KnuckleBoard: Knuckle-based Input in Augmented Reality while Sitting, Standing, and Walking

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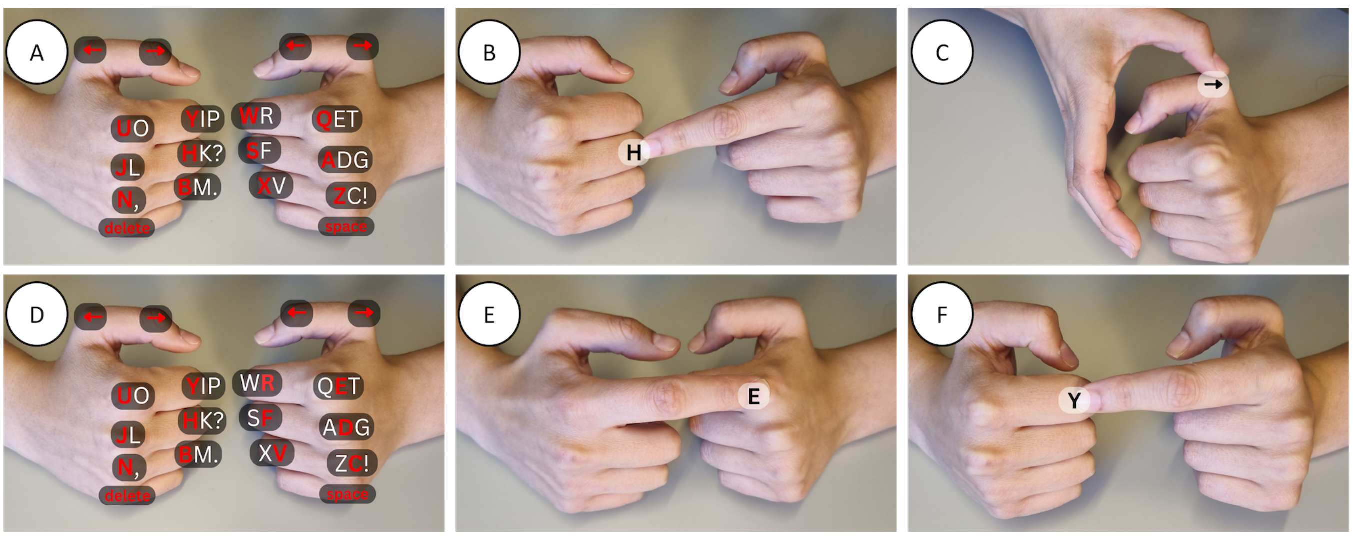

Figure 1: Typing "hey" using the knuckle-based technique. Active letters are in red, inactive in white. Thumb knuckles switch between QWERTY keyboard tabs on the index, middle, and ring fingers. The left pinky acts as "space," and the right pinky as "delete." (A) The first tab is selected, (B) "H" is entered, (C) the tab switches on the left hand, (D) the second tab activates, (E) "E" is entered, and (F) "Y" is entered.

Abstract

Interaction with digital content has changed substantially with the introduction of Augmented Reality (AR). User input in AR is essential for messaging or note-taking and typically relies on mid-air keyboards and controllers. However, these methods lead to fatigue, reduce visual attention, and are not designed for use in public spaces, making them impractical in dynamic contexts, e.g., walking. In this paper, we introduce knuckle-based input in AR for text entry. To explore this idea, we conducted a controlled experiment (N=18) comparing it to the state-of-the-art controller-based input while sitting, standing, and walking. We found that the knuckle method provided a better user experience and was preferred for walking due to its engaging nature and reduced visual focus. In contrast, controller input was favored for sitting and standing due to accuracy and ease of use.

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CCS Concepts

• **Human-centered computing** → **Text input**; **Empirical studies in HCI**.

Keywords

Knuckles, Augmented Reality, Text Input, Interaction On-the-Go

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1 Introduction

Augmented Reality (AR) has become a transformative technology for a wide range of sectors [1, 2, 5, 10, 13, 23, 40–42, 54], seamlessly integrating digital information in the real world. User input in AR is essential for messaging or note-taking and typically relies on mid-air keyboards and controllers; however, these methods are not designed for use in public spaces, making them impractical in dynamic contexts, e.g., walking.

Previous research has explored diverse text input approaches. Some methods support mid-air interactions through, for example, controller-pointing [26, 48], finger tracking [33, 55], or gaze-selection [47], but lack the haptic force feedback provided by desktop keyboards. Other methods provide haptic feedback [17, 27] but require a stationary surface, which is not suitable for dynamic mobile contexts. Hand-held devices with keyboard buttons can be used [30], but this occupies the user's hands for other interactions. To address these challenges, researchers have begun to explore wearable and on-body text input techniques, such as skin-based input [21, 37], headset buttons [22], and finger-worn keyboards [29]. These methods could provide a more natural text input for stationary and mobile contexts. However, users often experience physical fatigue, particularly in the hands, wrists, and elbows, due to mid-air input [43], making it important also to explore how user comfort can be facilitated. Moreover, most existing research focuses primarily on static, "stop-to-interact" scenarios, leaving a gap in understanding how wearable methods perform in mobile contexts where low visual attention is of key importance [34].

In this paper, we propose knuckle-based input in Augmented Reality and explore it in sitting, standing, and walking for text entry. Specifically, we utilized knuckles as interactive buttons augmented with soft textile gloves to reduce visual focus and offer haptic feedback without additional hardware. For this, we conducted a controlled experiment (N=18), in which participants' task was to enter text with a knuckle-based keyboard (*KnuckleBoard*) and controllers while sitting, standing, and walking. Our preliminary results indicate that, despite a steeper learning curve, knuckle-based input provides a better user experience and is preferred while walking due to its engaging nature and reduced visual focus. However, controllers were the preferred input method for sitting and standing. With this work, we contribute a novel knuckle-based input method, custom haptic gloves that augment the knuckles as an input interface and provide on-body haptic feedback, and the empirical evaluation of this method while sitting, standing, and walking.

