# Effects of Passive Shoulder Support Exoskeleton and Keyboard Interaction Design on Mid-Air Typing in Mixed Reality

Haejun Kim[1] [0009-0001-0717-6776], Qiuli Jin[1] [0009-0006-5657-3918], Seonghyeok Park[1] [0000-0001-6968-9289], Woojoo Kim[2]* [0000-0001-6203-7309], Shuping Xiong[1]* [0000-0003-1549-515X]

[1] Human Factors and Ergonomics Laboratory, Department of Industrial and Systems Engineering, Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
{vedonefor, qiuli, seonghyeok, shupingx}@kaist.ac.kr

[2] Division of Liberal Studies, Kangwon National University
1 Kangwondaehak-gil, Chuncheon-si, Gangwon-do 24341, Republic of Korea
woojoo.kim@kangwon.ac.kr

* Corresponding authors.

Woojoo Kim – Telephone: +82-33-250-7653 / Email: woojoo.kim@kangwon.ac.kr
Shuping Xiong – Telephone: +82-42-350-3132 / Email: shupingx@kaist.ac.kr

**Abstract**

Typing in Mixed Reality (MR) presents significant interaction and ergonomic challenges, particularly in mid-air scenarios. This study investigated how passive shoulder support exoskeletons and different keyboard interaction designs affect mid-air typing in Mixed Reality. Twenty participants performed typing tasks across three keyboard conditions (Physical, Virtual-Poking, and Virtual-Touch) both with and without exoskeleton support. Results showed exoskeletons significantly reduced deltoid muscle activity and self-reported fatigue without compromising typing performance. When wearing exoskeletons, participants exhibited increased shoulder flexion and abduction angles with decreased hand movement distance. Physical keyboards significantly outperformed virtual keyboards in typing metrics. Among virtual keyboards, the Poking interface received higher haptic sensation ratings than the Touch interface and demonstrated better compatibility with exoskeletons. These findings inform the development of sustainable mid-air text entry solutions that balance ergonomic support with performance and satisfaction, suggesting keyboard interfaces should match available physical support infrastructure to optimize user experience in extended MR applications.

**Keywords**: Mixed reality, Exoskeleton, Mid-air typing, Keyboard interface, User experience, Ergonomics

## 1. Introduction

Mixed Reality (MR) has emerged as a transformative platform for human-computer interaction (HCI), offering immersive experiences by creating virtual worlds (Cipresso et al., 2018; Cometti et al., 2018). Recent advancements in commercial MR headsets have significantly enhanced the quality and accessibility of MR experiences (Bailenson et al., 2024). These environments enable innovative applications across education (Radu, 2021), manufacturing (Plakas et al., 2020), healthcare (Kan Yeung et al., 2021), and numerous other domains (Helin et al., 2018; Ullo et al., 2019).

Within these MR environments, text entry remains a fundamental requirement, allowing users to enter information into system interfaces and facilitate communication in collaborative virtual spaces. However, typing in MR presents significant ergonomic challenges, particularly in mid-air typing scenarios. Unlike traditional interfaces where surfaces support users' arms, MR interactions require sustained arm elevation without physical support, which causes arm fatigue commonly referred to as the 'gorilla arm' effect (Jerald, 2015; Joseph J. LaViola Jr., 2017). This prolonged unsupported posture creates substantial musculoskeletal strain in the shoulder region (Cheng et al., 2022; Huang et al., 2022), resulting in user discomfort, accelerated fatigue, and diminished task performance (Jerald, 2015; Kang & Shin, 2014; Shin & Zhu, 2011). With MR technologies becoming increasingly integrated into various aspects of work and daily life, developing solutions to these ergonomic issues has become essential for enabling sustainable and comfortable user experiences.

Passive shoulder support exoskeletons, initially developed for industrial tasks involving prolonged overhead work, offer promising ergonomic interventions that could mitigate these MR-related ergonomic challenges. In manufacturing and assembly-line contexts, these exoskeletons have consistently demonstrated their capability to reduce muscle activation and alleviate discomfort, improving work endurance without compromising performance (Ma et al., 2023; Jorgensen et al., 2022a, 2022b; Naito et al., 2007; Sylla et al., 2014; Van Engelhoven et al., 2018). Given their effectiveness in addressing similar physical demands in industrial settings, these devices could effectively reduce the ergonomic burdens of sustained mid-air interactions in MR environments. However, to date, research has primarily focused on industrial applications. Although Kong et al. (2023) demonstrated that exoskeletons can significantly reduce shoulder muscle activity during AR interactions involving mid-air gestures such as pointing and tapping. However, their effects across extended tasks such as keyboard typing and on comprehensive performance metrics remain unclear.

While ergonomic support systems like exoskeletons might address the physical strain of MR mid-air typing, keyboard interaction design represents another critical avenue for improving mid-air typing experiences. The fundamental challenge with virtual keyboards lies in their significantly diminished performance compared to physical keyboards due to factors such as tracking inaccuracies and the absence of haptic feedback. This performance gap has motivated diverse research approaches to enhance virtual keyboard interactions (Speicher et al., 2018; Yeo et al., 2017; Yi et al., 2015).

The absence of haptic feedback in mid-air typing significantly deteriorates the user experience by failing to provide confirmation of user actions. Research consistently confirms this problem across multiple studies (Aromaa et al., 2020; Benko et al., 2006; Burnett, 2008; Faeth & Harding, 2014; Islam & Lim, 2022a; Zhao et al., 2014), and this has led researchers to explore pseudo-haptic features as an alternative solution—creating the illusion of haptic feedback through visual cues without requiring physical stimuli (Chattopadhyay, 2016; Hachisu et al., 2011).

Among the various pseudo-haptic features explored, key protrusion has received particular attention in MR text entry research, though under different names such as "pseudo-haptic button" (W. Kim & Xiong, 2022a; Speicher et al., 2018), "3D key" (Bermejo et al., 2021; Dube & Arif, 2020), or "spatial enhancement technique" (Yang et al., 2019)—has been studied in MR text entry with inconsistent results. Research has continued to investigate this promising approach in various contexts. Dube and Arif (2020) conducted a comparative study of six different key designs (3 shapes × 2 dimensions) and revealed that key shape significantly affects typing speed, while dimension impacts accuracy. Kim and Xiong (2022) examined pseudo-haptic and self-haptic approaches, finding that keys with pinch interactions and pseudo-haptic features like protrusion and hit effects, improved user experience, haptic sensation, and embodiment without requiring additional hardware. Akhoroz and Yildirim (2024) examined different key representations and found that protruded 3D keys with push-and-depress functionality (poke typing) outperformed flat 2D interfaces in text entry speed, error reduction, and cognitive load. However, these findings contrast with Bermejo et al., (2021), who found lower entry speed with protruded keys, highlighting the complexity of optimizing virtual keyboard design factors.

In addition to these inconsistent results, a significant methodological gap exists in the literature. Current research primarily relies on subjective evaluations of physical fatigue and basic hand movement metrics, but lacks analysis of more comprehensive objective indicators for muscle activity. Most notably, there remains a need for integrated examinations incorporating electromyography (EMG) data alongside precise measurements of shoulder angles and movement patterns to fully understand the ergonomic implications of differences between typing on physical and virtual keyboards, as well as variations among different virtual keyboard designs.

Lastly, while both exoskeleton and keyboard interaction design have shown potential individually, the synergy between these approaches remains insufficiently investigated. Previous studies have primarily assessed the isolated impact of exoskeleton support on non-typing task execution but have not systematically evaluated how variations in user interface (UI) design might interact with ergonomic interventions (Choi et al., 2024; Kong et al., 2023). A comparative analysis of various keyboard interaction designs under varying support conditions could yield valuable insights into potential interaction effects and uncover new design opportunities for sustainable MR text entry.

This study aims to address aforementioned research gaps by investigating the relationship between passive shoulder support exoskeleton and keyboard interaction design during mid-air typing tasks in MR environments. In this research, we evaluate conditions with and without exoskeleton support across three different keyboard interfaces: one physical keyboard and two virtual keyboards with different designs. Through this experimental design, we comprehensively examine: (1) the overall impact of exoskeleton support on virtual keyboard typing performance and ergonomics, (2) the comparative effects between physical and virtual keyboards, as well as between different virtual keyboard designs, and (3) the potential interaction effects between exoskeleton support and keyboard interfaces. We evaluate multiple metrics, including text entry performance, muscle activation patterns, motion tracking, self-reported fatigue, and subjective usability measures. By examining various factors, we seek to identify optimal design combinations that effectively balance ergonomic support with typing efficiency and user satisfaction, ultimately contributing to the development of more sustainable text entry solutions for extended MR applications.

## 2. Methods

### 2.1. Participants

Twenty gender-balanced, healthy young Korean adults (10 males and 10 females), all fluent in English typing (Grudin, 1983), participated in this study (Table 1). All participants had normal or corrected-to-normal vision and were right-handed. Each participant met the minimum height requirement of 165 cm specified in the exoskeleton manufacturer guidelines for proper fit and functionality. All participants had prior experience with MR headsets, although the majority (13 participants) were classified as light users, engaging with MR applications no more than once per year. All participants provided informed consent in accordance with the protocol approved by the University Institutional Review Board (IRB No. KAISTIRB-2025-22).

**Table 1**. Descriptive statistics (mean ± standard deviation) of the participants

| Gender | Number of participants | Age (years) | Body height (cm) | Arm length (cm) |
|---|---|---|---|---|
| Male | 10 | 23.70 ± 2.87 | 174.78 ± 5.24 | 54.70 ± 2.50 |
| Female | 10 | 23.80 ± 3.16 | 168.30 ± 3.16 | 52.40 ± 2.50 |
| Total | 20 | 23.75 ± 2.57 | 171.54 ±5.36 | 53.55 ± 2.74 |

## 2.2. Experimental design

A 3 × 2 within-subject factorial design was implemented to evaluate the effects of keyboard type (*Physical*, Virtual-*Poking*, and Virtual-*Touch*) and exoskeleton condition (with and without) on mid-air typing performance and user experience (Figure 1).

For the keyboard conditions, a Logitech MX Keys Mini served as the baseline Physical keyboard. The two virtual keyboard conditions were implemented as follows: the Touch keyboard consisted of a virtual 2D panel that responded to direct touch input, and the Poking keyboard incorporated protruded 3D keys with pseudo-haptic press-and-release interaction, adapted from Akhoroz & Yildirim (2024). The Poking keyboard featured keys with a pushable contact surface that could be visibly moved downwards to the base, providing enhanced visual feedback during key activation.

In the Poking keyboard, each key was modeled as a 3D object with a depressible surface rendered in Unity. When the fingertip cursor contacted the key surface, the key began to visually depress, and input was registered once it was fully pressed down by 0.3 cm, which corresponded to the physical key height. During this process, the system also provided visual cues: as the finger approached within 3 cm of the key center, the key color changed to light gray, and upon activation it transitioned to a brighter gray. This visual depression created the illusion of pressing a physical key, whereas the Touch keyboard registered input immediately upon contact without any depth-based depression animation. To prevent visual obstruction during typing, virtual hand representations were rendered semi-transparently throughout the experiment, guaranteeing a clear view of the keyboard.

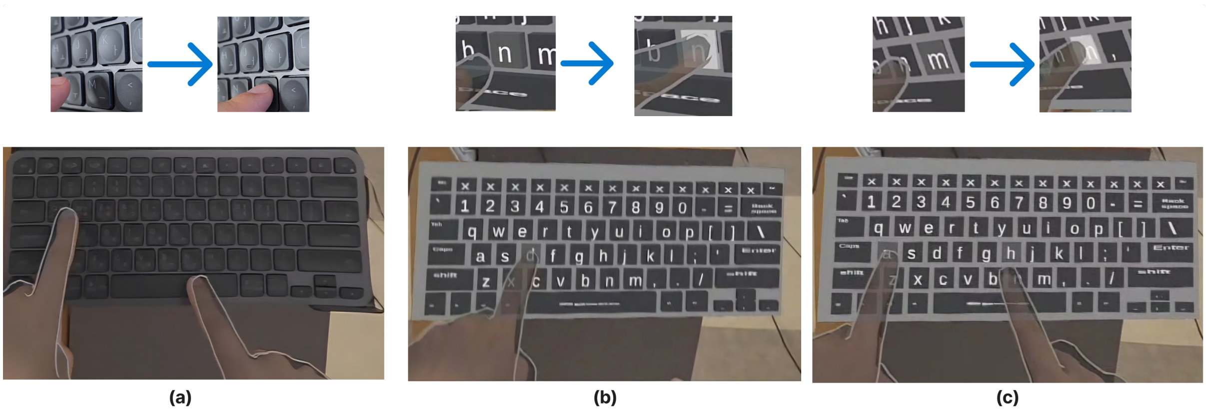


**Figure 1.** Three types of keyboards investigated in this study: (a) Physical, (b) Virtual-Poking, and (c) Virtual-Touch keyboards.


