider, the system registered the key press. Users also received visual and audio feedback during each key press. Additionally, we designed the keyboard slightly curve to enhance alignment with both the anterior and posterior surfaces of the forearm, ensuring ergonomic comfort during use.

In modern mobile text entry systems, it is common to suggest recommended words based on the typed letters. Therefore, we integrated a word suggestion feature that allowed participants to complete words before typing all the letters. Our word suggestion

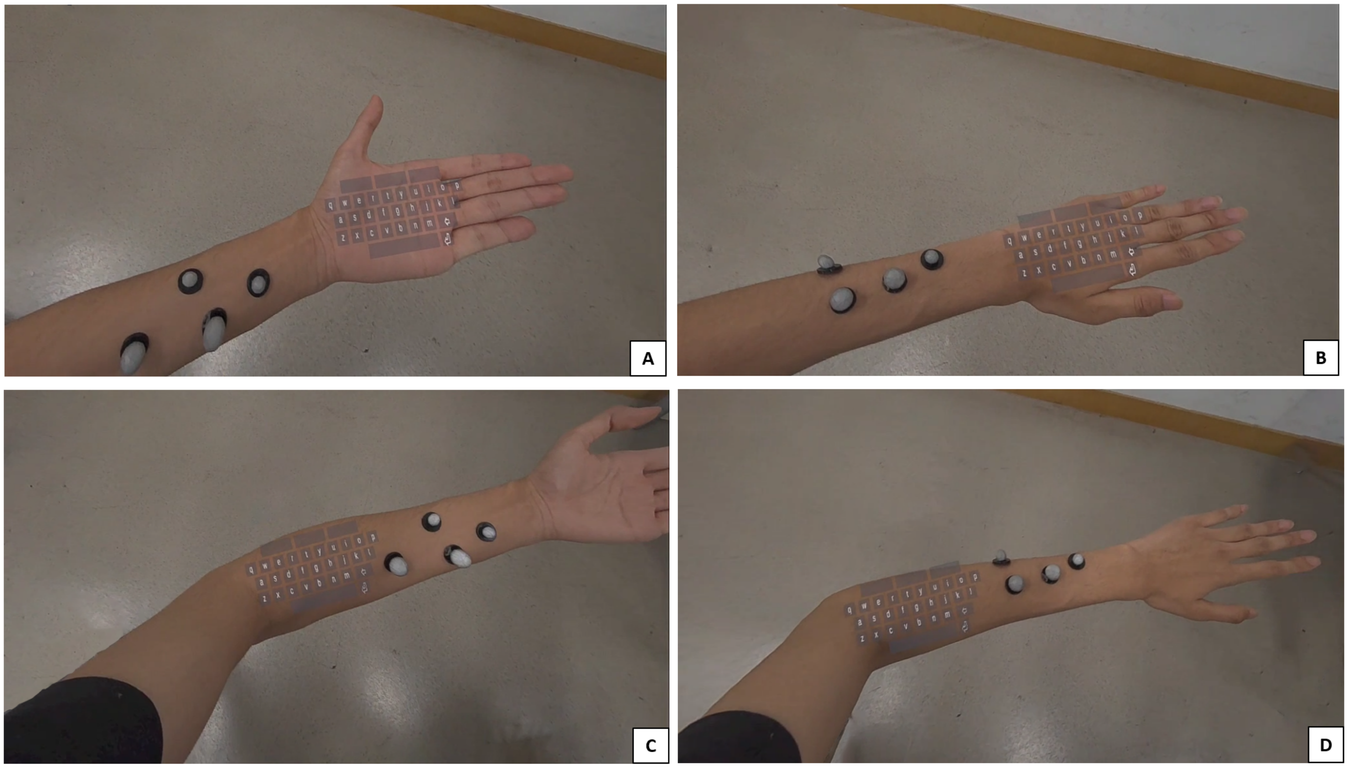


Figure 2: OnArmQWERTY projects a virtual keyboard of the same size on four different arm locations of the user's non-dominant hand: (A) palm, (B) back of the hand, (C) anterior side of the forearm, and (D) posterior side of the forearm.