2 Related work

2.1 Importance of Haptic Feedback for Input

Haptic feedback can enhance user experiences and typing performance, particularly in dynamic and visually demanding environments like AR [32]. Regular keyboards provide haptic feedback through tactile finger-specific sensations of the keys and the physical limit imposed by the keys (force feedback) [18]. Tactile key-click feedback improves accuracy and error rate on flat keyboards, also compared to auditory key-click feedback [31], and lack of tactile feedback leads to greater visual and cognitive attention during mid-air typing [18]. However, mid-air typing without force resistance (e.g., through surfaces) can lead to significantly higher error rates [11] and fatigue [43, 55]. Hand-held devices with keyboard buttons can be used [30]; however, this occupied the hands for other forms of interaction.

These limitations can be addressed through on-body touch interaction. Cheng and Chan investigated the accuracy and user experience of eye-free input, showing that on-body touch achieved higher accuracy and user preference compared to near-body touch [8]. Keyboard buttons can be attached to the headset, which can provide efficient text input [22], but will likely cause fatigue due to the position of the arms. Harrison et al. explored interactive input through the use of acoustic vibrations from finger taps on the arm and hands [21], and demonstrated a wearable depth-sensing and projection system that provides haptic feedback from the hands or other parts of the body or external surfaces [20]. Wang et al. used palms as interactive surfaces for smart wearable displays and showed precise input without visual attention, demonstrating faster text entry than traditional touchpad-based keyboards [50]. Whitmire et al.'s "DigiTouch" used textile gloves with conductive materials to detect finger taps and thumb-to-finger interactions for text input [53]. More recently, Mollyn et al. used the fingertip with a small sensor and the bare palm for skin input using just an RGB camera integrated into the AR headset and showed that this approach could be accurate and robust across diverse lighting conditions, skin tones and body motion, including input while walking [37]. Similarly to these methods, our two-handed technique employs intra-touch by combining the tactile sensation of the fingertips of one hand and the knuckles of another while simultaneously leveraging the hand's physical landmarks instead of a flat body surface.

2.2 Interactions On-the-Go

While smart glasses are becoming more widely adopted, text input remains primarily gesture-based, voice-based, or pointer-based, limiting integration into daily life [3]. Marshall and Tennent argue that most mobile systems are "stop-to-interact", designed for active interaction only when the user is standing still and paying visual and mental attention to the device [34]. However, people are increasingly using devices while engaged in various movement activities that require interaction support in motion. Bergstrom-Lehtovirta et al. investigated the trade-off between walking speed and user performance [4], in which they used a treadmill to vary users' walking speed and observe the effect on users' typing on a mobile touchscreen device. They found that users' walking speed decreases 20-60% to maintain an acceptable typing speed. Adaptive

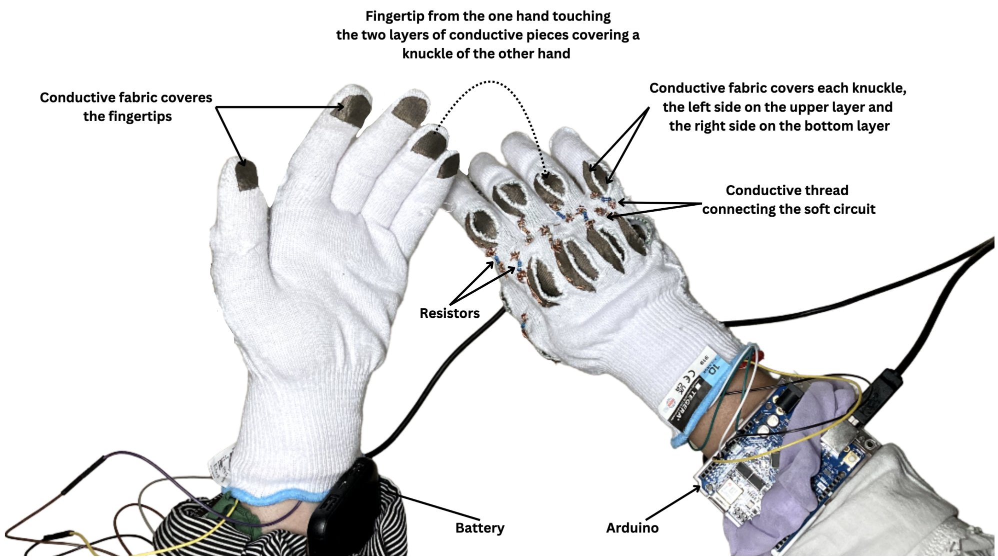

Figure 2: The KnuckleBoard: The gloves incorporate an embroidered soft circuit and conductive textiles to detect touch inputs on the knuckles. Each double-layered glove is connected to an Arduino microcontroller and a battery attached to the wrist.

walking user interfaces (WUIs) have been developed to compensate for the impairments caused by walking [25]. These interfaces dynamically adjust their layout based on the user's movement, improving usability and performance [25, 29].

A notable advancement for on-the-go interaction is the development of on-body methods, which leverage the human body as an input surface. For example, Vechev et al. explored on-body athletic interaction for running and cycling, identifying specific body locations, such as the chest and wrists, suitable for tapping gestures [49]. Fang et al.'s work on handwriting letters on the body highlights how tactile feedback reduces cognitive load for efficient on-the-move tasks [15]. At the same time, Lee et al. showed that intra-hand touches between the thumb and fingers improve typing speed and error rate in mobile scenarios [29], emphasizing the benefits of tactile-enhanced interactions. Lastly, text input methods for cyclists underscore the importance of tactile feedback to maintain safety and focus on the surroundings [35]. In our work, we explore a novel on-body text input method using the knuckles as an always-available input in different interaction contexts.