**Figure 2.** Keyboard layouts and dimensions. (a) The Logitech MX Keys Mini used in the Physical keyboard condition, and (b) the layout of virtual keyboards used in both Poking and Touch conditions. The key height of the Poking keyboard condition was 0.3 cm, identical to that of the Physical keyboard.

## 2.3. Experimental settings

The experimental apparatus integrated multiple hardware and software components to create a controlled MR environment for text entry evaluation (Figure 3). Participants were equipped with a Meta Quest 3 MR headset connected to a Windows 11 PC (Intel Core i9-14900K processor, 32 GB RAM, NVIDIA RTX 4070 GPU) via Oculus Link using a USB 3.0 cable. We used the Meta Quest's built-in functionality for real-time hand tracking. The experimental environment was carefully controlled to eliminate potential tracking interference sources.

The study utilized the CDYS shoulder exoskeleton (Crimson Dynamics Technology Co. Ltd., Dalian, China), weighing 2.6 kg, which incorporated a mechanical spring system, shoulder and waist straps, metallic frames, and upper-arm support components (Figure 3a). This exoskeleton employed a spring-based mechanism in which supporting force increased proportionally with the angle of shoulder flexion up to 150°, after which the support gradually decreased (Jonathan & Xiong, 2024). The device was individually adjusted to accommodate each participant's anthropometric measurements.

To measure muscle activity, four Delsys Trigno Avanti EMG sensors (1250 Hz sampling rate), were attached to the participant's dominant arm: three on the anterior, middle, and posterior deltoid muscles, and one on the upper trapezius muscle (Ho Kim et al., 2020). Motion tracking was conducted using an eight-camera OptiTrack Flex 13 system (120 Hz sampling rate), with markers placed on the participant's dominant hand side at the waist, shoulder, elbow, and hand (Figure 3a). The virtual test environment was developed in Unity 2022.5.23f. The virtual keyboard was positioned in front of the participant at chest height, angled at 67.5° relative to the ground. Participants were allowed to adjust their standing distance from the keyboard to establish their optimal typing position (Figure 3b). Participants experienced the environment through the Quest 3's passthrough mode. This allowed them to simultaneously see both virtual keyboards and the physical Logitech MX Keys Mini while maintaining awareness of their physical surroundings.

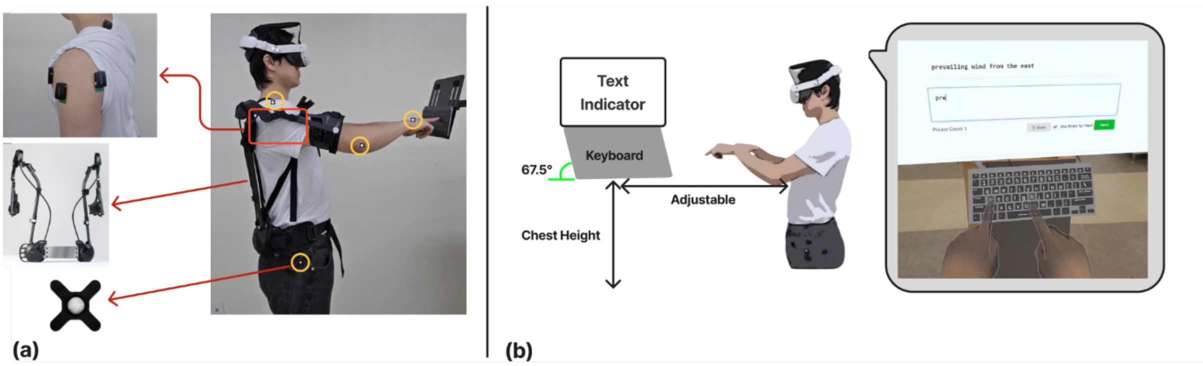


**Figure 3.** Experimental configuration: (a) hardware setup comprising the Meta Quest 3 headset, passive shoulder support exoskeleton, EMG sensor placements, and motion tracking markers for the Optitrack system (yellow circles); and (b) the virtual environment.

## 2.4. Experimental procedure

The experimental protocol followed a systematic six-phase procedure designed to comprehensively assess the effects of keyboard interaction design and exoskeleton support on mid-air typing performance: (1) pre-test questionnaire, (2) familiarization, (3) main experimental trials, (4) subjective evaluation, (5) keyboard preference rating, and (6) open-ended question (Figure 4). All six phases were conducted on the same day within a single experimental session for each participant, which took about 90 minutes on average.

During the pre-test questionnaire phase, participants completed a standardized form documenting demographic characteristics (age, gender, height, and arm length) and prior MR experience. This established baseline participant profiles and verified compliance with inclusion criteria. Subsequently, participants underwent a 5-minute familiarization protocol with both the MR environment and exoskeleton operation to minimize novelty effects and ensure competence with the experimental apparatus. During this period, participants practiced raising and lowering their arms while wearing the exoskeleton and tested mid-air typing motions at chest level to become accustomed to the system.

We implemented a counterbalanced design to minimize order effects during the experimental testing phase. Exoskeleton conditions (with and without) were administered in blocks, with participants randomly assigned to start either with or without the exoskeleton. Ten participants began testing with the exoskeleton, while the other ten started without it. For each exoskeleton block, the three keyboard conditions (Physical, Poking, and Touch) were presented in randomized sequence.

For each experimental condition, participants completed standardized text entry tasks comprising 13 phrases from the phrase set of  Mackenzie and Soukoreff (2003), an established benchmark in text entry research. Text entry performance was evaluated using TextTest++ (Wobbrock et al., 2006; Zhang & Wobbrock, 2019), a validated assessment platform that precisely captures speed, error rates, and correction behaviors during typing. The first three phrases served as practice trials, with subsequent phrases used for analysis. Participants were instructed to type each phrase as quickly and accurately as possible, balancing typing speed and accuracy.

After each experimental condition, participants removed the MR headset and completed a comprehensive 21-item evaluation instrument. This multi-dimensional assessment included subjective strain measures using the Borg CR-10 scale (Borg, 1982). The scale was used to quantify localized discomfort in the hand, shoulder and trapezius muscles. It also featured MR interaction quality assessment using nine items evaluating haptic sensation, embodiment, sense of reality, spatiotemporal perception, and overall satisfaction (Gonzalez-Franco & Peck, 2018; W. Kim & Xiong, 2022a; Schwind et al., 2018). Additionally, user experience was evaluated using the UEQ-S instrument (Schrepp et al., 2017) to assess both pragmatic attributes and hedonic qualities (Table 2). To minimize potential language barriers, participants were provided with both the official English version and a validated Korean translation obtained from the UEQ project website (UEQ, n.d).

To mitigate fatigue effects, participants took a mandatory three-minute rest period between conditions, during which they were instructed to relax their upper extremities completely. Following completion of all conditions within each exoskeleton block, participants performed a comparative ranking of the three keyboard types, providing an explicit preference hierarchy. The protocol concluded with interviews soliciting qualitative feedback regarding participants' experiences with the keyboard interaction designs and exoskeleton conditions, facilitating deeper insights into user perceptions and preferences beyond quantitative measures.

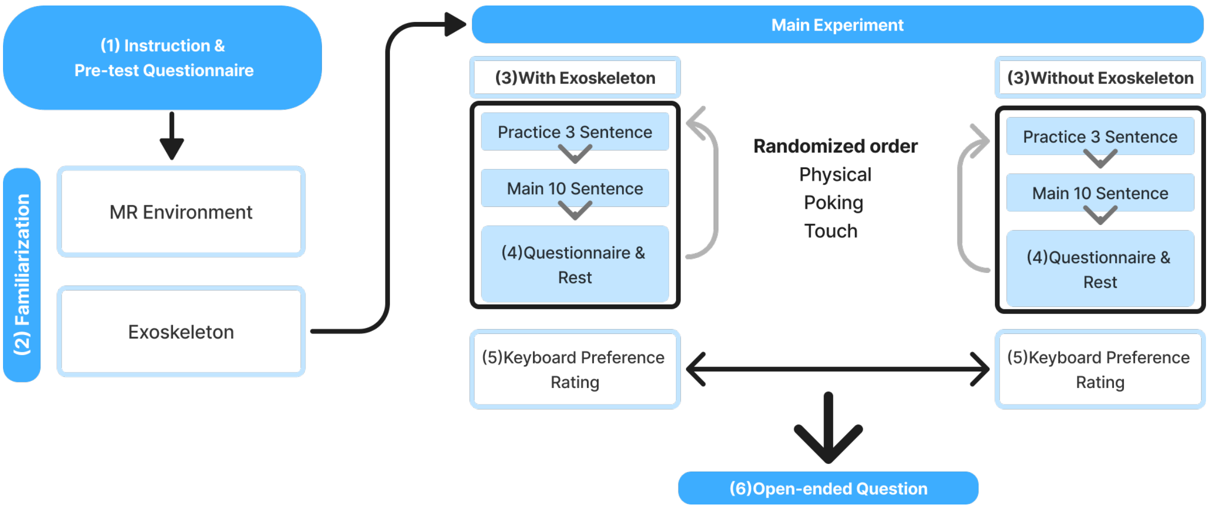


**Figure 4.** Flowchart of the experimental procedure. The order of exoskeleton conditions (with and without) was randomized for each participant.

**Table 2**. Survey items used to assess subjective evaluation and user experience in this study. Participants responded using 7-point Likert scales. For subjective evaluation items, the scale ranged from 1 (strongly disagree) to 7 (strongly agree). For user experience items, responses ranged from -3 (strongly aligned with negative descriptor) to +3 (strongly aligned with positive descriptor). These survey items were adapted from the work of Kim & Xiong (2022b), which incorporated validated measures from previous research (Gonzalez-Franco & Peck, 2018; Schwind et al., 2018).

| Questionnaire | Aspect | No | Item |
|---|---|---|---|
| **Subjective evaluation** | Haptic sensation | 1 | I could feel a haptic sensation as if I were touching a real keyboard. |
| | | 2 | I felt the key being pressed at the exact location where the key was actually pressed. |
| | Embodiment | 3 | When pressing the keypad, my virtual hand (actual hand) was perceived as if it were my real hand. |
| | | 4 | When pressing the keypad, it felt like I could treat the virtual hand (actual hand) as my own hand. |
| | Sense of reality | 5 | The experience in MR felt consistent with the experience in real life. |
| | | 6 | Pressing the keyboard in MR felt similar to pressing a keyboard in real life. |
| | Spatiotemporal perception | 7 | When pressing the keyboard, it was easy to perceive the distance between my hand and the keypad |
| | | 8 | When pressing the keyboard, it was easy to recognize when the key was actually pressed. |
| | Satisfaction | 9 | Overall, I am satisfied with the experience of pressing the keyboard. |
| **User experience (UEQ-S)** | Hedonic quality | 1 | Boring – Exciting |
| | | 2 | Not interesting – Interesting |
| | | 3 | Conventional – Inventive |
| | | 4 | Usual – Leading edge |
| | Pragmatic quality | 5 | Obtrusive - Supportive |
| | | 6 | Complicated – Easy |
| | | 7 | Inefficient – Efficient |
| | | 8 | Confusing – Clear |

## 2.5. Data analysis

### 2.5.1. Text entry performance

Text entry performance was measured using three metrics: Words Per Minute (WPM), Corrected Error Rate (CER), and Uncorrected Error Rate (UER). WPM was calculated as Equation (1).