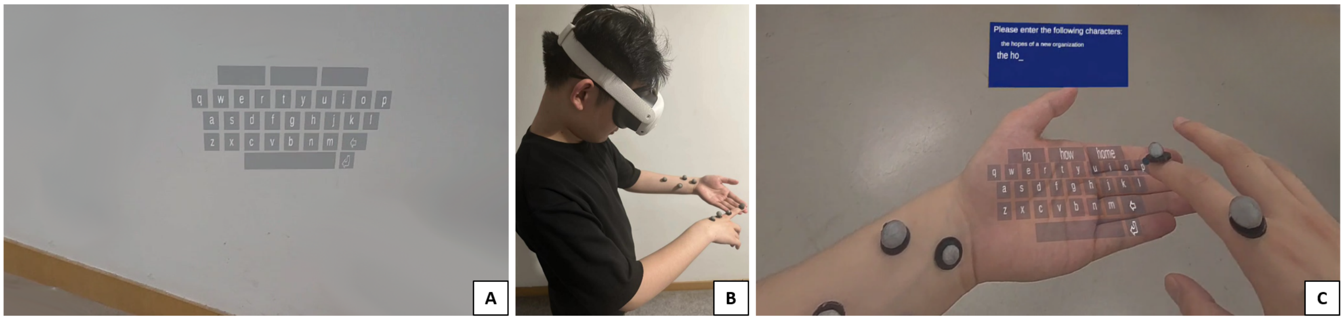


Figure 3: (A) Mid-air virtual keyboard, which is the same size as the keyboard projected on the body; (B) overall setup where a user wears a Meta Quest 3 headset and Vicon markers placed on different locations of the dominant and non-dominant hands; (C) user sees the projected virtual keyboard on the palm through the Quest headset for entering text.

algorithm leverages language model probabilities based on a preloaded corpus of 10K words [49] with associated usage frequencies. With each key press, it filters and ranks words based on how likely they are to match the typed input. The algorithm dynamically updates probabilities as additional characters are typed or deleted, refining its suggestions continuously. It presents the top three word predictions, adjusting in real-time to each keystroke or deletion, to provide relevant and immediate recommendations. The three words with the highest probability appeared on the top row of the keyboard (see Figure 3(C)). To select a suggested word, the user can tap on it, and the system automatically appends a space after the selected word. Hitting the space key also appends a space after the input, while the backspace key deletes one character at a time.

We also implemented a mid-air virtual keyboard as a baseline condition, as shown in Figure 3(A). This keyboard was the same size as the OnArmQWERTY and was positioned at arm's length in front of the user in world space. The rectangular keyboard was tilted at a 30-degree angle, with the bottom edge oriented toward the user and the top edge away, to facilitate comfortable interaction. Additionally, the keyboard height was adjusted according to each

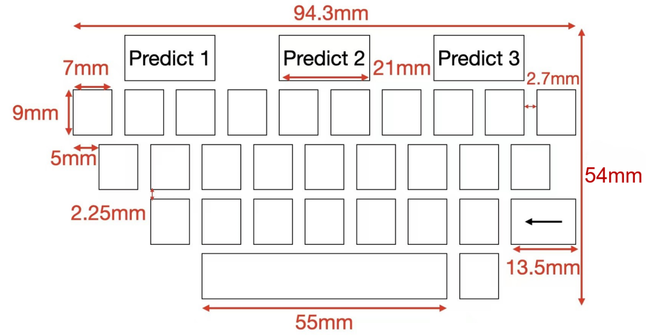


Figure 4: OnArmQWERTY keyboard dimensions.

user's height to ensure ergonomic accessibility. Users tapped on each key with the index finger of their dominant hand, which was tracked by the Vicon system throughout the interaction. Key press detection was accomplished using collision detection, similar to the technique used for the on-arm keyboard.