3 Knuckles as Input

Knuckles are prominent body landmarks [52] that provide a consistent reference point for the fingers and natural awareness of hand positioning, orientation, and finger movements. Moreover, knuckles harness natural affordances of human anatomy through "intra-touch" (self-touch), i.e., a fingertip touching a knuckle, which provides a tactile on-body sensation [6]. They can be interpreted as buttons due to their physical characteristics, e.g., round and rigid, that provide a tactile surface for pressing and tapping with the fingers of the opposite hand [45]. Each knuckle also supports several distinct touch regions nearby, which makes it appropriate to choose the outer part of the hand for a touch interface [19]. Users could rest one hand on the other while typing or rest both hands on their knees using their elbows. By choosing the knuckle region for input, we rely on proprioception and humans' natural haptic distinction when touching their own bodies. We build on the advantages of using our hands as an interface that have been previously explored by Faleel et al. [14], who proposed a framework for hand-proximate user interfaces (HPUIs), which are virtual interfaces registered to the user's hand or the space around it. Thus, given the knuckle affordances, we designed and developed a novel knuckle-based input method that turns knuckles into buttons.

We employed a QWERTY layout mapped on the knuckles to facilitate comparison with a state-of-the-art input method – ray-traced pointing with controllers. We split the keyboard into two parts, where each hand has half the set of keys (Figure 1). The QWERTY layout was assigned to four fingers: index, middle, ring, and pinky. Each finger had two input sources on each side of the knuckle, allowing the selection of two tabs from the QWERTY layout. As this configuration supports 8 x 2 unique keys, the thumbs were used as navigation buttons to switch between tabs for different keys. The pinky on the left hand was assigned as the "space", and the pinky on the right was the "delete".

To implement the knuckle-based interaction, we created a prototype consisting of gloves with hand-sewn circuits made out of conductive threads and textiles. Each knuckle button functioned as a switch. Touch events are registered when the fingertip of one hand covers both sides of the textile button of the other hand, closing the circuit. The knuckle button had a "coffee bean" shape (Figure 2) to accommodate a wider range of hand shapes. The gloves were connected to two Arduino Uno Wifi boards powered by lightweight power banks attached to the wrists. We used a User Datagram Protocol (UDP) to facilitate communication between the Arduino and the Unity Application running on Meta Quest 3. We used two

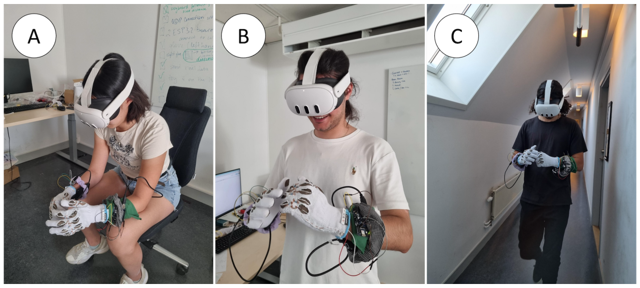

Figure 3: We explored three interaction contexts for text input: (A) sitting, (B) standing, and (C) walking.

analog inputs on the Arduino: one responsible for the upper and one for the bottom row of knuckles (Figure 2). To determine which button was pressed, each knuckle button was connected to a unique resistor. Therefore, the voltage variation could be mapped to the unique button.

4 Evaluation

To explore knuckle-based interactions in Augmented Reality (AR) while sitting, standing, and walking, we conducted a controlled indoor experiment with the following research question: *How can knuckle-based input increase user experience and usability compared to controller-based input for text entry in AR while sitting, standing and walking?*

4.1 Participants

We conducted a controlled experiment with 18 participants (7 male, 11 female) between 21 and 44 years old ($M = 27.5, SD = 6.1$). They were recruited using social networks and the university's marketing channels. All participants had to fit a (stretchable) glove, size eight (medium) and tried all conditions. The participants had different levels of experience with AR (9 beginners, 3 intermediate users and 6 experts). They did not receive any compensation for their participation.

4.2 Study Design

The study employed a within-subject design with two independent variables: (1) *input method* and (2) *interaction context*. The input method included two levels that employ two-handed interaction techniques based on (1) controllers as a baseline and (2) knuckles. For the controllers, we used the most popular and conventional way of input in a VR based on "aim and shoot," in which a hand-held controller is used to cast a virtual ray to select a particular key. The final confirmation is made using a controller button [30]. We used the knuckles as a keyboard, building on the advantages that textile gloves offer haptic feedback from the body and allow tangible interaction, enhancing immersion and user experience [53]. Interaction contexts include (1) sitting, (2) standing, and (3) walking (Figure 3). Sitting provides a stationary interaction context where the user can focus on the input method [12], standing introduces moderate physical demand and more freedom and is sometimes the preferred interaction case for VR or AR [9, 51], and walking represents dynamic mobile context, testing the effectiveness of input methods in

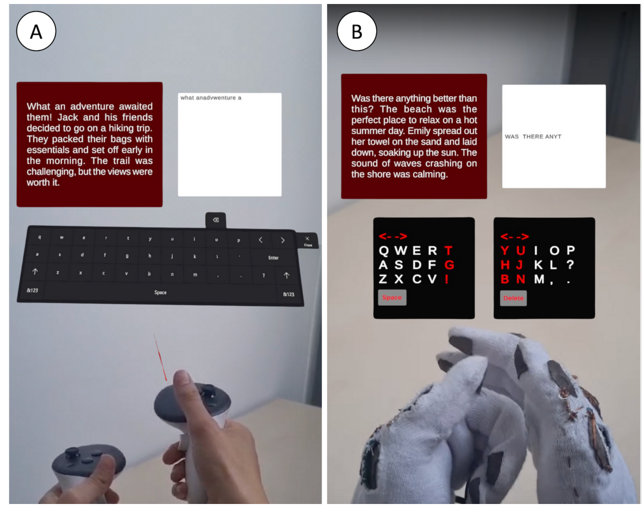

Figure 4: Typing task and AR interface with controllers (A) and gloves (B).

challenging contexts [4, 28]. To explore all levels of independent variables, we created six experimental conditions by combining two types of input methods and three contexts. The order of the conditions was counterbalanced for the two input methods (gloves or controllers) using a balanced Latin square and randomized for interaction contexts within each method. Participants experienced the three interaction contexts in a randomized order with each typing method. To avoid repeatedly putting on and off the gloves and the accompanying hardware, participants changed an input method after experiencing all three scenarios.