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

where S represents the typing duration in seconds and |T| denotes the transcribed text length in characters. The constant 60/5 converts the input rate to the standard WPM measure, assuming an average word length of 5 characters. Error rates were computed as Equation (2) and (3).

$$CER = INF/(C+INF+IF) \qquad (2)$$

$$UER = IF/(C+INF+IF) \qquad (3)$$

where C represents correct characters, INF is the minimum string distance between presented and transcribed text (Soukoreff, 2001), and IF denotes deleted characters. Detailed explanations of these metrics can be found in Zhang and Wobbrock (2019).

### 2.5.2. Muscle activity

Muscle activity was recorded at a sampling rate of 1,250 Hz using a wireless EMG system, monitoring four key muscles: anterior deltoid, middle deltoid, posterior deltoid, and upper trapezius. These muscles were selected based on their established role in shoulder and upper extremity movements during AR tasks (Ho Kim et al., 2020).

Following the European Surface Electromyography (SENIAM) guidelines, maximal voluntary contractions (MVCs) were recorded for normalization purposes (Hermens et al., 2000) before the main experiment. For all deltoid muscles, MVC measurements adhered to the protocol established by Boettcher et al. (2008). Upper trapezius MVC measurements required participants to perform shoulder shrugs against resistance while keeping their arms straight at their sides, ensuring no trunk movement (Harms-Ringdahll et al., 1996). Each MVC test was conducted twice per muscle, lasting 5 seconds per trial, with a 3-minute rest interval between contractions as per SENIAM guidelines (Hermens et al., 2000). The highest 2-second segments from each trial were extracted and averaged to establish MVC normalization values.

The collected EMG signals from both MR typing tasks and MVC trials underwent processing through a 20–400 Hz band-pass filter. After filtering, signals were normalized as percentages of their corresponding MVC values. Muscle activation was quantified by calculating root mean square (RMS) values from these normalized signals, using 100 ms windows with 50% overlap (Renshaw et al., 2010).

### 2.5.3. Shoulder and hand movement

Shoulder movements were tracked using the OptiTrack motion capture system operating at 120 Hz. The capture volume was approximately 2 m × 2 m. After standard wand calibration, the system achieved a mean 3D error of ~0.3 mm, which is close to the manufacturer's 0.2 mm specification, thereby ensuring sub-millimeter tracking precision. The coordinate system was oriented with the X-axis directed forward, the Y-axis oriented upward, and the Z-axis extending laterally to the participant's right side. For analysis, shoulder flexion/extension and abduction/adduction angles were characterized using their 5th, 50th, and 95th percentile values to provide a comprehensive representation of postural distribution throughout the tasks. Additionally, the range of motion (ROM) was computed during the keyboard typing tasks. Hand movement distance was measured as the total path length traveled by the dominant hand marker during the typing tasks.

To align motion tracking and EMG signals temporally, both systems were hardware-synchronized using a shared trigger pulse initiated at the start of each trial.

### 2.5.4. Statistical analysis

In analyzing performance and behavioral metrics, we excluded data from the first three phrases, which served as practice trials. The subsequent analysis utilized the mean values derived from the following ten phrases, explicitly omitting trials prematurely terminated due to unintended activation of the Enter key. Because such missing cases were extremely rare, only two trials across all participants, no imputation was performed. Instead, we excluded these trials from all subsequent analyses using a complete case approach.

Ryan-Joiner normality tests were conducted to verify distributional assumptions of the collected data, with results indicating that most dependent variables satisfied the normality criterion ($p > .05$) or showed negligible deviations from the Gaussian distribution. To assess statistical significance across measured responses, we conducted repeated measures analysis of variance (RM-ANOVA). The independent variables were exoskeleton condition (with and without) and keyboard type (Physical, Poking, and Touch), while dependent variables included text entry performance metrics, muscle activity, motion tracking, self-reported strain ratings, and subjective evaluation scores.

For significant effects, pairwise comparisons were conducted using Bonferroni correction. In cases where Mauchly's test indicated a violation of the sphericity assumption (epsilon < 0.75), Greenhouse-Geisser corrections were applied to adjust the degrees of freedom. Effect sizes for all ANOVA results were reported as partial eta-squared ($\eta_p^2$) and interpreted according to Cohen's (1988) benchmarks: 0.01 (small), 0.06 (medium), and 0.14 (large). Statistical analyses and data processing were carried out using R (version 4.4.1), with a predetermined significance threshold set at $\alpha = 0.05$.

## 3. Results

### 3.1. Text entry performance

Figure 5 presents the mean text entry performance metrics (WPM, UER, and CER) across different keyboard types and exoskeleton conditions. Results from Figure 5 and the RM-ANOVA (Table 3) showed that no significant interaction effects between keyboard type and exoskeleton condition for any text entry performance metrics. For main factor effects, the exoskeleton condition showed no significant impact on any of the three-performance metrics. However, keyboard type demonstrated significant main effects on both WPM (p<0.001) and CER (p<0.001). Post-hoc comparisons revealed that the physical keyboard condition resulted in significantly higher WPM and lower CER compared to both virtual keyboard conditions. However, no statistically significant differences were identified in UER across conditions.

**Table 3.** F, $\eta_p^2$, and p values from the RM-ANOVA results showing the effects of exoskeleton and keyboard on mid-air text entry performance metrics. *p <.05, **p <.01, ***p <.001; applies to all tables

| Variables | Exoskeleton | | | Keyboard | | | Exoskeleton × Keyboard | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p |
| **WPM** | 0.08 | <0.001 | 0.779 | 428.39 | 0.807 | ***<0.001 | 0.513 | 0.005 | 0.554 |
| **UER** | 0.63 | <0.001 | 0.436 | 3.02 | 0.033 | 0.091 | 0.336 | <0.001 | 0.649 |
| **CER** | 0.26 | <0.001 | 0.619 | 24.94 | 0.139 | ***<0.001 | 0.458 | 0.002 | 0.611 |

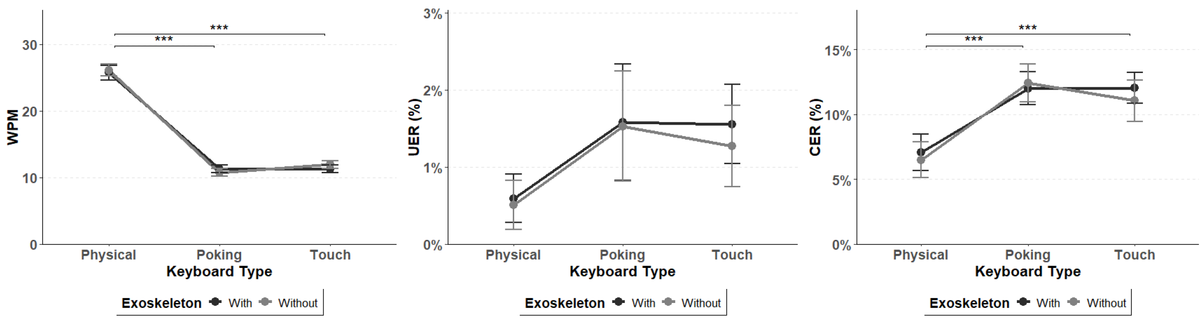


**Figure 5.** Mean (± SE) values of WPM, UER, and CER across exoskeleton conditions and keyboard types. Statistical significance was assessed using Bonferroni-corrected paired t-tests. Asterisks denote significant differences between keyboard conditions (*p < 0.05, **p < 0.01, ***p < 0.001). This applies to all line graphs.

### 3.2. Shoulder and hand movement

Analysis of hand movement characteristics revealed significant interaction effects between exoskeleton and keyboard conditions for hand movement distance and ROM-flexion/extension (Table 4 and Figure 6).

Specifically, when participants wore the exoskeleton, differences in hand movement and flexion among keyboard types were minimal. However, without the exoskeleton, substantial differences emerged between the physical and virtual keyboard conditions.

**Table 4.** F, $\eta_p^2$, and p values from the RM-ANOVA results showing the effects of exoskeleton and keyboard on shoulder and hand movement metrics during mid-air typing. FE: Flexion/extension; AA: Abduction/adduction.

| Variables | Exoskeleton | | | Keyboard | | | Exoskeleton × Keyboard | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p |
| **Hand Movement** | 31.07 | 0.162 | ***<0.001 | 24.41 | 0.236 | ***<0.001 | 11.50 | 0.065 | ***<0.001 |
| **ROM-FE** | 87.71 | 0.331 | ***<0.001 | 7.51 | 0.093 | **0.005 | 5.19 | 0.060 | *0.016 |
| **ROM-AA** | 4.59 | 0.064 | *0.045 | 6.83 | 0.048 | **0.003 | 1.25 | 0.008 | 0.296 |
| **5th-FE** | 31.57 | 0.298 | ***<0.001 | 1.94 | 0.007 | 0.167 | 9.15 | 0.016 | ***<0.001 |
| **50th-FE** | 20.90 | 0.215 | ***<0.001 | 1.90 | 0.006 | 0.174 | 2.24 | 0.004 | 0.120 |
| **95th-FE** | 15.68 | 0.164 | ***<0.001 | 3.46 | 0.010 | 0.050 | 0.83 | 0.002 | 0.437 |
| **5th-AA** | 7.28 | 0.107 | *0.014 | 0.86 | 0.003 | 0.396 | 0.48 | 0.002 | 0.552 |
| **50th-AA** | 8.08 | 0.125 | *0.010 | 0.11 | <0.001 | 0.826 | 0.88 | 0.004 | 0.391 |
| **95th-AA** | 8.69 | 0.133 | **0.008 | 0.53 | 0.002 | 0.528 | 0.61 | 0.002 | 0.503 |

Participants consistently exhibited reduced hand movement distances when wearing the exoskeleton compared to the condition without it. The exoskeleton condition also resulted in a significantly more constrained range of flexion/extension movements but was associated with an increased range of abduction/adduction movements (Figure 6). Keyboard type effects showed that the physical keyboard consistently produced lower behavior metrics across all parameters compared to both virtual keyboard conditions. However, no statistically significant differences were observed between the two virtual keyboard types.

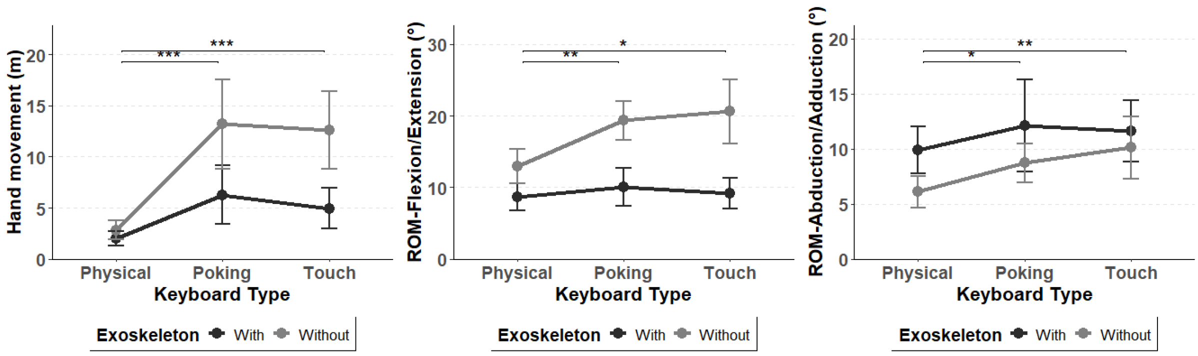


**Figure 6.** Mean (± SE) hand movement distance, ROM-flexion/extension, and ROM-abduction/adduction by exoskeleton and keyboard type.

Analysis of shoulder joint angles revealed statistically significant interactions between exoskeleton and keyboard conditions for 5th-FE (Table 4). As shown in the line graph (Figure 7), the exoskeleton condition showed slightly higher angles with virtual versus physical keyboards, whereas in the non-exoskeleton condition, the difference between the keyboards was small.

The exoskeleton condition consistently exhibited significantly higher shoulder flexion angles across all percentile measurements. Similarly, shoulder abduction angles were significantly higher under the exoskeleton condition across all measured percentiles. In contrast, keyboard type had no significant effect on shoulder positioning, with comparable flexion and abduction angles observed across all three keyboard conditions (Table 4 and Figure 7).