4 User Study

We conducted an experiment to evaluate the text entry performance of the OnArmQWERTY technique. We also included mid-air virtual keyboard typing as a baseline condition. We intentionally used the same keyboard size for both the mid-air virtual keyboard and our proposed OnArmQWERTY to observe the performance differences between the two methods.

4.1 Participants and Apparatus

We recruited 13 participants (P1-P13), comprising 9 males and 4 females, from a local university campus for our experiment. Their ages ranged from 19 to 24 years, with a mean of 21.36. All participants were right-handed, and they rated their familiarity with the QWERTY keyboard layout on a scale from 1 (novice) to 5 (expert). The average familiarity score reported was 4, with the lowest score being 3. Regarding their experience with AR/VR technology, three participants reported no prior exposure. All participants had either normal or corrected-to-normal vision. Compensation was provided for their participation. The experimental apparatus and prototype utilized in this study are detailed in Subsection 3.2.

4.2 Study Procedure

At the beginning of the study, participants provided their demographic information and were briefed on the study's objectives and the conditions to be tested. They were asked to roll up their sleeves so that Vicon markers could be placed directly on their skin. The experiment was conducted while standing within a tracking volume measuring 3m x 3m x 2.5m. For each on-arm condition, we first placed markers on the body and then adjusted the keyboard position slightly to ensure it rested on the skin, as the same keyboard size was used for all participants. When users tapped on the keyboard, the index finger of their dominant hand also touched the skin of their non-dominant arm, resulting in self-haptic feedback during the on-body interaction. Once the keyboard was positioned on the arm surface, participants transcribed two sample phrases to familiarize themselves with that specific on-arm keyboard condition. When ready, participants transcribed ten phrases for each condition, randomly generated from the Mackenzie and Soukoreff phrase set [46]. All phrases contained four words or more and 40 characters or fewer, following an initial filtering of this phrase set. We also confirmed that all words in the phrase set were present in our 10K-word corpus. No phrases were repeated across different conditions. Participants were informed that their typing speed would be recorded from the moment they pressed the first letter, allowing them to memorize the target phrase before starting the transcription if desired. They were instructed to type as quickly and accurately as possible. While transcribing the target phrase, users could complete a word by tapping on one of three word suggestions offered in our design. Error correction was facilitated by the use of the backspace key. By pressing the 'Enter' key, participants recorded the text they had just typed. Conditions were separated by a 5-minute break. After completing all five conditions, we conducted interviews to gather participants' feedback on the different locations where the keyboard was projected. The entire experiment lasted approximately one hour per participant.

4.3 Study Design

The experiment employed a within-subjects design. The independent variable was the location of the keyboard, which consisted of five settings: the palm, the back of the hand, both the anterior and posterior sides of the forearm, and mid-air. In our study, text entry speed, word suggestion usage, and error rate were the three main dependent variables. Text entry speed was measured in Words Per Minute (WPM) and calculated using the following formula [69]:

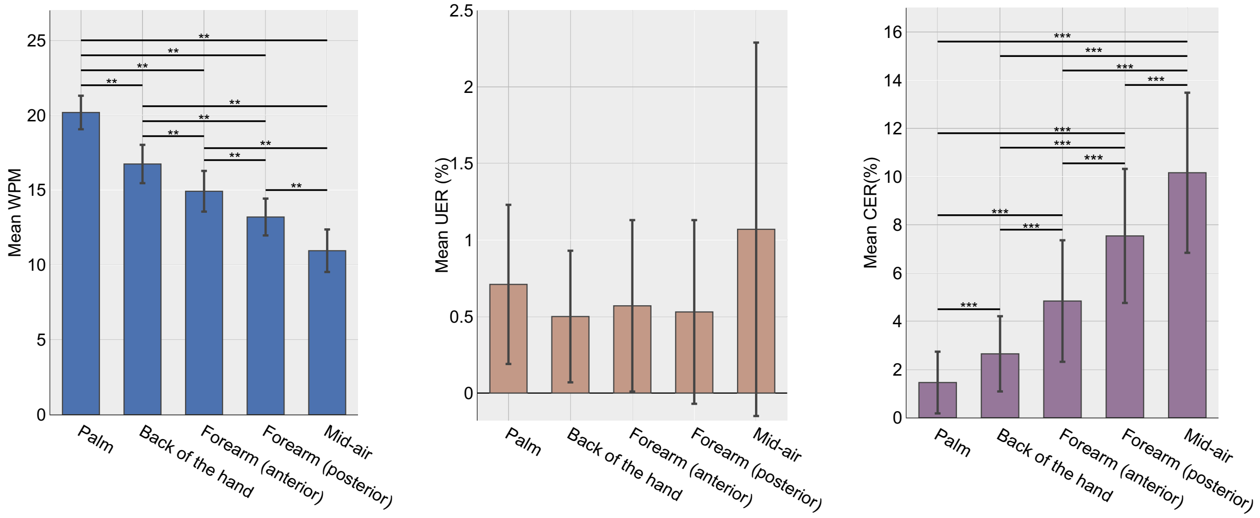
$$\text{WPM} = \frac{(|T| - 1)}{S} \times 60 \times \frac{1}{5} \quad (1)$$