Participants were tasked with entering a pre-defined text shown in front of them in the virtual space within three minutes. The texts for the transcription typing task were easy to understand and consisted of simple words taken from children's books. Since we did not want the participants to remember the typed text between the conditions, there were six different texts randomized for each condition (input method with interaction context), as it has been previously used for reading in dynamic contexts [36]. The AR environment, made with Unity (version 2022.3.18f1), provided a realistic pass-through mode, allowing participants to see the virtual keyboard mapped to their knuckles or the controller-based input interface. The interface looked the same for both typing methods, with the text that had to be written placed in the upper left corner, the input field in the upper right corner, and the keyboard underneath (Fig. 4). This interface was always in front of the users' view with a constant distance of 70 cm following previous studies on text entry in VR [48]. The QWERTY virtual keyboard was selected for controller typing by pointing to the ray and pressing the trigger button. For knuckle typing, users navigated through the split QWERTY interface by touching the knuckle of one hand to the other, with thumbs used for navigation (changing tabs). We used the Meta Quest 3 headset in an empty indoor space with consistent lighting conditions, with a chair for the sitting condition, a marked walking path for walking, and a designated standing area for the standing condition. In the walking conditions, participants walked a straight line back and forth in a corridor (30m) without any obstructions. To compare two input methods while sitting, standing, and walking, we measured the following dependent variables: (1) **User Experience** using a concise version of the standardized User Experience Questionnaire (UEQ-S) [44] and (2) **Workload** using the NASA Raw Task Load Index (NASA RTLX) [16].

4.3 Procedure

After obtaining informed consent, we collected participants' demographic data. Afterward, we provided a brief overview of the procedures, including explanations of the input methods and an AR test to familiarize the participants with the methods. Once comfortable, they proceeded with the experimental tasks, completing text input tasks with two different input methods in three different interaction contexts and entering a different text in each condition. At the end of the study, we interviewed participants regarding their preferences and experiences with the different text input methods and interaction contexts. The entire study lasted approximately one and a half hours.

5 Results

5.1 User Experience

We used the Shapiro-Wilk test to check the normality of the UEQ short scores [46]. Given that data was not normally distributed, we used the non-parametric Mann-Whitney U test. The pragmatic quality scores, encompassing ease of use and efficiency, did not show a statistically significant difference between gloves and controllers ($W = 2237.5, p = 0.1468$), suggesting that the pragmatic quality of both input methods was comparable. In contrast, the hedonic quality scores, reflecting excitement and interest, revealed a statistically significant difference between gloves and controllers ($W = 4899.5, p < 0.001$), indicating that the gloves were perceived as more enjoyable than the controllers. The overall quality scores, combining pragmatic and hedonic qualities, also showed a statistically significant difference between gloves and controllers ($W = 14958, p < 0.001$).

5.2 Mental Load

The values for the six subscales were rescaled to the 0-100 range, and Raw TLX was calculated as the mean of the subscales. The Shapiro-Wilk test was conducted to test for the normality of the NASA RTLX scores. Given that NASA RTLX scores were not normally distributed, we employed the Mann-Whitney U for each NASA RTLX score. We found a significant difference in mental demand between gloves and controllers, with gloves being more demanding ($W = 229.5, p = 0.033$), but no significant difference in physical ($W = 154.5, p = 0.824$) and temporal ($W = 185.5, p = 0.461$) demand, performance ($W = 187.5, p = 0.424$), effort ($W = 173, p = 0.735$), and frustration ($W = 207.5, p = 0.153$).

5.3 Qualitative Results

Knuckles. Participants enjoyed the novelty and haptics of knuckle input: *"The inventiveness, the creativity, and the fact that with practice you can get very skilled and efficient using this method."*[P1]. *"I think it is nice using your own body, since you always have it with you, and have like a haptic feedback."* [P8]. Participants also appreciated the reduced physical effort required in dynamic scenarios and preferred knuckles while walking:

"It felt way more natural and comfortable to use gloves while walking. My movement didn't affect this input method." [P16]. Since knuckles provided tactile feedback, participants appreciated the feeling of it and the fact that the knuckles are always with them: *"...it reminded me more of the feeling of a keyboard, in the sense you actually have to press something with fingers (like you do with the keyboard)."* [P10], The ability to develop body memory for key positions on the knuckles made the typing process quicker: *"I liked that a tap on the knuckles would equal a character and if you knew where the characters were, you did not have to look at the keyboard or your hand and could look at what you typed."* [P5], *"I think it takes a little bit more time to get used to it so you can become fluent. Probably using the method will help me to develop this 'body memory' after a while."* [P17]. The gloves allowed users to focus more on walking and less on typing, which was impossible with controllers due to the need to look at the virtual keyboard and correct mistakes constantly: *"The biggest difference is that I can use the gloves without looking."* [P8]. Participants also mentioned the potential for a discrete typing method for public spaces: *"I think it is a good method for a public setting, I like that it is discrete and taking quick notes while someone is talking will be great."* [P14] People did not like that it was sometimes inaccurate and took time to learn: *"I was not able to type many words correctly."* [P16]. Some participants suggested other layouts for better usability: *"Top and bottom do not match for me when I hold my hands differently"* [P0], *"Qwerty does not translate well into this interaction."* [P7].