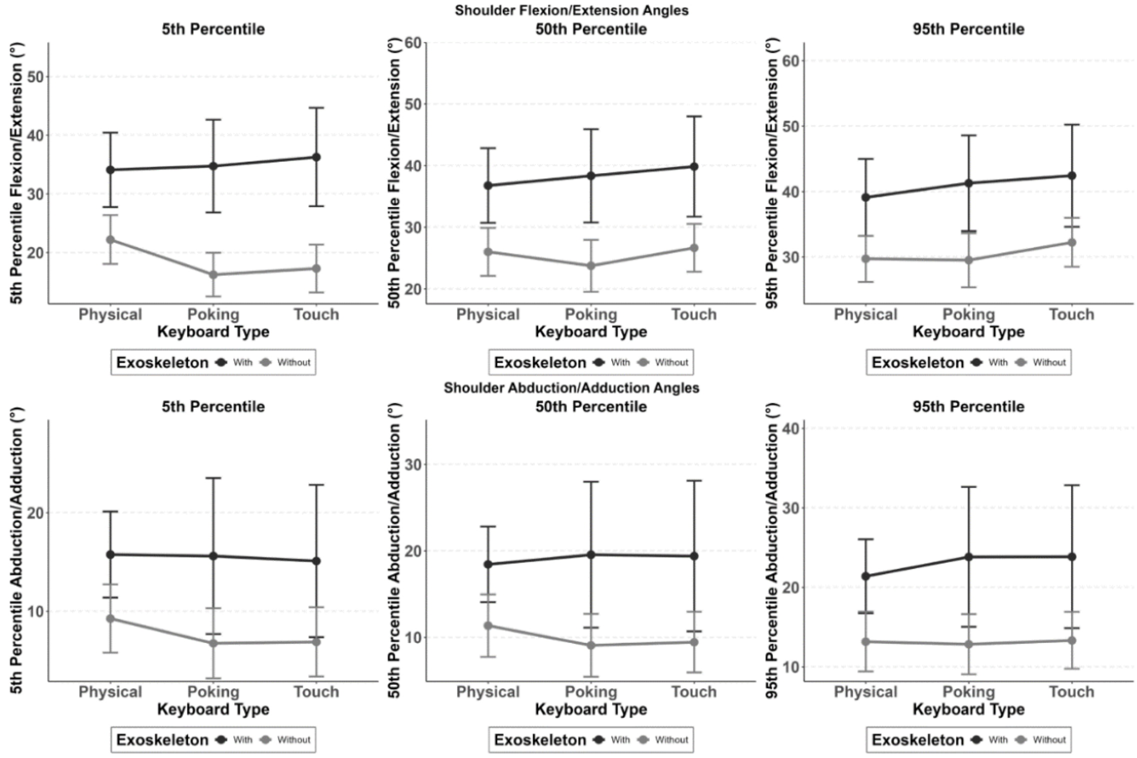


**Figure 7.** Mean (± SE) shoulder joint angles at different percentiles (5th, 50th, and 95th) for both flexion/extension and abduction/adduction across exoskeleton conditions and keyboard types.

### 3.3. Muscle activity

Analysis of the EMG data revealed no significant interaction between exoskeleton condition and keyboard type in all muscle activities, except for the middle deltoid muscle (Table 5). Even in this case, the interaction effect size was negligible ($\eta_p^2 < 0.001$), showing minimal practical differences and no consistent patterns across conditions (Figure 8). Therefore, we focus on the main effects.

**Table 5.** F, $\eta_p^2$, and p values from the RM-ANOVA results showing the effects of exoskeleton and keyboard on muscle activity metrics during mid-air typing. *AD: anterior deltoid; MD: middle deltoid; PD: posterior deltoid; UT: upper trapezius.*

| Variables | Exoskeleton | | | Keyboard | | | Exoskeleton × Keyboard | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p |
| **RMS-AD** | 22.44 | 0.327 | ***<0.001 | 0.49 | 0.003 | 0.518 | 0.17 | 0.001 | 0.709 |
| **RMS-MD** | 8.06 | 0.003 | *0.011 | 1.14 | <0.001 | 0.328 | 4.31 | <0.001 | *0.021 |
| **RMS-PD** | 0.08 | <0.001 | 0.781 | 1.05 | <0.001 | 0.345 | 1.78 | <0.001 | 0.192 |
| **RMS-UT** | 0.07 | <0.001 | 0.801 | 0.23 | <0.001 | 0.744 | 1.70 | 0.003 | 0.205 |

The exoskeleton condition showed a significant main effect across muscle groups (Table 5). Participants exhibited notably reduced anterior deltoid activation when wearing the exoskeleton, approximately half the activation compared to the without-exoskeleton condition (Figure 8). Although differences in middle deltoid activation between exoskeleton conditions were less pronounced, statistical significance was still observed. The main effect of keyboard type alone was not statistically significant for any measured muscle groups.

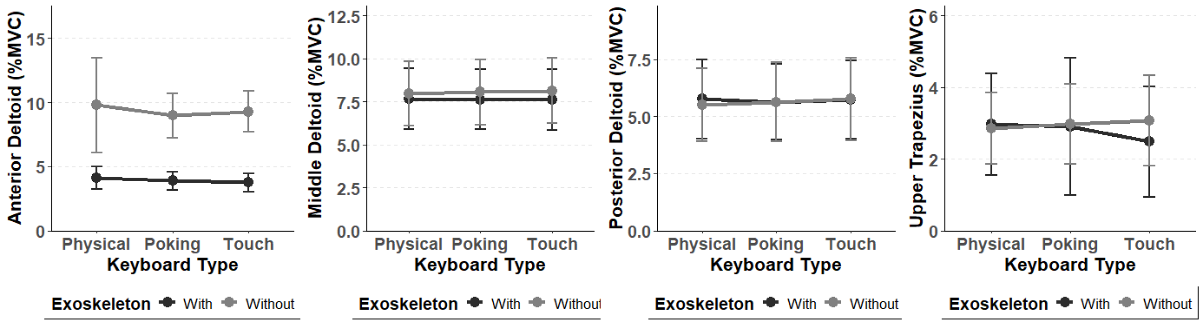


**Figure 8.** Mean (± SE) muscle activation (% MVC) for anterior deltoid, middle deltoid, posterior deltoid, and upper trapezius muscles across exoskeleton conditions and keyboard types.

### 3.4 Self-reported body strain, subjective evaluation, user experience, and preference

Analysis of self-reported body strain revealed significant interaction effects between exoskeleton conditions and virtual keyboard types for hand and trapezius muscle strain (Table 6 and Figure 9). Participants rated the Touch keyboard as resulting in lower fatigue compared to the Poking keyboard under the condition without the exoskeleton. However, this pattern reversed when the exoskeleton was used, showing increased fatigue ratings for the Touch keyboard relative to the Poking keyboard.

**Table 6.** F, $\eta_p^2$, and p values from the RM-ANOVA results showing the effects of exoskeleton and keyboard on self-reported body strain, subjective evaluation, user experience, and preference metrics during mid-air typing.

| Variables | Exoskeleton | | | Keyboard | | | Exoskeleton × Keyboard | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p | F | $\eta_p^2$ | p |
| **Hand Strain** | 13.72 | 0.044 | **0.002 | 25.07 | 0.176 | ***<0.001 | 5.03 | 0.007 | *0.016 |
| **Shoulder Strain** | 42.42 | 0.231 | ***<0.001 | 28.02 | 0.270 | ***<0.001 | 2.00 | 0.014 | 0.161 |
| **Trapezius Strain** | 52.02 | 0.235 | ***<0.001 | 44.19 | 0.240 | ***<0.001 | 3.64 | 0.025 | *0.045 |
| **Embodiment** | 0.21 | 0.001 | 0.649 | 39.80 | 0.376 | ***<0.001 | 3.70 | 0.014 | *0.034 |
| **Haptic sensation** | 0.09 | <0.001 | 0.764 | 87.78 | 0.606 | ***<0.001 | 1.13 | 0.006 | 0.330 |
| **Satisfaction** | 1.18 | 0.008 | 0.292 | 32.33 | 0.363 | ***<0.001 | 2.06 | 0.015 | 0.142 |
| **Sense of Reality** | 0.63 | 0.002 | 0.438 | 62.78 | 0.416 | ***<0.001 | 2.32 | 0.012 | 0.115 |
| **Spatio-temporal** | 1.40 | 0.006 | 0.252 | 44.12 | 0.485 | ***<0.001 | 4.04 | 0.022 | *0.031 |
| **Hedonic** | 5.86 | 0.050 | *0.026 | 10.36 | 0.161 | ***<0.001 | 4.00 | 0.025 | *0.030 |
| **Pragmatic** | 0.45 | 0.005 | 0.509 | 44.71 | 0.434 | ***<0.001 | 5.24 | 0.054 | *0.016 |
| **Preference** | 0.00 | <0.001 | 1.000 | 38.55 | 0.512 | ***<0.001 | 4.29 | 0.098 | *0.031 |

Participants consistently reported reduced fatigue in their hands, shoulders, and trapezius muscles when using the exoskeleton. Similarly, a significant main effect of keyboard type was observed. Post-hoc analyses further revealed that the physical keyboard significantly reduced reported fatigue in these areas compared to both virtual keyboard conditions (Table 6 and Figure 9).

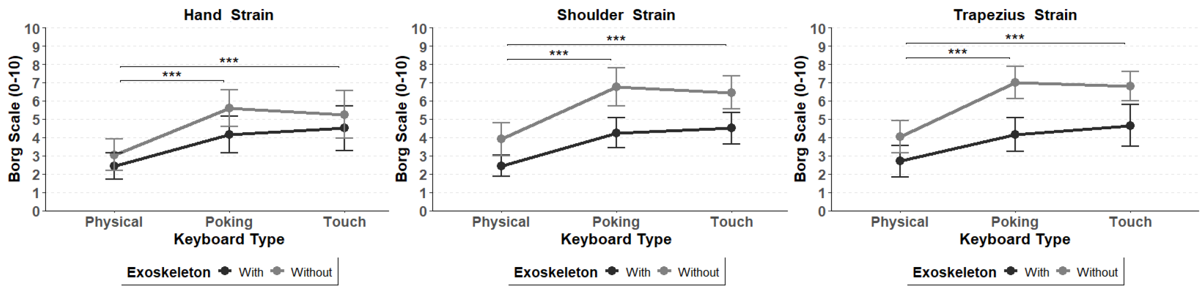


**Figure 9.** Mean (± SE) self-reported body strain by exoskeleton and keyboard type.

For subjective evaluations, significant interaction effects were observed across embodiment and spatiotemporal perception measures (Table 6 and Figure 10). While the Touch keyboard generally received higher average ratings than the Poking keyboard without the exoskeleton, these ratings notably decreased below those of the Poking keyboard when the exoskeleton was worn. No significant interaction effects were detected for other subjective dimensions.

Examining main effects, the exoskeleton condition showed no significant impact across subjective evaluation dimensions (Figure 10). However, keyboard type demonstrated significant main effects across all subjective factors. Post-hoc analyses indicated that the physical keyboard consistently received higher ratings compared to both virtual keyboards. Between the virtual keyboard conditions, a significant difference emerged only in haptic sensation (T=2.12, p=0.047); the Poking keyboard (M=3.72, SD=1.29) was rated significantly higher than the Touch keyboard (M=3.22, SD=1.28).