Here, $|T|$ represents the total number of characters in the transcribed text, and S denotes the time in seconds from the first to the last key entry for each phrase. The subtraction of 1 from $|T|$ adjusts for the final character ('Enter' key in this case), which may not be included in the final count. The multiplication by 60 converts the rate from seconds to minutes, and the division by 5 translates the character count into words, based on the definition that a word consists of five characters, including spaces.

Word suggestion usage was defined as the number of times participants selected a word from the top three suggestions provided by the word suggestion feature, instead of typing the whole word manually. This metric was measured on a per-phrase basis and was used to assess the extent to which participants relied on the word prediction algorithm to complete words during the text entry task. Each instance where a participant tapped on a suggested word was counted towards word suggestion usage.

We computed three error rate metrics: the Uncorrected Error Rate (UER), the Corrected Error Rate (CER), and the number of times the backspace key was pressed [60]. The UER counted the errors in the submitted text based on the Minimum String Distance [69]. The CER was similar to the UER but also included the count of backspace usage as additional errors.

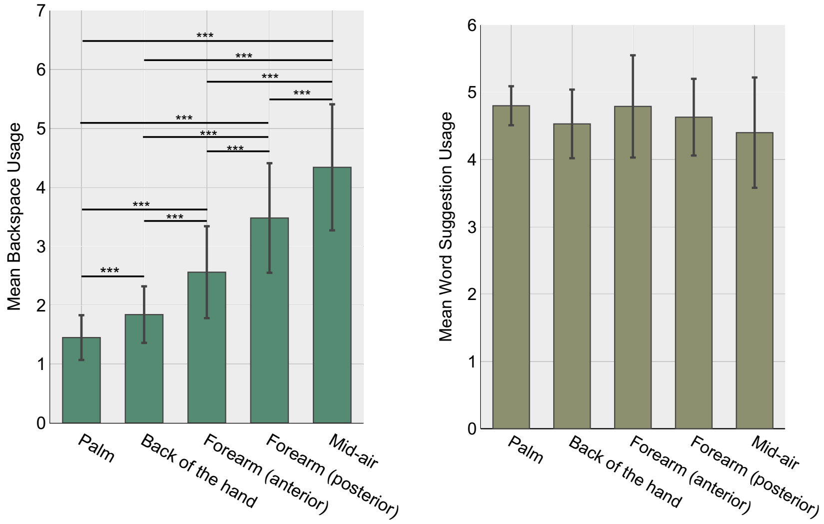
The location of the keyboard was counterbalanced among participants using a Latin Square design. In total, we collected data for 13 participants x 5 keyboard locations x 10 phrases = 650 phrases.



(a) Text entry speed

(b) Uncorrected Error Rate (UER)

(c) Corrected Error Rate (CER)



(d) The number of times the backspace key was pressed per target phrase.

(e) The number of times a word from the suggested word list was selected while typing each target phrase.