Controllers. The controller typing method was mostly preferred because of accuracy and familiarity: *"It was easy to learn since it was more familiar."* [P8] Sitting and standing were the most comfortable scenario for using controllers, as participants could rest their hands and focus on typing: *"While sitting you don't have to focus that much on what is happening around you, so it is ok to look at the keyboard constantly. While standing and walking I would use gloves since you can focus more on what is happening around you."* [P9]. Many participants mentioned that they did not like controllers while walking because it was difficult and it made them dizzy and unsafe: *"While walking it was dangerous since I always had to take my eyes on the keyboard while pointing with the controllers."*[P9] Participants found the input slow because it took longer to fix mistakes: *"I was staring at the keyboard a lot so I missed when I had made errors in the text and had to backspace a lot."* [P6].

Interaction scenarios. Participants reported walking to be difficult in general, but extremely so with the controllers: *"Yes, walking and using the controllers was vastly more demanding than sitting or standing"* [P5]. Participants found interaction with gloves to be similar while sitting, standing, and walking: *"I felt comfortable and confident in all the scenarios."* [P9]. Most of them (13/18) preferred the controller over the gloves while sitting due to a higher comfort level and hand rest: *"The controllers are very good when sitting and standing as they give a visual indication of what you're going to input and if the input was registered on the keyboard."* [P12] Most participants (12/18) preferred the controller typing method while standing. Some participants thought standing requires more physical effort due to the need to keep their hands raised: *"While* *standing is similar to sitting with the controllers, but it requires a bit more demand because it is harder to stand still."* [P1]. Most participants (14/18) preferred walking with the knuckle input, finding it intuitive and advantageous for focusing on walking while typing. Typing while walking was challenging with controllers because the virtual keyboard bounced and led to errors: *"Controllers made it very hard to walk as they were so unsteady and I also had to look down a lot and wasn't looking where I was going at all, so I felt like I might fall over. With the gloves although the accuracy was much worse overall, I felt significantly more confident when walking, and were they to work correctly they would be a much superior method."* [P6]. Some participants walked faster than others because they felt comfortable with the wearable knuckle keyboard. *"Because it is very difficult to type with controllers when walking. Gloves would be more suitable when you are moving around so much. But when you are staying still, it is so much more efficient and comfortable with controllers."* [P1].

6 Discussion and Future Work

Text input in AR primarily focuses on aspects such as accuracy or error rate, which are important for the efficiency of a system but often leave the user experience and preference out of the scope. Our results show that using knuckles as a keyboard is a promising novel idea for users, which should be explored further, preferably with more accurate technological implementation. However, why does using knuckles for input work as a concept? As Gustafson et al. suggested, intra-touch allows users to explore interfaces while finding the location of the discovered target without looking [19]. Knuckle typing might leverage intra-touch to an even greater extent than the flat palms [19] because of the ability of the body to remember and associate the physical body landmarks to the digital interface [52], reinforced by the distinct skeletal structure of the outer hand [45].

Since our method was entirely based on knuckles, participants have reported that they could easily find the buttons and touch them without looking. Similarly, Chen et al. designed Body-Centric Interactions for a novel mobile browser application [7]. They introduced interactions beyond the small screen, driven instead by users' movement of the device on and around the body. Based on users' responses, the natural movement and feeling from the knuckles is what helped improve the user experience, making the interaction more akin to real-world actions. This approach utilizes users' pre-existing knowledge of the physical world to improve interaction, which can possibly enhance both usability and immersion in AR environments [24], but it has to be further explored in future studies. Our findings, specifically the appreciation of the haptic feedback coming from the body and the accessible and intuitive input method, show promise for creating more hand interfaces that combine the physical and the digital world, focusing on using the more distinguishable haptic body landmarks as interaction triggers, or use whole body parts, such as toes [39], eliminating the need for visual focus.

In stationary contexts, controller pointing is more efficient since there is no additional body movement, as mentioned by the participants. However, typing while walking presents challenges of divided attention and stable input. Returning to Marshall and Tennent's argument that most mobile systems are designed for interaction only when a user stands still and pays visual and mental attention to the device [34], we argue that controller-pointing fits into that description. In the case of knuckle-based input, we assume that the intuitiveness of interaction potentially leverages proprioception, tactile, and force feedback, but it has to be systematically explored in the future. These findings align with the Exertion Framework by Mueller et al. - the concept of the moving body, where the repositioning of body parts relative to one another during physical activity supports more natural and effective interaction [38]. Touching the outer part of the hand holds the potential for walking, contributing to the research of dynamic scenarios using the body as input. However, it can be used when both hands are available.

Previous work has found that typing performance diminishes and walking speed decreases when users have to input text on a smartphone while walking [4]. Our participants reported the same feeling when using controller-pointing in walking conditions. Having no physical proxy to hold and the obligatory task of looking at the interface reduced the interaction's complexity while using the knuckles. That became clear only when attention is divided, or there are two tasks, like walking and typing. Similar ideas have been explored in developing adaptive walking user interfaces, which compensate for situational impairments caused by walking [25]. These interfaces dynamically adjust their layout based on the user's movement. Our physical interface is the hands, which can always be adjusted to fit the movement.

A limitation of this study is the number of participants and the fact that the recruited group consisted mainly of university students. Future studies might focus on testing on bigger and more diverse groups. Another limitation was the size of the gloves. Everyone has different finger lengths and thicknesses, and the placement of knuckles can vary significantly. All participants tried the glove and were only chosen to proceed with the experiment if their hands fit. Moreover, while textiles were chosen to keep the glove as sleek as possible, they were not reliable for prolonged use since slight deformations affected the sensor capabilities and resulted in noisy or undetectable values for tap recognition. Thus, to improve the accuracy of the gloves, future researchers should find other more durable materials and improve the fit and flexibility of the gloves to better accommodate a wider range of hand sizes. Additionally, the higher mental load for using knuckles is possibly caused by the steep learning curve compared to the more familiar controllers. Therefore, future studies can explore the long-term use of knuckle-based input in more diverse scenarios; for example, to explore social acceptability, other input tasks such as using the buttons for control and navigation, and alternative technical solutions, such as hand tracking, to avoid additional hardware. In the case of text entry, different keyboard layouts should be tested. We acknowledge the lack of performance metrics such as speed or accuracy. This study focused on user experience findings with a proof-of-concept prototype, and a future study with an improved technical solution should be conducted to evaluate the proposed novel knuckle method more thoroughly and compare it to other gesture-based or on-body interaction methods.