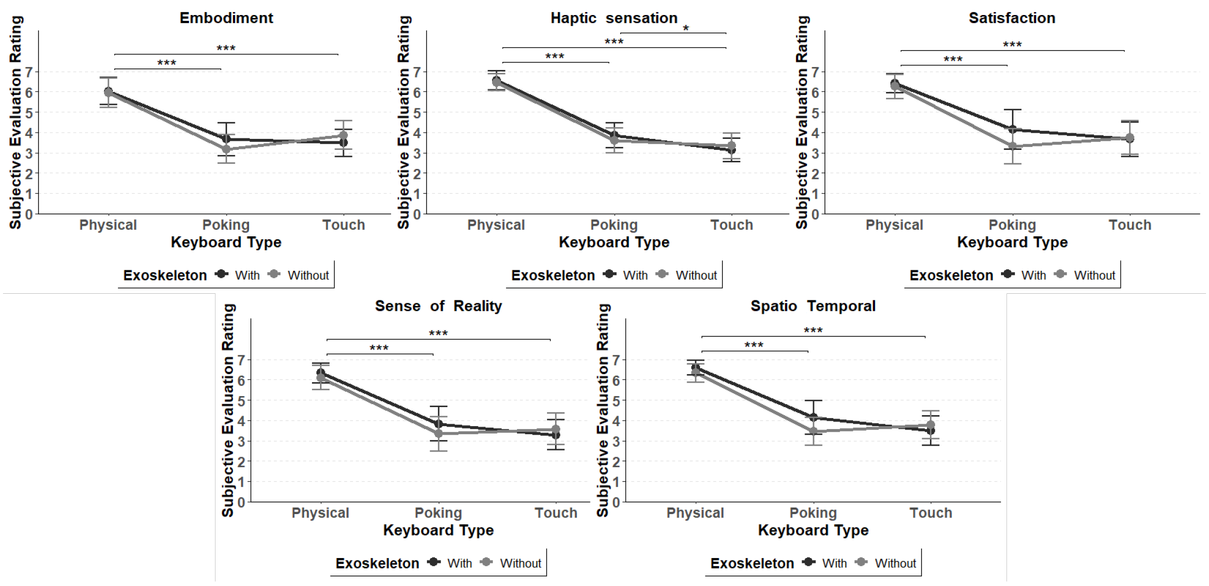


**Figure 10.** Mean (± SE) subjective evaluation rating by exoskeleton and keyboard type.

User experience analysis revealed significant interaction effects for both hedonic and pragmatic quality measures (Table 6 and Figures 11). The Touch keyboard's ratings decreased more substantially than the Poking keyboard's when paired with the exoskeleton, particularly for pragmatic quality. For main effects, the exoskeleton condition resulted in higher hedonic scores but had no statistically significant effect on pragmatic scores. Keyboard type demonstrated significant effects on both measures, with the physical keyboard associated with significantly higher pragmatic ratings but lower hedonic ratings compared to both virtual keyboards.

Analysis of user preference indicated a significant interaction between exoskeleton and keyboard type (Table 6 and Figures 11), reflecting a notable decrease in preference for the Touch keyboard specifically when participants wore the exoskeleton. For main effects, significant differences emerged across keyboard types, with the physical keyboard consistently preferred over both virtual keyboards, whereas no significant main effect was found for the exoskeleton. No significant differences emerged between the two virtual keyboard conditions in overall preference.

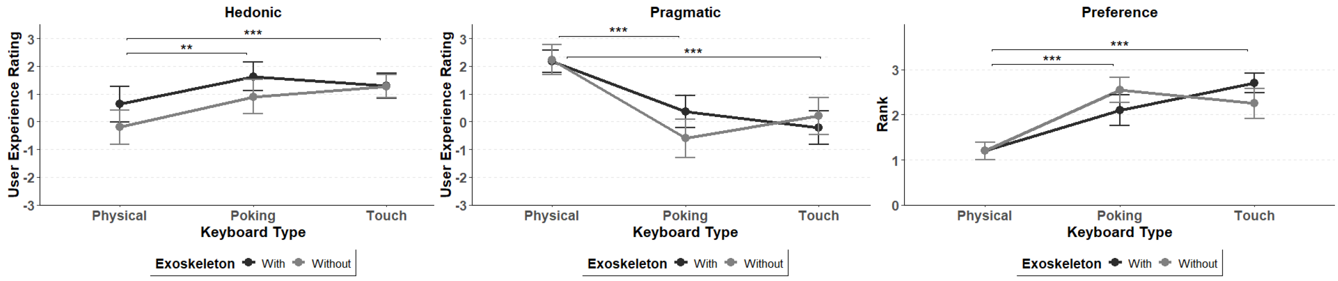


**Figure 11.** Mean (± SE) user experience rating and preference for ranking scores by exoskeleton and keyboard type.

### 3.5 Qualitative feedback from open-ended responses

In addition to quantitative measures, participants provided open-ended feedback on their experiences with the exoskeleton and keyboard interaction designs. Representative comments are summarized in Table 7. These qualitative insights complement the quantitative findings by highlighting nuanced user perceptions regarding comfort, usability challenges, and interaction effects.

Several participants noted that while the exoskeleton was initially unfamiliar, it provided noticeable comfort through supportive force (e.g., P02, P20). Others emphasized that physical keyboards felt most natural, whereas the Poking keyboard facilitated clearer recognition of key activation compared to the Touch keyboard (e.g., P15, P16, P19). Some participants also reported that the exoskeleton occasionally restricted their movement during virtual typing, leading to unintended key activations on the Touch keyboard but less so on the Poking keyboard (e.g., P11, P13, P15). These qualitative findings enrich and contextualize the quantitative results reported above.

**Table 7.** Representative responses from open-ended questions

| Factor | Participants No | Comments |
|---|---|---|
| **Exoskeleton** | P02, P20 | Wearing the Exo was awkward at first since it was my first time. However, I could still feel the comfort provided by its supportive force. |
| **Keyboard** | P19 | Physical was the easiest because it was most similar to reality. Poking made it easier to recognize when a key was actually pressed compared to the Touch keyboard. |
| | P16 | Poking was relatively easier to use and quicker to adapt to compared to Touch. With the Touch keyboard, it was hard to identify key positions. |
| | P15 | With Touch, it was difficult to recognize when a key was pressed incorrectly, and the depth sensation of pressing keys with hand felt different. |
| | P04 | With the Touch method, it was difficult to distinguish when a key had been registered. |
| **Exoskeleton × Keyboard** | P15 | The Exo was comfortable, but it created movement constraints that made virtual keyboard typing more challenging |
| | P13 | When the exoskeleton provided shoulder support, it created an upward pushing effect that caused unintended activation of upper keys with the Touch keyboard, but this occurred less frequently with the Poking keyboard. |
| | P11 | While the exoskeleton significantly helped reduce shoulder muscle fatigue |

| | |
|---|---|
| | when typing on virtual keyboards, my arm seemed to shake more during typing due to the interaction between the exoskeleton's shoulder support and the hand movements required for keystrokes, which decreased accuracy. |

# 4. Discussion

## 4.1. Effects of exoskeleton assistance

### 4.1.1. Reduced muscle activity but unchanged typing performance

One of the primary objectives of this study was to examine how passive shoulder support exoskeletons alleviate upper-limb muscular demands and influence typing performance during sustained mid-air typing tasks. The EMG results demonstrated that exoskeleton usage significantly reduced muscular activation, with the anterior deltoid exhibiting the most substantial decrease (approximately 50%). This finding aligns with previous research, as the anterior deltoid experienced the highest muscular load among all measured muscles due to the substantial shoulder flexions required during the experimental tasks (Kong et al., 2023). The exoskeleton implemented in this study was specifically engineered to support shoulder flexion movements, which consequently yielded the most pronounced impact on the anterior deltoid—the primary muscle responsible for this motion. These results support previous investigations on exoskeletons in overhead or assembly settings, which have similarly demonstrated significant reductions in anterior deltoid muscle activity when appropriate upper limb support is provided (Choi et al., 2024; Jorgensen et al., 2022a, 2022b; Lauret et al., 2025; Musso et al., 2024; Van Engelhoven et al., 2018).

In self-reported strain assessments, participants indicated substantially reduced fatigue in shoulder and trapezius regions. Participants also reported increased hand comfort, though less pronounced than the relief in shoulder and trapezius regions. This enhanced hand comfort may be attributed to either: the reduced hand movement distance when wearing the exoskeleton, as the shoulder support facilitated more efficient positioning (Cheng et al., 2022), or as postulated by previous research (Alabdulkarim & Nussbaum, 2019), the exoskeleton's redistribution of hand weight through its mechanical structure to the back, thereby reducing the muscular effort required to support this load. These findings demonstrate that passive shoulder support exoskeletons not only achieve their primary purpose of shoulder relief but also provide secondary comfort benefits to other body regions.

Interestingly, however, exoskeleton support did not translate into significant improvements or decrements in text entry performance metrics. This outcome supports previous research, which observed that exoskeletons can effectively reduce physical strain without necessarily impacting task performance (S. Kim et al., 2018; Kong et al., 2023). Additionally, our findings contrast with studies on table-based arm supports, which have demonstrated performance improvements for mid-air tasks (Cheng et al., 2022), highlighting the distinct biomechanical effects of exoskeletons compared to static surface supports despite both providing arm support.

### 4.1.2. Postural adjustments and subjective evaluation

Comprehensive motion capture analysis revealed that exoskeleton usage systematically influenced participants' shoulder kinematics, resulting in significantly increased shoulder flexion and abduction angles across all measured percentiles (5th, 50th, and 95th). As illustrated in the postural comparison (Figure 12), the exoskeleton's support mechanism produced distinct changes in upper extremity positioning, particularly in terms of shoulder angle maintenance during typing tasks.

Without the exoskeleton, participants tended to maintain a posture with elbows closer to their torso, seeking a more stable position that would reduce fatigue in the shoulder muscles (Wiker et al., 1990). When wearing the exoskeleton, participants adopted distinctly different postures. This change occurred mainly because the exoskeleton gives stronger support when the shoulder is raised higher (Jonathan & Xiong, 2024), encouraging participants to find and maintain shoulder positions that balanced typing effectiveness with maximum support from the exoskeleton.

Significant differences were additionally observed in range of motion and hand movement distance, which appear to originate from fundamental alterations in motor control strategies induced by the exoskeleton. Without exoskeleton, as shown in Figure 12b, participants primarily modulated shoulder flexion while typing. In contrast, when wearing the exoskeleton, Figure 12a demonstrates that participants shifted to control typing movements through shoulder abduction adjustments. This adaptation occurred because the exoskeleton provides support primarily in the flexion direction; therefore, when participants needed to move in the extension direction, they had to exert additional force to overcome the exoskeleton's supportive resistance (Lauret et al., 2025). As a result, participants naturally favored abduction movements where the exoskeleton offered less interference with their intended motion. The observed reduction in hand movement distance can be attributed to stability effects similar to those provided by table-like surfaces, suggesting that the exoskeleton offers comparable support benefits that naturally constrain excessive movement (Cheng et al., 2022).

These substantial postural adaptations did not adversely affect subjective usability metrics; conversely, participants gave slightly higher hedonic scores in the exoskeleton condition. This positive evaluation could be attributed to the fact that all participants were first-time users of the exoskeleton, and the novelty of this experience likely contributed to their favorable assessments (Skavronskaya et al., 2020).

While participants consistently reported that the exoskeleton effectively mitigated muscle fatigue, it demonstrated no significant enhancement of pragmatic usability metrics. The exoskeleton condition did not yield higher pragmatic ratings or task-specific user satisfaction for typing. As supported by our qualitative data from open-ended responses (Table 7), although most participants acknowledged the exoskeleton's benefits for reducing muscular fatigue, the constraints it imposed on movement freedom during precise typing tasks likely counterbalanced these ergonomic advantages (Kranenborg et al., 2023; Ma & Xiong, 2024; Pacifico et al., 2020).