Figure 5: Each figure includes error bars that represent 95% confidence intervals. Statistical significance is denoted by stars, with * indicating p < 0.001, ** indicating p < 0.01, and * indicating p < 0.05.**

4.4 Results

One-way RM-ANOVAs were used to analyze metrics with normal distributions, such as word suggestion usage, Corrected Error Rate (CER), and backspace usage count. For metrics without normal distributions, such as text entry speed and Uncorrected Error Rate (UER), Friedman tests were employed. Post-hoc comparisons for the one-way RM-ANOVAs were conducted using paired-sample t-tests with Holm correction, while those for the Friedman tests were performed using Wilcoxon signed-rank tests, also with Holm correction. We set a significance threshold of $\alpha = 0.05$, the standard for statistical significance.

4.4.1 Text Entry Speed. The Friedman test revealed a significant effect of keyboard location on Words Per Minute ($\chi^2(4) = 52$, $p < 0.001$). Subsequent pairwise post-hoc comparisons confirmed statistically significant differences between all pairs of keyboard locations. The palm achieved the highest mean text input speed at 20.18 WPM (SD = 1.12), followed by the back of the hand at 16.74 WPM (SD = 1.28), the anterior side of the forearm at 14.93 WPM

(SD = 1.36), the posterior side of the forearm at 13.19 WPM (SD = 1.23), and finally, mid-air at 10.95 WPM (SD = 1.42). Figure 5(a) shows the average WPM across all five keyboard locations.

4.4.2 Word Suggestion Usage.

A RM-ANOVA was conducted to compare the effect of keyboard location on word suggestion usage. The results indicated that there was no statistically significant difference in word suggestion usage across the different keyboard locations, $F(4,48) = 1.21$, $p = 0.319$. The mean word suggestion usage was 4.81 (SD = 0.29) for the palm, 4.54 (SD = 0.52) for the back of the hand, 4.79 (SD = 0.76) for the anterior side of the forearm, 4.63 (SD = 0.58) for the posterior side of the forearm, and 4.40 (SD = 0.83) for mid-air. Figure 5(e) shows the average word suggestion usage for each keyboard location.

4.4.3 Error Rates.

The Friedman test revealed no significant differences in UER across all five keyboard locations ($\chi^2(4) = 3.35$, $p = 0.51$). The mean UER was 0.71% (SD = 0.52) for the palm, 0.5% (SD = 0.43) for the back of the hand, 0.57% (SD = 0.56) for the anterior side of the forearm, 0.53% (SD = 0.6) for the posterior side of the forearm, and 1.07% (SD = 1.22) for mid-air. Figure 5(b) illustrates the mean UER across all keyboard locations.

However, the RM-ANOVA indicated a significant effect of keyboard location on the CER ($F(4,48) = 31.39, p < 0.001$). Subsequent pairwise post-hoc comparisons confirmed statistically significant differences between all pairs of keyboard locations. These comparisons revealed that the palm had the lowest mean CER at 1.46% (SD = 1.28). This was followed by the back of the hand with a mean CER of 2.65% (SD = 1.56), the anterior side of the forearm at 4.84% (SD = 2.52), and the posterior side of the forearm at 7.54% (SD = 2.78). The highest mean CER was observed in the mid-air condition, with a value of 10.16% (SD = 3.32). Figure 5(c) shows the mean CER across all keyboard locations.

The RM-ANOVA also demonstrated significant effects of keyboard location on backspace usage ($F(4,48) = 33.7$, $p < 0.001$). Post-hoc comparisons revealed significant differences between all pairs of keyboard locations, confirming variations in backspace usage based on location. On average, participants used the backspace key 1.45 times (SD = 0.38) with the palm, 1.84 times (SD = 0.48) with the back of the hand, 2.56 times (SD = 0.78) on the anterior side of the forearm, 3.48 times (SD = 0.93) on the posterior side of the forearm, and 4.34 times (SD = 1.07) in mid-air. Figure 5(d) represents these variations across all keyboard locations.