7 Conclusion

In this paper, we presented a novel knuckle input method showcased for text entry in Augmented Reality while sitting, standing, and walking. From the preliminary evaluation of the designed and developed prototype based on the proposed concept, we discovered that participants prefer knuckle-based input over controller-pointing while walking since it allows them to maintain focus while simultaneously typing. However, the controllers were better suited for sitting and standing due to comfort, higher accuracy, and familiarity. Lastly, participants found the knuckle-based input intuitive after an initial learning phase, but it requires further refinement and possibly a different technological solution.

References

[1] Murat Akçayır and Gökçe Akçayır. 2017. Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review* 20 (Feb. 2017), 1–11. https://doi.org/10.1016/j.edurev.2016.11.002

[2] Ronald T. Azuma. 1997. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments* 6, 4 (Aug. 1997), 355–385. https://doi.org/10.1162/pres.1997.6.4.355

[3] Nuri Basoglu, Ali Emre Ok, and Tugrul U. Daim. 2017. What will it take to adopt smart glasses: A consumer choice based review? *Technology in Society* 50 (Aug. 2017), 50–56. https://doi.org/10.1016/j.techsoc.2017.04.005

[4] Joanna Bergstrom-Lehtovirta, Antti Oulasvirta, and Stephen Brewster. 2011. The effects of walking speed on target acquisition on a touchscreen interface. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services* (Stockholm, Sweden) *(MobileHCI '11)*. Association for Computing Machinery, New York, NY, USA, 143–146. https://doi.org/10.1145/2037373.2037396

[5] Mark Billinghurst and Andreas Duenser. 2012. Augmented Reality in the Classroom. *Computer* 45, 7 (July 2012), 56–63. https://doi.org/10.1109/MC.2012.111 Conference Name: Computer.

[6] S. J. Bolanowski, R. T. Verrillo, and Francis McGlone. 2004. Passive, active and intra-active (self) touch. *Behavioural Brain Research* 148, 1-2 (Jan. 2004), 41–45. https://doi.org/10.1016/s0166-4328(03)00157-8

[7] Xiang 'Anthony' Chen, Nicolai Marquardt, Anthony Tang, Sebastian Boring, and Saul Greenberg. 2012. Extending a mobile device's interaction space through body-centric interaction. In *Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services* (San Francisco, California, USA) *(MobileHCI '12)*. Association for Computing Machinery, New York, NY, USA, 151–160. https://doi.org/10.1145/2371574.2371599

[8] Wen-Wei Cheng and Liwei Chan. 2024. BodyTouch: Investigating Eye-Free, On-Body and Near-Body Touch Interactions with HMDs. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 4, Article 152 (jan 2024), 22 pages. https://doi.org/10.1145/3631426

[9] Yi Fei Cheng, Christoph Gebhardt, and Christian Holz. 2023. Interaction-Adapt: Interaction-driven Workspace Adaptation for Situated Virtual Reality Environments. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 109, 14 pages. https://doi.org/10.1145/3586183.3606717

[10] Oscar Danielsson, Magnus Holm, and Anna Syberfeldt. 2020. Augmented reality smart glasses in industrial assembly: Current status and future challenges. *Journal of Industrial Information Integration* 20 (Dec. 2020), 100175. https://doi.org/10.1016/j.jii.2020.100175

[11] John Dudley, Hrvoje Benko, Daniel Wigdor, and Per Ola Kristensson. 2019. Performance Envelopes of Virtual Keyboard Text Input Strategies in Virtual Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 289–300. https://doi.org/10.1109/ISMAR.2019.00027 ISSN: 1554-7868.

[12] John J. Dudley, Keith Vertanen, and Per Ola Kristensson. 2018. Fast and Precise Touch-Based Text Entry for Head-Mounted Augmented Reality with Variable Occlusion. *ACM Trans. Comput.-Hum. Interact.* 25, 6, Article 30 (dec 2018), 40 pages. https://doi.org/10.1145/3232163

[13] Barrett Ens, Joel Lanir, Anthony Tang, Scott Bateman, Gun Lee, Thammathip Piumsomboon, and Mark Billinghurst. 2019. Revisiting collaboration through mixed reality: The evolution of groupware. *International Journal of Human-Computer Studies* 131 (Nov. 2019), 81–98. https://doi.org/10.1016/j.ijhcs.2019.05.011

[14] Shariff AM Faleel, Michael Gammon, Kevin Fan, Da-Yuan Huang, Wei Li, and Pourang Irani. 2021. HPUI: Hand Proximate User Interfaces for One-Handed Interactions on Head Mounted Displays. *IEEE Transactions on Visualization and Computer Graphics* 27, 11 (2021), 4215–4225. https://doi.org/10.1109/TVCG.2021.3106493

[15] Fengyi Fang, Hongwei Zhang, Lishuang Zhan, Shihui Guo, Minying Zhang, Juncong Lin, Yipeng Qin, and Hongbo Fu. 2023. Handwriting Velcro: Endowing AR Glasses with Personalized and Posture-adaptive Text Input Using Flexible Touch Sensor. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 4, Article 163 (jan 2023), 31 pages. https://doi.org/10.1145/3569461

[16] Mattias Georgsson. 2020. NASA RTLX as a Novel Assessment Tool for Determining Cognitive Load and User Acceptance of Expert and User-based UsabilityEvaluation Methods. https://api.semanticscholar.org/CorpusID:222448058

[17] Yizheng Gu, Chun Yu, Zhipeng Li, Zhaoheng Li, Xiaoying Wei, and Yuanchun Shi. 2020. QwertyRing: Text Entry on Physical Surfaces Using a Ring. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 4, Article 128 (dec 2020), 29 pages. https://doi.org/10.1145/3432204

[18] Aakar Gupta, Majed Samad, Kenrick Kin, Per Ola Kristensson, and Hrvoje Benko. 2020. Investigating Remote Tactile Feedback for Mid-Air Text-Entry in Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 350–360. https://doi.org/10.1109/ISMAR50242.2020.00062 ISSN: 1554-7868.