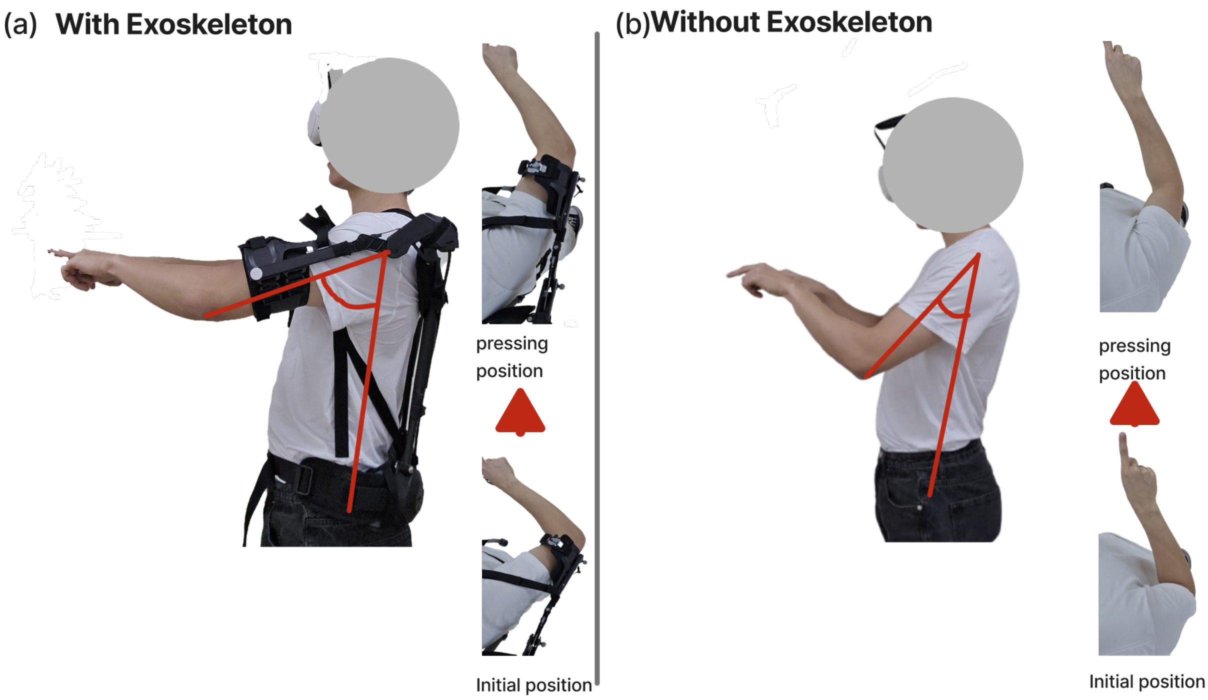


**Figure 12.** Visual representation of typical shoulder posture during mid-air typing tasks (a) with and (b) without exoskeleton, showing the difference in upper arm support and positioning

## 4.2. Effects of keyboard interaction design

### 4.2.1. Difference between physical and virtual keyboards

Our empirical results consistently demonstrated significant performance advantages for the Physical keyboard compared to both virtual keyboards across multiple objective metrics. The Physical keyboard yielded significantly higher text entry speeds and lower corrected error rates, supporting established literature highlighting the crucial role of tactile feedback in efficient text entry (Dudley et al., 2019).

The physical keyboard showed clear advantages across all subjective evaluation metrics compared to virtual keyboards. This pattern aligns with findings from extensive prior research which has established that the absence of tactile confirmation in virtual keyboards creates substantial cognitive and perceptual challenges for users (Cheng et al., 2022; Dudley et al., 2019; Gupta et al., 2020; Schmitz et al., 2024). Paradoxically, however, results from the UEQ-S showed that virtual keyboards received higher hedonic scores than the physical keyboard, suggesting that while virtual keyboards may underperform functionally, they offer an engaging and novel experience that users find appealing. This contrast between functional performance and experiential value is consistent with established literature where virtual reality interfaces often elicited higher hedonic ratings despite functional limitations, highlighting the experiential value of novel interaction modalities (McLoughlin et al., 2024; Pizzolante et al., 2024; Szczechowicz et al., 2024).

Our analysis uncovered a notable discrepancy between objective physiological and subjective perceptual measures of physical strain. While EMG measurements showed no significant differences in muscle activation between keyboard types, self-reported body strain indicated that participants perceived significantly higher fatigue in their hands, shoulders, and trapezius muscles when using virtual keyboards compared to the physical keyboard. This divergence between objective and subjective measures likely originates from the temporal efficiency achieved with the Physical keyboard, resulting in shorter overall task completion times. Consequently, the reduced duration of sustained arm positioning and hand movements with the Physical keyboard likely contributed to lower perceived fatigue, despite similar muscle activation levels during the actual typing process (Dallaway et al., 2022; Mohd Nur et al., 2015). This suggests that enhancing mid-air typing efficiency could substantially reduce perceived fatigue despite similar muscle activation levels. Faster, more accurate mid-air typing would shorten task duration, potentially decreasing both cognitive and physical fatigue to levels more comparable with physical keyboards.

Physical keyboard usage also demonstrated distinct user behavior patterns. Lower hand movement can be attributed to both higher typing efficiency with the physical keyboard, allowing users to complete tasks with fewer overall hand movements, and the physical keyboard's surface, which naturally limits excessive hand movement by providing tactile boundaries and resistance (Dudley et al., 2019). The significantly reduced ROM observed in physical keyboard conditions can be explained by the combination of tactile feedback and physical constraints that create more economical movement patterns. Users receive immediate haptic confirmation of successful keystrokes without requiring visual verification, while the keyboard's surface establishes natural boundaries that restrict excessive motion. The significant interaction effect observed in 5th-FE further illustrates this compensatory behavior. Without exoskeleton support, participants maintained lower shoulder flexion when typing on virtual keyboards compared to the physical keyboard, likely adopting more stable postures to compensate for the absence of physical surface support. In contrast, when wearing the exoskeleton, the postural differences between keyboard types were not notable, as the exoskeleton's support provided assistance at lower flexion angles.

### 4.2.2. Difference between virtual keyboards

When comparing the two virtual keyboard designs, our analysis uncovered subtle but meaningful differences in user experience. The Poking keyboard with protruded 3D keys scored significantly higher in haptic sensation compared to the standard Touch keyboard, indicating that the pseudo-haptic feedback generated by the visual depression of keys established a more compelling tactile illusion. This aligns with previous research demonstrating that visual cues simulating tactile depth can enhance the perceived realism of virtual interfaces (Akhoroz & Yildirim, 2024; W. Kim & Xiong, 2022b).

A particularly notable finding emerged in our analysis of interaction effects between keyboard type and exoskeleton use across multiple measures. This interaction effect can be explained by examining the divergent precision requirements of each keyboard design. The Touch keyboard necessitates more precise targeting as input is registered immediately upon contact with the virtual panel, offering minimal opportunity for correction before keystroke commitment (Dube & Arif, 2020). Conversely, the Poking keyboard's protruded design provides an additional visual confirmation step during the pressing action, potentially reducing error rates through this extended feedback mechanism. Previous research suggests that 2D touch interfaces often require more correction attempts compared to interfaces with depth-based interaction models (Akhoroz & Yildirim, 2024). This distinction was supported by participant feedback, as P19 noted: *"Poking made it easier to recognize when a key was actually pressed compared to the Touch keyboard,"* highlighting the improved keystroke confirmation afforded by the protruded design.

This distinction was amplified when participants used the exoskeleton. As prior studies have demonstrated, exoskeletons can increase task error rates and reduce stability in horizontal movements (Raveendranath et al., 2024). These constraints likely make the Touch keyboard's precision challenges worse. As P13 explicitly articulated in our open-ended responses: *"When the exoskeleton provided shoulder support, it created an upward pushing effect that caused unintended activation of upper keys with the Touch keyboard, but this occurred less frequently with the Poking keyboard."* Similarly, P17 reported that *"When movement was restricted, lightly touching (Touch keyboard) felt more difficult than the Poking method."* The Poking keyboard's more forgiving interaction process—with its clear visual feedback during key depression—appears to better accommodate the reduced fine motor control experienced when wearing the exoskeleton. This mechanistic explanation clarifies why participants' overall experience ratings for the Touch keyboard declined more substantially when paired with the exoskeleton, as the combination presented compounding precision challenges that affected both performance and comfort.

### 4.3. Practical implications

Our empirical findings yield several substantive implications for MR interface design and implementation. First, passive shoulder support exoskeletons show promise for reducing physical strain during extended mid-air text entry without compromising mid-air typing performance, establishing them as viable ergonomic solutions for workplace environments where users engage in prolonged MR typing tasks. The significant reductions in anterior and middle deltoid muscle activity suggest that exoskeleton may contribute to mitigating risk factors associated with elevated arm postures, which could have implications for ergonomics as MR adoption accelerates across professional settings.

While exoskeletons help reduce muscle fatigue, they can potentially limit natural movement and may cause increased activity in certain muscle groups (De Bock et al., 2023). However, the benefits outweigh the drawbacks, especially when using MR for extended periods, as reducing long-term physical strain compensates for any side effects. This is particularly relevant in industrial workplaces where MR technology adoption is growing. In these settings, exoskeletons are already being utilized for standard industrial tasks, and this integration makes it easier to implement MR's mid-air interaction tasks in such environments (Rosa-Garcia et al., 2025).

Second, this study reveals an interesting relationship between perceived and objectively measured muscle fatigue when using virtual keyboards. Despite EMG data showing no significant differences in muscle activation between keyboard types, participants reported higher subjective fatigue when using virtual keyboards compared to physical keyboard. This suggests that the extended task duration resulting from virtual keyboards' lower efficiency increased cumulative fatigue. Therefore, improving virtual keyboard performance to approach physical keyboard levels is not merely about enhancing usability but is an essential condition for sustainable text entry in MR environments. In particular, reducing task duration through improved typing speed and accuracy will be a key strategy for addressing fatigue issues associated with prolonged MR use. Specifically, our results suggest that the inefficiency of virtual keyboards stems in part from greater hand travel, longer typing durations, and less distinct keystroke feedback compared to physical keyboards. To overcome these limitations, several strategic directions can be pursued. (1) While prior work has shown that aligning virtual keyboards with physical surfaces reduces hand movement (Dudley et al., 2019), future research could extend these benefits to mid-air settings through body-anchored interfaces or adaptive keyboards that conform to surrounding surfaces. (2) Post-hoc correction algorithms may help compensate for typical virtual keyboard errors such as key ambiguity and unintended inputs, with probabilistic decoding approaches like Streli et al (2024) showing promise for broader application. (3) Systematic integration of multimodal feedback, particularly auditory cues as highlighted by Krasner and Gabbard (2024), could compensate for the lack of tactile feedback and enhance typing confidence in mid-air conditions.

Third, our findings strongly indicate that keyboard interaction design should be contextually matched to the available physical support infrastructure. When users wear exoskeletons, interfaces with 3D poking keyboard appear to better accommodate the reduced precision imposed by the exoskeleton. This interaction effect highlights the need for designers to conceptualize input devices and ergonomic support solutions as integrated systems rather than as separate components. The higher preference for protruded interfaces when wearing exoskeletons illuminates how contextual factors can fundamentally influence user experience.

Finally, regarding effect sizes, some statistically significant results were associated with small partial eta-squared values, suggesting limited effect magnitudes. While such small ergonomic changes may appear modest in single-session contexts, they can accumulate during prolonged MR use and at deployment scale to yield meaningful comfort gains. Thus, practitioners should interpret these findings as directionally informative for design, while avoiding overemphasis on the magnitude observed in a single session.

### 4.4. Limitations and future work

Several methodological limitations in our study warrant consideration and suggest promising directions for future research. First, our experimental sessions were relatively brief. While the exoskeleton already demonstrated significant reductions in muscle activity and strain, extended testing sessions (e.g., 60 minutes or above) would more comprehensively explain cumulative fatigue effects during prolonged MR interactions and better simulate real-world usage scenarios.

Second, our evaluation was limited to a single passive shoulder exoskeleton model. Different designs (active vs. passive systems, varied support angles, adjustable tension) may yield different outcomes. Comparative analyses of multiple exoskeleton configurations could identify optimal design parameters specifically tailored for fine motor tasks in MR environments.

Third, our participant sample consisted exclusively of first-time exoskeleton users with limited MR experience. Moreover, all participants were young and healthy adults, which may limit the generalizability of our findings to broader age groups or individuals with varying physical conditions. Longitudinal studies could reveal whether exoskeleton benefits increase as users adapt to the device or whether constraints on movement freedom become more pronounced with extended use. Additionally, investigating expert users and more diverse user groups could provide valuable insights into adaptation strategies and factors influencing long-term acceptance.