4.5 Discussion

In our user study, participants preferred OnArmQWERTY over the baseline mid-air keyboard, noting they could type faster and with fewer errors. Overall, the total error rate (TER = UER + CER) for on-arm tap typing was approximately 56.81% lower than that of mid-air typing. P8 and P11 commented, *"Even though we can only select a key with the tip of the index finger and the keyboards are the same size in both the on-arm and mid-air conditions, I found myself making more unintended key presses in the mid-air scenario due to the lack of tactile feedback"*. P13 shared, *"Tactile feedback aids in motor control by providing immediate physical responses to actions. Without it, I felt less control over my index finger movement, making precise keystrokes more challenging"*. Further, P1 mentioned, *"Although visual and audio feedback were extremely helpful in providing immediate feedback when hitting a key in mid-air, I still needed to visually monitor my finger position closely to avoid passing through the key, which increased the cognitive load."*. These findings are consistent with existing research [13, 15], which suggests that the presence of haptic cues significantly enhances the typing experience. Using OnArmQWERTY, users also don't need to constantly adjust their hand position relative to the keyboard for tactile feedback, unlike with the STAR technique [37].

The palm was overwhelmingly favored as the location for projecting the keyboard, compared to all other body locations. Participants found tap typing in the palm area to be quite comfortable because it allowed them to keep their arms positioned in front of them with their elbows close to their bodies. This position maintains a more natural and relaxed posture, which helps prevent muscle fatigue over time. In our current setup, we projected a rectangular QWERTY layout directly onto the body. Consequently, depending on the individual hand size, a portion of the keyboard was positioned in the finger area (see Figure 2(A) and Figure 3(C)). This placement could potentially hinder typing efficiency and comfort. Participants suggested optimizing the keyboard layout to avoid placing keys in inter-finger spaces, thereby making typing more intuitive, reducing errors, and enhancing the overall typing experience.

In contrast, other on-arm keyboard locations—such as the back of the hand, and the anterior and posterior sides of the forearm—were not ergonomic enough to support fast and accurate text typing. For example, the skin on the back of the hand is thinner and has less fatty tissue compared to the palm, making it more closely associated with underlying bones such as the metacarpals and offering less friction and grip. As a result, participants noticed that the index finger of their dominant hand sometimes accidentally slipped while attempting to tap keys quickly on the projected keyboard, leading to more 'fat finger' typing errors than when using the palm. Similarly to the palm, they also suggested not placing keys in the inter-finger space areas. Additionally, users needed to rotate the back of their hand slightly clockwise after positioning their arm in front of them to view the entire keyboard properly. This posture potentially led to discomfort over time.

To type on the anterior side of the forearm, participants had to significantly raise their arms, causing their elbows to extend quite far from their bodies. A similar posture was necessary for typing on the posterior side of the forearm, with the additional requirement of rotating the forearm slightly clockwise to properly view the keyboard. In both conditions, these arm postures were fatiguing. These observations align with findings from existing research [52]. P5 mentioned, *"Particularly, I found typing on the posterior side of the forearm very uncomfortable compared to the anterior side, primarily because of the extra rotation required"*. Although we made the projected keyboard slightly curved to match both forearm surfaces, there were still some discrepancies. Since these surfaces have slight curvatures, users made comparatively more typing errors than on the almost flat surfaces like the palm. P4 and P12 noted, *"I encountered more typing errors on the posterior side of my forearm than the anterior side, primarily due to its greater anatomical curvature, which impacts my typing"*. When typing on forearm surfaces, the angle at which the index finger of the dominant hand approached the keys continually changed as it moved across different parts of the curvature where the keyboard was projected. Unlike typing on the palm, where the finger approached each key at a consistent angle, the curvature introduced variability and required more precise motor control, leading to more mistakes.