[19] Sean G. Gustafson, Bernhard Rabe, and Patrick M. Baudisch. 2013. Understanding palm-based imaginary interfaces: the role of visual and tactile cues when browsing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 889–898. https://doi.org/10.1145/2470654.2466114

[20] Chris Harrison, Hrvoje Benko, and Andrew D. Wilson. 2011. OmniTouch: wearable multitouch interaction everywhere. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology* (Santa Barbara, California, USA) *(UIST '11)*. Association for Computing Machinery, New York, NY, USA, 441–450. https://doi.org/10.1145/2047196.2047255

[21] Chris Harrison, Desney Tan, and Dan Morris. 2010. Skinput: appropriating the body as an input surface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 453–462. https://doi.org/10.1145/1753326.1753394

[22] Wahyu Hutama, Hikari Harashima, Hironori Ishikawa, and Hiroyuki Manabe. 2021. HMK: Head-Mounted-Keyboard for Text Input in Virtual or Augmented Reality. In *Adjunct Proceedings of the 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 115–117. https://doi.org/10.1145/3474349.3480195

[23] María-Blanca Ibáñez and Carlos Delgado-Kloos. 2018. Augmented reality for STEM learning: A systematic review. *Computers & Education* 123 (Aug. 2018), 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

[24] Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. 2008. Reality-based interaction: a framework for post-WIMP interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 201–210. https://doi.org/10.1145/1357054.1357089

[25] Shaun Kane, Jacob Wobbrock, and Ian Smith. 2008. Getting off the treadmill: evaluating walking user interfaces for mobile devices in public spaces. 109–118. https://doi.org/10.1145/1409240.1409253

[26] Florian Kern, Florian Niebling, and Marc Erich Latoschik. 2023. Text Input for Non-Stationary XR Workspaces: Investigating Tap and Word-Gesture Keyboards in Virtual and Augmented Reality. *IEEE Transactions on Visualization and Computer Graphics* 29, 5 (2023), 2658–2669. https://doi.org/10.1109/TVCG.2023.3247098

[27] Pascal Knierim, Valentin Schwind, Anna Maria Feit, Florian Nieuwenhuizen, and Niels Henze. 2018. Physical keyboards in virtual reality: Analysis of typing performance and effects of avatar hands. In *Proceedings of the 2018 CHI conference on human factors in computing systems*. 1–9.

[28] Thomas Kosch, Andrii Matviienko, Florian Müller, Jessica Bersch, Christopher Katins, Dominik Schön, and Max Mühlhäuser. 2022. NotiBike: Assessing Target Selection Techniques for Cyclist Notifications in Augmented Reality. *Proc. ACM Hum.-Comput. Interact.* 6, MHCI, Article 197 (Sept. 2022), 24 pages. https://doi.org/10.1145/3546732

[29] DoYoung Lee, Jiwan Kim, and Ian Oakley. 2021. FingerText: Exploring and Optimizing Performance for Wearable, Mobile and One-Handed Typing. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 283, 15 pages. https://doi.org/10.1145/3411764.3445106

[30] Yongjae Lee and Gerard J Kim. 2017. Vitty: Virtual touch typing interface with added finger buttons. In *Virtual, Augmented and Mixed Reality: 9th International Conference, VAMR 2017, Held as Part of HCI International 2017, Vancouver, BC, Canada, July 9-14, 2017, Proceedings 9*. Springer, 111–119. https://doi.org/10.1007/978-3-319-57987-0_9

[31] Zhaoyuan Ma, Darren Edge, Leah Findlater, and Hong Z. Tan. 2015. Haptic keyclick feedback improves typing speed and reduces typing errors on a flat keyboard. In *2015 IEEE World Haptics Conference (WHC)*. 220–227. https://doi.org/10.1109/WHC.2015.7177717

[32] Nazih Mallouk, Majid Roshanfar, Pedram Fekri, and Javad Dargahi. 2024. A Brief Review on Recent Advances in Haptic Technology for Human-Computer Interaction: Force, Tactile, and Surface Haptic Feedback. In *2024 7th International Conference on Information and Computer Technologies (ICICT)*. 34–39. https://doi.org/10.1109/ICICT62343.2024.00012 ISSN: 2769-4542.

[33] Daniela Markov-Vetter, Eckard Moll, and Oliver Staadt. 2012. Evaluation of 3D selection tasks in parabolic flight conditions: pointing task in augmented reality user interfaces. In *Proceedings of the 11th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry* (Singapore, Singapore) *(VRCAI '12)*. Association for Computing Machinery, New York, NY, USA, 287–294. https://doi.org/10.1145/2407516.2407583

[34] Joe Marshall and Paul Tennent. 2013. Mobile interaction does not exist. 2069–2078. https://doi.org/10.1145/2468356.2468725

[35] Andrii Matviienko, Jean-Baptiste Durand-Pierre, Jona Cvancar, and Max Mühlhäuser. 2023. Text Me if You Can: Investigating Text Input Methods for Cyclists. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 270, 7 pages. https://doi.org/10.1145/3544549.3585734

[36] Andrii Matviienko, Damir Mehmedovic, Florian Müller, and Max Mühlhäuser. 2022. "Baby, You can Ride my Bike": Exploring Maneuver Indications of Self-Driving Bicycles using a Tandem Simulator. *Proc. ACM Hum.-Comput. Interact.* 6, MHCI, Article 188 (Sept. 2022), 21 pages. https://doi.org/10.1145/3546723

[37] Vimal Mollyn and Chris Harrison. 2024. EgoTouch: On-Body Touch Input Using AR/VR Headset Cameras. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 69, 11 pages. https://doi.org/10.1145/3654777.3676455

[38] Florian 'Floyd' Mueller, Darren Edge, Frank Vetere, Martin R. Gibbs, Stefan Agamanolis, Bert Bongers, and Jennifer G. Sheridan. 2011. Designing sports: a framework for exertion games. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2651–2660. https://doi.org/10.1145/1978942.1979330

[39] Florian Müller, Daniel Schmitt, Andrii Matviienko, Dominik Schön, Sebastian Günther, Thomas Kosch, and Martin Schmitz. 2023. TicTacToes: Assessing Toe Movements as an Input Modality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 520, 17 pages. https://doi.org/10.1145/3544548.3580954

[40] Riccardo Palmarini, John Ahmet Erkoyuncu, Rajkumar Roy, and Hosein Torabmostaedi. 2018. A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing* 49 (Feb. 2018), 215–228. https://doi.org/10.1016/j.rcim.2017.06.002

[41] Pranav Parekh, Shireen Patel, Nivedita Patel, and Manan Shah. 2020. Systematic review and meta-analysis of augmented reality in medicine, retail, and games. *Visual Computing for Industry, Biomedicine, and Art* 3, 1 (Sept. 2020), 21. https://doi.org/10.1186/s42492-020-00057-7

[42] Roberto Pierdicca, Emanuele Frontoni, Rama Pollini, Matteo Trani, and Lorenzo Verdini. 2017. The Use of Augmented Reality Glasses for the Application in Industry 4.0. In *Augmented Reality, Virtual Reality, and Computer Graphics*, Lucio Tommaso De Paolis, Patrick Bourdot, and Antonio Mongelli (Eds.). Springer International Publishing, Cham, 389–401. https://doi.org/10.1007/978-3-319-60922-5_30

[43] Marius Schenkluhn, Christian Peukert, Anke Greif-Winzrieth, and Christof Weinhardt. 2023. Does One Keyboard Fit All? Comparison and Evaluation of Device-Free Augmented Reality Keyboard Designs. In *Proceedings of the 29th ACM Symposium on Virtual Reality Software and Technology* (Christchurch, New Zealand) *(VRST '23)*. Association for Computing Machinery, New York, NY, USA, Article 5, 11 pages. https://doi.org/10.1145/3611659.3615692

[44] Martin Schrepp. 2015. User Experience Questionnaire Handbook. https://doi.org/10.13140/RG.2.1.2815.0245

[45] Robert J Schwarz and C Taylor. 1955. The anatomy and mechanics of the human hand. *Artificial limbs* 2, 2 (1955), 22–35.

[46] S. S. SHAPIRO and M. B. WILK. 1965. An analysis of variance test for normality (complete samples)†. *Biometrika* 52, 3-4 (Dec. 1965), 591–611. https://doi.org/10.1093/biomet/52.3-4.591 _eprint: https://academic.oup.com/biomet/article-pdf/52/3-4/591/962907/52-3-4-591.pdf.

[47] Rongkai Shi, Yushi Wei, Xueying Qin, Pan Hui, and Hai-Ning Liang. 2023. Exploring Gaze-Assisted and Hand-Based Region Selection in Augmented Reality. *Proc. ACM Hum.-Comput. Interact.* 7, ETRA, Article 160 (may 2023), 19 pages. https://doi.org/10.1145/3591129

[48] Marco Speicher, Anna Maria Feit, Pascal Ziegler, and Antonio Krüger. 2018. Selection-based Text Entry in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174221

[49] Velko Vechev, Alexandru Dancu, Simon T Perrault, Quentin Roy, Morten Fjeld, and Shengdong Zhao. 2018. Movespace: on-body athletic interaction for running and cycling. In *Proceedings of the 2018 international conference on advanced visual interfaces*. 1–9.

[50] Cheng-Yao Wang, Wei-Chen Chu, Po-Tsung Chiu, Min-Chieh Hsiu, Yih-Harn Chiang, and Mike Y. Chen. 2015. PalmType: Using Palms as Keyboards for Smart Glasses. *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services* (2015). https://api.semanticscholar.org/CorpusID:15509837

[51] Yanbin Wang, Yizhou Hu, and Yu Chen. 2021. An experimental investigation of menu selection for immersive virtual environments: fixed versus handheld menus. *Virtual Reality* 25, 2 (June 2021), 409–419. https://doi.org/10.1007/s10055-020-00464-4

[52] Martin Weigel, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. 2017. SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3095–3105. https://doi.org/10.1145/3025453.3025704

[53] Eric Whitmire, Mohit Jain, Divye Jain, Greg Nelson, Ravi Karkar, Shwetak Patel, and Mayank Goel. 2017. DigiTouch: Reconfigurable Thumb-to-Finger Input and Text Entry on Head-mounted Displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3, Article 113 (sep 2017), 21 pages. https://doi.org/10.1145/3130978

[54] Hsin-Kai Wu, Silvia Wen-Yu Lee, Hsin-Yi Chang, and Jyh-Chong Liang. 2013. Current status, opportunities and challenges of augmented reality in education. *Computers & Education* 62 (March 2013), 41–49. https://doi.org/10.1016/j.compedu.2012.10.024

[55] Xin Yi, Chen Liang, Haozhan Chen, Jiuxu Song, Chun Yu, Hewu Li, and Yuanchun Shi. 2023. From 2D to 3D: Facilitating Single-Finger Mid-Air Typing on QWERTY Keyboards with Probabilistic Touch Modeling. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 1, Article 38 (mar 2023), 25 pages. https://doi.org/10.1145/3580829