Last but not least, the experimental paradigm employed a predominantly static typing task, with participants standing in a fixed position throughout the experiment. Future studies should examine more dynamic MR scenarios involving movement throughout the environment, reaching actions, or transitions between sitting and standing positions, thereby better representing ecological usage conditions and potentially revealing differential patterns of exoskeleton benefits and constraints across varied task demands. Future research could also draw inspiration from recent advances in exoskeleton control across different applications. For example, lower-limb exoskeletons have adopted sophisticated approaches including CPG-based multimodal cooperation (Kou et al., 2025), robust model predictive control (Xu et al., 2025), and modified dynamic movement primitives (Yu & Bai, 2024). While these methods primarily focus on locomotion, similar adaptive principles could potentially inform the design of future active upper-limb exoskeletons.

## 5. Conclusion

This study examined the effects of passive shoulder support exoskeletons and different keyboard interfaces on mid-air typing in MR environments. The findings reveal that exoskeletons significantly reduce muscle activation and perceived physical strain without compromising typing performance, although they induce postural adaptations through increased shoulder flexion and abduction. Physical keyboards consistently outperformed virtual keyboards in both objective and subjective measures, while the Virtual-Poking keyboard with pseudo-haptic feedback demonstrated advantages over the Virtual-Touch keyboard, particularly when users wore the exoskeleton. A notable interaction effect between keyboard design and exoskeleton use suggests that interface design should be contextually matched to physical support infrastructure, as protruded interfaces better accommodate the reduced precision when wearing exoskeletons. These insights contribute to developing sustainable MR text entry solutions that effectively balance ergonomic support with user performance and satisfaction. Future research should explore extended usage scenarios, varied exoskeleton designs, and more dynamic MR tasks to further enhance understanding of these complex interactions.

## Acknowledgements

This work was supported by the Basic Science Research Programs through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning under Grants NRF-2022R1F1A1061045 and NRF-2022M3J6A1063021; the Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korean government (MSIT) under Grant IITP-2025-RS-2023-00260267; and the National Research Foundation of Korea (NRF) grants funded by the Korean government (MSIT) under Grants RS-2024-00343882 and RS-2023-00242528.

## Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

## References

Akhoroz, M., & Yildirim, C. (2024). Poke Typing: Effects of Hand-Tracking Input and Key Representation on Mid-Air Text Entry Performance in Virtual Reality. *ACM International Conference Proceeding Series*, 293–301. https://doi.org/10.1145/3678957.3685734

Alabdulkarim, S., & Nussbaum, M. A. (2019). Influences of different exoskeleton designs and tool mass on physical demands and performance in a simulated overhead drilling task. *Applied Ergonomics*, *74*, 55–66. https://doi.org/10.1016/j.apergo.2018.08.004

Aromaa, S., Väätänen, A., Aaltonen, I., Goriachev, V., Helin, K., & Karjalainen, J. (2020). Awareness of the real -world environment when using augmented reality head-mounted display. Applied Ergonomics, 88, 103145. https://doi.org/10.1016/j.apergo.2020.103145

Bailenson, J. N., Beams, B., Brown, J., DeVeaux, C., Han, E., Queiroz, A. C. M., Ratan, R., Santoso, M., Srirangarajan, T., Tao, Y., & Wang, P. (2024). Seeing the world through digital prisms: Psychological implications of passthrough video usage in mixed reality. *Technology, Mind, and Behavior*, *5*(2), 1–16. https://doi.org/10.1037/tmb0000129

Benko, H., Wilson, A. D., & Baudisch, P. (2006). Precise selection techniques for multi-touch screens. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06) (pp. 1263–1272). Association for Computing Machinery. https://doi.org/10.1145/1124772.1124963

Bermejo, C., Lee, L. H., Chojecki, P., Przewozny, D., & Hui, P. (2021). Exploring Button Designs for Mid-air Interaction in Virtual Reality: A Hexa-metric Evaluation of Key Representations and Multi-modal Cues. *Proceedings of the ACM on Human-Computer Interaction*, *5*(EICS). https://doi.org/10.1145/3457141

Borg, G. A. V. (1982). Psychophysical bases of perceived exertion. Medicine and Science in Sports and Exercise, 14(5), 377–381. https://doi.org/10.1249/00005768-198205000-00012

Bowman, D. A., Kruijff, E., LaViola, J. J., Jr., & Poupyrev, I. (2004). 3D user interfaces: Theory and practice. Addison Wesley Longman Publishing Co.

Burnett, M. (2008). Investigating the effectiveness of tactile feedback for mobile touchscreens. In Proceedings of the 26th Annual CHI Conference on Human Factors in Computing Systems (pp. 1573-1582). https://doi.org/10.1145/1357054.1357300

Chattopadhyay, D. (2016). Understanding interaction mechanics in touchless target selection [Doctoral dissertation, Indiana University].

Cheng, Y. F., Luong, T., Fender, A. R., Streli, P., & Holz, C. (2022). ComforTable User Interfaces: Surfaces Reduce Input Error, Time, and Exertion for Tabletop and Mid-air User Interfaces. *Proceedings - 2022 IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2022*, 150–159. https://doi.org/10.1109/ISMAR55827.2022.00029

Choi, B., Park, J., & Kim, J. H. (2024). Assessment of an arm-support exoskeleton on physical demands, task performance, and usability during simulated agricultural tasks. International Journal of Industrial Ergonomics, 101, 103569. https://doi.org/10.1016/j.ergon.2024.103569

Cipresso, P., Giglioli, I. A. C., Raya, M. A., & Riva, G. (2018). The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature. Frontiers in Psychology, 9, 2086. https://doi.org/10.3389/fpsyg.2018.02086

Cometti, C., Païzis, C., Casteleira, A., Pons, G., & Babault, N. (2018). Effects of mixed reality head-mounted glasses during 90 minutes of mental and manual tasks on cognitive and physiological functions. PeerJ, 6, e5847. https://doi.org/10.7717/peerj.5847

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587

Dallaway, N., Lucas, S. J. E., & Ring, C. (2022). Cognitive tasks elicit mental fatigue and impair subsequent physical task endurance: Effects of task duration and type. Psychophysiology, 59(12), e14126. https://doi.org/10.1111/psyp.14126

De Bock, S., Ampe, T., Rossini, M., Tassignon, B., Lefeber, D., Rodriguez-Guerrero, C., Roelands, B., Geeroms, J., Meeusen, R., & De Pauw, K. (2023). Passive shoulder exoskeleton support partially mitigates fatigue-induced effects in overhead work. *Applied Ergonomics*, *106*. https://doi.org/10.1016/j.apergo.2022.103903

Dube, T. J., & Arif, A. S. (2020). Impact of key shape and dimension on text entry in virtual reality. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-12). https://doi.org/10.1145/3334480.3382882

Dudley, J. J., Benko, H., Wigdor, D., & Kristensson, O. (2019). Performance envelopes of virtual keyboard text input strategies in virtual reality. In 2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) (pp. 289-300). https://doi.org/10.1109/ISMAR.2019.00027

Faeth, A., & Harding, C. (2014). Emergent effects in multimodal feedback from virtual buttons. *ACM Transactions on Computer-Human Interaction*, *21*(1). https://doi.org/10.1145/2535923

Gonzalez-Franco, M., & Peck, T. C. (2018). Avatar embodiment. Towards a standardized questionnaire. Frontiers in Robotics and AI, 5, 74. https://doi.org/10.3389/frobt.2018.00074

Grudin, J.T. (1983). Error Patterns in Novice and Skilled Transcription Typing. In: Cooper, W.E. (eds) Cognitive Aspects of Skilled Typewriting. Springer, New York, NY. https://doi.org/10.1007/978-1-4612-5470-6_6

Gupta, A., Samad, M., Kin, K., Kristensson, P. O., & Benko, H. (2020). Investigating Remote Tactile Feedback for Mid-Air Text-Entry in Virtual Reality. *Proceedings - 2020 IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2020*, 350–360. https://doi.org/10.1109/ISMAR50242.2020.00062

Harms-Ringdahl, K., Ekholm, J., Schüldt, K., & Linder, J. (1996). Assessment of jet pilots' upper trapezius load calibrated to maximal voluntary contraction and a standardized load. Journal of Electromyography and Kinesiology, 6(1), 41-46.

Helin, K., Kuula, T., Vizzi, C., Karjalainen, J., & Vovk, A. (2018). User experience of augmented reality system for astronaut's manual work support. Frontiers in Robotics and AI, 5, 106. https://doi.org/10.3389/frobt.2018.00106

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. Journal of Electromyography and Kinesiology, 10(5), 361-374. https://doi.org/10.1016/s1050-6411(00)00027-4

Hoggan, E., Brewster, S. A., & Johnston, J. (2008). Investigating the effectiveness of tactile feedback for mobile touchscreens. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08) (pp. 1573–1582). Association for Computing Machinery. https://doi.org/10.1145/1357054.1357300

Kim, J. H., Ari, H., Madasu, C., & Hwang, J. (2020). Evaluation of hologram distances in reducing shoulder stress during augmented reality interactions. Proceedings of the Human Factors and Ergonomics Society, 64(1), 868–871. https://doi.org/10.1177/1071181320641201

Krasner, A., & Gabbard, J. (2024). MusiKeys: Exploring haptic-to-auditory sensory substitution to improve mid-air text-entry. IEEE Transactions on Visualization and Computer Graphics, 30(5), 2247–2256. https://doi.org/10.1109/TVCG.2024.3372065

Huang, J., Mao, L., Qi, M., Zhang, D., An, M., Han, R., & Ji, T. (2022). Differences in muscle activity, kinematics, user performance, and subjective assessment between touchscreen and mid-air interactions on a tablet. *Behaviour and Information Technology*, *41*(14), 3028–3043. https://doi.org/10.1080/0144929X.2021.1970227

Hachisu, T., Cirio, G., Marchal, M., Lécuyer, A., & Kajimoto, H. (2011). Pseudo-haptic feedback augmented with visual and tactile vibrations. In 2011 IEEE International Symposium on VR Innovation (pp. 327-328). https://doi.org/10.1109/ISVRI.2011.5759662

Radu, I. (2012). *Why should my students use AR? A comparative review of the educational impacts of augmented-reality*. IEEE International Symposium on Mixed and Augmented Reality (ISMAR). https://ieeexplore.ieee.org/abstract/document/6402590

Islam, M. S., & Lim, S. (2022). Vibrotactile feedback in virtual motor learning: A systematic review. In *Applied Ergonomics* (Vol. 101). Elsevier Ltd. https://doi.org/10.1016/j.apergo.2022.103694

Jerald, J. (2015). *The VR Book: Human-Centered Design for Virtual Reality*. Association for Computing Machinery and Morgan & Claypool.