Our logged data analysis showed that participants used the word suggestion feature an average of 4.64 times (SD = 0.59) per target phrase across all keyboard locations. Since each phrase averaged 5 to 6 words, with 5 characters per word, this indicates that participants consistently relied on word suggestions to enter nearly all words in a phrase, regardless of keyboard location. When using the word suggestion feature, users typically needed to type a portion of the target word (e.g., the first few letters) before relevant word suggestions appeared. If an error occurred while typing these initial characters, it could disrupt the typing flow, leading to slower WPM and increased cognitive load. In ergonomic locations like the palm, users made fewer errors when typing the initial characters, resulting in faster typing speeds. Conversely, in challenging locations like mid-air, users made more errors while typing the initial characters and required more corrections before using word suggestions, which slowed down typing. This explains the WPM variation across keyboard locations, despite similar word suggestion usage rates.

Interestingly, our participants found that OnArmQWERTY, particularly typing on the palm, should be socially acceptable in on-the-go scenarios. They compared it to holding a smartphone with the non-dominant hand and using the index finger of the dominant hand to interact with the phone's touchscreen.

5 Limitations and Future Work

The current research has a number of limitations that suggest directions for future work.

First, we standardized the keyboard size across all on-arm and mid-air locations for all participants to maintain consistent experimental conditions. However, when projecting a rectangular QWERTY keyboard layout onto the palm, a significant portion of the keyboard often extended onto the finger area, especially for users with smaller hands compared to those with larger hands. Optimizing the keyboard layout, similar to PalmType [66], to avoid placing keys in inter-finger spaces would enhance the user experience. This adjustment would allow users to keep their fingers spread in a more relaxed manner during typing, instead of holding them together. The same adjustment could be beneficial for the back of the hand condition. Further, personalizing the keyboard size based on the user's hand size remains a valuable opportunity.

Second, in our study, we deliberately maintained the same keyboard size for both on-arm and mid-air conditions to explore the impact of self-haptic feedback on text entry performance. In the mid-air condition, our results show that users achieved an average typing speed of 10.95 WPM and an error rate of 1.07% after 10 phrases. In contrast, Dudley et al. [17] reported an average typing speed of 25.6 WPM and an error rate of 2.25% after 160 phrases, achieved through tap typing with two index fingers on a mid-air keyboard that was 30 cm wide—218.13% wider than our mid-air keyboard. This discrepancy suggests that participants could significantly improve their typing speeds, potentially exceeding 20 WPM in mid-air conditions, with extensive practice on a larger keyboard. Building on this idea, it would be interesting to further explore users' typing performance with our OnArmQWERTY, particularly when projected onto the palm, with additional practice. Currently, users achieve an average typing speed of 20.18 WPM and a 0.71% error rate after typing 10 phrases in the palm location.

Third, assessing OnArmQWERTY in real-world settings is an important aspect. Initially evaluated in a lab under standing conditions, text entry naturally occurs in diverse situations—ranging from multitasking activities such as listening to music or conversing, to various postures like sitting, walking, or lying down. Understanding user experiences and text input performance in these varied environments is essential for practical applications. To implement the proof of concept for OnArmQWERTY, we utilized the Vicon tracking system. However, for the technique to be viable in real-world applications, achieving robust hand tracking with the built-in cameras of the headset is necessary.

Finally, our study focused on tap-based typing; however, exploring swipe typing [79] across various body locations presents a promising direction for future research. Additionally, we used a simplified keyboard layout, but a full keyboard, complete with punctuation, numerals, and case modification capabilities, will likely be necessary to fully meet user needs during text input. While our proposed OnArmQWERTY primarily addressed the AR context, this technique is also applicable to VR. The main distinction in VR is that users see a virtual representation of their hands rather than their physical hands. Further investigation is needed to determine how this difference impacts on-arm typing performance.

6 Conclusion

We introduce OnArmQWERTY, a text input technique for AR HMDs that projects a virtual QWERTY keyboard onto the user's non-dominant hand, including the palm, back of the hand, and both the anterior and posterior sides of the forearm. Our user study shows that OnArmQWERTY significantly outperforms mid-air keyboard in typing speed and accuracy, with a 56.81% lower error rate. The palm was preferred for its ergonomic comfort and reduced fatigue, while other locations had higher error rates and discomfort. These findings suggest palm-based interfaces are efficient for AR text entry. Future research should optimize keyboard layouts for different hand sizes and evaluate this method in real-world settings.

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