Jonathan, E., & Xiong, S. (2024). Influence of passive arm-support exoskeleton on static postural balance in load-holding tasks: effects of supportive force, weight and load location. *Ergonomics*. https://doi.org/10.1080/00140139.2024.2376334

Jorgensen, M. J., Hakansson, N. A., & Desai, J. (2022a). Influence of different passive shoulder exoskeletons on shoulder and torso muscle activation during simulated horizontal and vertical aircraft squeeze riveting tasks. *Applied Ergonomics*, *104*. https://doi.org/10.1016/j.apergo.2022.103822

Jorgensen, M. J., Hakansson, N. A., & Desai, J. (2022b). The impact of passive shoulder exoskeletons during simulated aircraft manufacturing sealing tasks. *International Journal of Industrial Ergonomics*, *91*. https://doi.org/10.1016/j.ergon.2022.103337

Kang, H., & Shin, G. (2014). Hand usage pattern and upper body discomfort of desktop touchscreen users. *Ergonomics*, *57*(9), 1397–1404. https://doi.org/10.1080/00140139.2014.924574

Kan Yeung, A. W., Tosevska, A., Klager, E., Eibensteiner, F., Laxar, D., Stoyanov, J., Glisic, M., Zeiner, S., Kulnik, S. T., Crutzen, R., Kimberger, O., Kletecka-Pulker, M., Atanasov, A. G., & Willschke, H. (2021). Virtual and augmented reality applications in medicine: Analysis of the scientific literature. In *Journal of Medical Internet Research* (Vol. 23, Issue 2). JMIR Publications Inc. https://doi.org/10.2196/25499

Kim, S., Nussbaum, M. A., Mokhlespour Esfahani, M. I., Alemi, M. M., Alabdulkarim, S., & Rashedi, E. (2018). Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I – "Expected" effects on discomfort, shoulder muscle activity, and work task performance. *Applied Ergonomics*, *70*, 315–322. https://doi.org/10.1016/j.apergo.2018.02.025

Kim, W., & Xiong, S. (2022a). Pseudo-haptic button for improving user experience of mid-air interaction in VR. *International Journal of Human Computer Studies*, *168*. https://doi.org/10.1016/j.ijhcs.2022.102907

Kim, W., & Xiong, S. (2022b). Pseudo-haptics and self-haptics for freehand mid-air text entry in VR. *Applied Ergonomics*, *104*. https://doi.org/10.1016/j.apergo.2022.103819

Kong, Y. K., Park, S. S., Shim, J. W., Choi, K. H., Shim, H. H., Kia, K., & Kim, J. H. (2023). A passive upper-limb exoskeleton reduced muscular loading during augmented reality interactions. *Applied Ergonomics*, *109*. https://doi.org/10.1016/j.apergo.2023.103982

Kou, J., Wang, Y., Chen, Z., Shi, Y., & Guo, Q. (2025). Gait Planning and Multimodal Human-Exoskeleton Cooperative Control Based on Central Pattern Generator. IEEE/ASME Transactions on Mechatronics, 30(4), 2598–2608. https://doi.org/10.1109/TMECH.2024.3453037

Kranenborg, S. E., Greve, C., Reneman, M. F., & Roossien, C. C. (2023). Side-effects and adverse events of a shoulder- and back-support exoskeleton in workers: A systematic review. In *Applied Ergonomics* (Vol. 111). Elsevier Ltd. https://doi.org/10.1016/j.apergo.2023.104042

Lauret, L., Raiteri, B. J., Tecchio, P., & Hahn, D. (2025). *A passive upper-limb exoskeleton effectively reduces shoulder muscle activity over a large shoulder workspace*. https://doi.org/10.1101/2025.02.26.640421

Mackenzie, I. S., & Soukoreff, R. W. (2003). Phrase sets for evaluating text entry techniques. In Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems - Extended Abstracts (pp. 754-755). https://doi.org/10.1145/765891.765971

Ma, T., & Xiong, S. (2024). Effects of passive shoulder-support exoskeleton entity and support force on user range of motion under external loads. *International Journal of Industrial Ergonomics*, *104*.

https://doi.org/10.1016/j.ergon.2024.103655

Ma, T., Zhang, Y., Choi, S., & Xiong, S. (2023). Modelling for Design and Evaluation of Industrial Exoskeletons: A Systematic Review. *Applied Ergonomics,* 113 (104100). https://doi.org/10.1016/j.apergo.2023.104100

McLoughlin, R., McDonnell, M., & McEvoy, D. (2024). *The Impact of 3D and AR Product Presentation on Mental Imagery, Product Uncertainty and User Experience* (pp. 425–443). https://doi.org/10.1007/978-3-031-73110-5_28

Mohd Nur, N., Zawiah Md Dawal, S., Dahari, M., & Sanusi, J. (2015). Muscle activity, time to fatigue, and maximum task duration at different levels of production standard time. Journal of Physical Therapy Science, 27(7), 2323-2327. https://doi.org/10.1589/jpts.27.2323

Musso, M., Oliveira, A. S., & Bai, S. (2024). Influence of an upper limb exoskeleton on muscle activity during various construction and manufacturing tasks. *Applied Ergonomics*, *114*. https://doi.org/10.1016/j.apergo.2023.104158

Naito, J., Obinata, G., Nakayama, A., & Hase, K. (2007). Development of a Wearable Robot for Assisting Carpentry Workers. *International Journal of Advanced Robotic Systems*, *4*(4).

Pacifico, I., Molteni, F., Giovacchini, F., Vitiello, N., Crea, S., Scano, A., Guanziroli, E., Moise, M., Morelli, L., Chiavenna, A., Romo, D., Spada, S., & Colombina, G. (2020). An experimental evaluation of the proto-mate: A novel ergonomic upper-limb exoskeleton to reduce workers' physical strain. *IEEE Robotics and Automation Magazine*, *27*(1), 54–65. https://doi.org/10.1109/MRA.2019.2954105

Pizzolante, M., Bartolotta, S., Sarcinella, E. D., Chirico, A., & Gaggioli, A. (2024). Virtual vs. real: exploring perceptual, cognitive and affective dimensions in design product experiences. *BMC Psychology*, *12*(1). https://doi.org/10.1186/s40359-023-01497-5

Plakas, G., Ponis, S. T., Agalianos, K., Aretoulaki, E., & Gayalis, S. P. (2020). Augmented reality in manufacturing and logistics: Lessons learnt from a real-life industrial application. *Procedia Manufacturing*, *51*, 1629–1635. https://doi.org/10.1016/j.promfg.2020.10.227

Raveendranath, B., Pagano, C. C., & Srinivasan, D. (2024). Effects of arm-support exoskeletons on pointing accuracy and movement. *Human Movement Science*, *95*. https://doi.org/10.1016/j.humov.2024.103198

Renshaw D, Bice MR, Cassidy C, Eldridge JA, Powell DW. A Comparison of Three Computer-based Methods Used to Determine EMG Signal Amplitude. Int J Exerc Sci. 2010 Jan 15;3(1):43-48. doi: 10.70252/AYBG1535. PMID: 27182326; PMCID: PMC4738945.

Rosa-Garcia, A. D. La, Soto-Marrufo, A., Luviano-Cruz, D., Rodriguez-Ramirez, A., & Garcia-Luna, F. (2025). Bridging Remote Operations and Augmented Reality: A Survey of Current Trends. *IEEE Access*. https://doi.org/10.1109/ACCESS.2025.3544633

Schmitz, C., Reynolds, J., Kuhl, S., & Vertanen, K. (2024). *The Impact of Surface Co-location and Eye-tracking on Mixed Reality Typing*. http://arxiv.org/abs/2410.04177

Schrepp, M., Hinderks, A., & Thomaschewski, J. (2017). Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S). *International Journal of Interactive Multimedia and Artificial Intelligence*, *4*(6), 103. https://doi.org/10.9781/ijimai.2017.09.001

Schwind, V., Lin, L., Di Luca, M., Jörg, S., & Hillis, J. (2018, August 10). Touch with foreign hands: The effect of virtual hand appearance on visual-haptic integration. *Proceedings - SAP 2018: ACM Symposium on Applied Perception*. https://doi.org/10.1145/3225153.3225158

Shin, G., & Zhu, X. (2011). User discomfort, work posture and muscle activity while using a touchscreen in a desktop PC setting. *Ergonomics*, *54*(8), 733–744. https://doi.org/10.1080/00140139.2011.592604

Skavronskaya, L., Moyle, B., & Scott, N. (2020). The Experience of Novelty and the Novelty of Experience. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.00322

Soukoreff, R. W., & MacKenzie, I. S. (2001). Measuring errors in text entry tasks: An application of the Levenshtein string distance statistic. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 319-320). https://doi.org/10.1145/634067.634256

Speicher, M., Feit, A. M., Ziegler, P., & Krüger, A. (2018). Selection-based text entry In Virtual Reality. *Conference on Human Factors in Computing Systems - Proceedings*, *2018-April*. https://doi.org/10.1145/3173574.3174221

Streli, P., Richardson, M., Botros, F., Ma, S., Wang, R., & Holz, C. (2024). TouchInsight: Uncertainty-aware rapid touch and text input for mixed reality from egocentric vision. In Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24) (Article 7, pp. 1–16). Association for Computing Machinery. https://doi.org/10.1145/3654777.3676330

Sylla, N., Bonnet, V., Colledani, F., & Fraisse, P. (2014). Ergonomic contribution of ABLE exoskeleton in automotive industry. *International Journal of Industrial Ergonomics*, *44*(4), 475–481. https://doi.org/10.1016/j.ergon.2014.03.008

Szczechowicz, B., Ryśnik, J., Polechoński, J., & Tomik, R. (2024). A Multi-Aspect Assessment of Experiences of People Engaging in Recreational Physical Activity in Real Life as well as Immersive and Non-Immersive VR. *Studia Periegetica*, *46*(2), 7–32. https://doi.org/10.58683/sp.1987

UEQ Project. (n.d.). *User Experience Questionnaire (UEQ)*. Retrieved August 29, 2025, from https://www.ueq-online.org/

Ullo, S. L., Piedimonte, P., Leccese, F., & De Francesco, E. (2019). A step toward the standardization of maintenance and training services in C4I military systems with Mixed Reality application. *Measurement: Journal of the International Measurement Confederation*, *138*, 149–156. https://doi.org/10.1016/j.measurement.2019.02.036

Van Engelhoven, L., Poon, N., Kazerooni, H., Ban, A., Rempel, D., & Harris-Adamson, C. (2018). Evaluation of an adjustable support shoulder exoskeleton on static and dynamic Overhead tasks. *Proceedings of the Human Factors and Ergonomics Society*, *2*, 804–808. https://doi.org/10.1177/1541931218621184

Wiker, S. F., Chaffin, D. B., & Langolf, G. D. (1990). SHOULDER POSTURAL FATIGUE AND DISCOMFORT A Preliminary Finding of No Relationship with Isometric Strength Capability in a Light-Weight Manual Assembly Task. In *International Journal of Industrial Ergonomics* (Vol. 5).

Wobbrock, J. O., Myers, B. A., & Myers, B. A. (2006). Analyzing the Input Stream for Character-Level Errors in Unconstrained Text Entry Evaluations Analyzing the Input Stream for Character-Level Errors. In *ACM Transactions on Computer-Human Interaction* (Vol. 13, Issue 4).

Xu, L., Li, Z., Li, G., & Jin, L. (2025). Robust Model Predictive Control of a Gait Rehabilitation Exoskeleton With Whole Body Motion Planning and Neuro-Dynamics Optimization. IEEE Transactions on Cybernetics, 55(5), 2124–2137. https://doi.org/10.1109/TCYB.2025.3545064

Yang, Z., Chen, C., Lin, Y., Wang, D., Li, H., & Xu, W. (2019). Effect of spatial enhancement technology on input through the keyboard in virtual reality environment. *Applied Ergonomics*, *78*, 164–175. https://doi.org/10.1016/j.apergo.2019.03.006

Yeo, H. S., Phang, X. S., Ha, T., Woo, W., & Quigley, A. (2017). TiTAN: Exploring midair text entry using freehand input. *Conference on Human Factors in Computing Systems - Proceedings*, *Part F127655*, 3041–3049. https://doi.org/10.1145/3027063.3053228

Yi, X., Yu, C., Zhang, M., Gao, S., Sun, K., & Shi, Y. (2015). ATK: Enabling ten-finger freehand typing in air based on3D hand tracking data. *UIST 2015 - Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology*, 539–548. https://doi.org/10.1145/2807442.2807504

Yu, L., & Bai, S. (2024). A Modified Dynamic Movement Primitive Algorithm for Adaptive Gait Control of a Lower Limb Exoskeleton. IEEE Transactions on Human-Machine Systems, 54(6), 778–787. https://doi.org/10.1109/THMS.2024.3458905

Zhang, M., & Wobbrock, J. O. (2019). Beyond the input stream: Making text entry evaluations more flexible with transcription sequences. *UIST 2019 - Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, 831–842. https://doi.org/10.1145/3332165.3347922

Zhao, X., Niikura, T., & Komuro, T. (2014). Evaluation of visuo-haptic feedback in a 3D touch panel interface. *ITS 2014 - Proceedings of the 2014 ACM International Conference on Interactive Tabletops and Surfaces*, 299–304. https://doi.org/10.1145/2669485.2669536

## CRediT Author Statement

**Haejun Kim**: Conceptualization, Formal analysis, Investigation, Data curation, Methodology, Software, Visualization, Writing – original draft

**Qiuli Jin:** Data curation, Formal analysis, Investigation, Software

**Seonghyeok Park**: Methodology, Writing – review & editing

**Woojoo Kim**: Funding acquisition, Project administration, Supervision, Writing – review & editing

**Shuping Xiong**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing