CrowbarLimbs: A Fatigue-Reducing Virtual Reality Text Entry Metaphor

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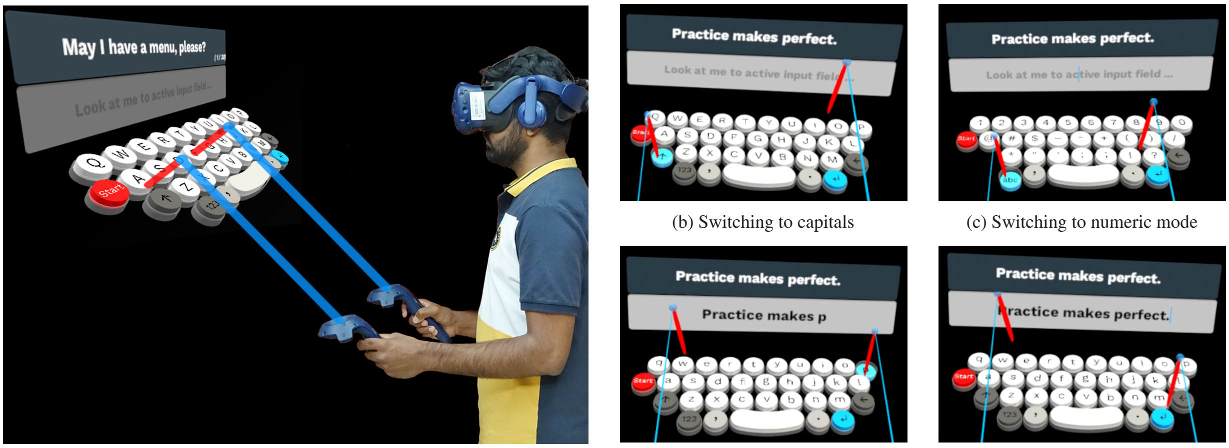

(a) Typing with CrowbarLimbs (a mixed-reality visualization of our system)
(b) Switching to capitals
(c) Switching to numeric mode
(d) Typing a phrase
(e) Finishing a phrase

Fig. 1: (a) To assist a user in maintaining a comfortable typing posture in virtual environments, we propose a novel crowbar-like metaphor, called ”CrowbarLimbs,” such that the physical fatigue in different body parts can be effectively reduced. (b)-(e) The screenshots of our system while a user is typing with CrowbarLimbs.

Abstract—Text entry remains challenging in virtual environments, where users may quickly experience physical fatigue in some body parts using existing methods. In this paper, we propose "CrowbarLimbs," a novel virtual reality (VR) text entry metaphor with two deformable extended virtual limbs. By using a crowbar-like metaphor and placing the virtual keyboard at a user-preferred location based on the user's physical stature, our method can assist the user in placing their hands and arms in a comfortable posture, thus effectively reducing the physical fatigue in various body parts, such as hands, wrists, and elbows. In an initial user study, we found that CrowbarLimbs achieved text entry speed, accuracy, and system usability comparable to those of previous VR typing methods. To investigate the proposed metaphor in more depth, we further conducted two additional user studies to explore the ergonomically user-friendly shapes of CrowbarLimbs and virtual keyboard locations. The experimental results indicate that the shapes of CrowbarLimbs have significant effects on the fatigue ratings in various body parts and text entry speed. Furthermore, placing the virtual keyboard near the user and at half their height can lead to a satisfactory text entry rate of 28.37 words per minute.

Index Terms—Virtual reality, text entry, selection keyboard, fatigue, metaphor shapes, keyboard locations

1 Introduction

Text entry is used in various virtual reality (VR) applications, including Google Earth VR [24], vSpatial [44], VR web browsing [21], and social VR platforms [14]. The main text entry methods in modern VR applications are based on selection [42] and nonselection (such as speech [37]). A classic example of selection-based methods is text entry with handheld controllers and a virtual keyboard [9, 27, 42].

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Although many related approaches have been shown to be user-friendly and effective, they are mostly suitable for short-term tasks, such as account/password typing and searching with a few keywords. For mid- and long-term tasks, such as document editing and email writing, some body parts may soon begin to experience fatigue owing to frequent physical movements of the hands and arms. For example, the drum-like VR keyboard [5, 9] (called "DrumKeyboard" in this paper) utilizes handheld controllers as virtual drumsticks to strike keyboard buttons. The striking action is a rather large spatial movement when compared to text entry with a physical keyboard, and may quickly cause hand/wrist fatigue.

To overcome this problem, we present "CrowbarLimbs," a new metaphor for selection-based VR text entry, to reduce the physical fatigue of a user over a medium/long period of time. Our key idea is to employ two deformable and crowbar-like virtual limbs as a metaphor for typing. As shown in Figure 1, each virtual limb comprises an extendable bar with the front end bent toward the keyboard, such that the user can place their hands and arms in a comfortable posture to reduce the physical fatigue in different body parts, especially hands, wrists, and elbows.

In an initial user study, we allowed users to change the shape of CrowbarLimbs and the virtual keyboard location according to their preferences. The experimental results indicated significant differences in fatigue ratings between CrowbarLimbs and DrumKeyboard [9]. On average, CrowbarLimbs also provided a satisfactory text entry rate of 21.57 words per minute (WPM) and a good system usability score of 85.47. We further conducted two additional user studies to investigate the ergonomically user-friendly shapes of CrowbarLimbs and keyboard locations in more depth. Five representative shapes with different lengths of (or angles between) the front end and bar of the virtual limb were precisely examined, and five keyboard locations at different distances (from the user) and heights were also explored. Surprisingly, significant differences were found among locations in terms of text entry speed, accuracy, and system usability.

In summary, the major contributions of this paper are as follows:

- We propose a new VR text entry metaphor, namely CrowbarLimbs, to allow less physical fatigue, achieve comparable text entry speed and accuracy, and ensure good system usability.
- We examine five shapes of CrowbarLimbs and provide suggestions on ergonomically user-friendly shapes.
- We investigate how various keyboard locations influence the efficiency of CrowbarLimbs.

A practical scenario of CrowbarLimbs is the VR office [15], where people may edit documents or intermittently perform long-term text entry tasks. Another favorable scenario is VR programming. Without an efficient text entry interface, VR developers may repetitively take on and off head-mounted displays (HMDs) for testing, debugging, and changing their programs throughout the day. Moreover, CrowbarLimbs is also suitable for other VR applications that are executed by a user while standing/walking, because CrowbarLimbs can help the user to retain their hands and arms in a comfortable posture and substantially reduce the necessary physical movements.

2 Related Work

In this section, we briefly discuss previous VR text entry methods. However, a comprehensive survey is beyond the scope of this paper. Readers may refer to [10] for a more in-depth examination of existing approaches.

2.1 Noncontroller-Based Approaches

Typing with a physical keyboard in virtual environments is one of the most common related techniques without the use of controllers. Many studies have been conducted to investigate the characteristics related to physical keyboards, such as performance [17], keyboard visual representations/reconfiguration in virtual environments [33, 41, 45], and hand representations [16, 22, 25, 28]. Although these solutions provide high text entry speed, mobility remains a major issue for similar methods. To provide versatile text entry, Pham and Stuerzlinger [36] introduced a portable physical keyboard, namely "HawKEY," which can be used while a user is walking or sitting. They required the user to wear a keyboard tray and attach an RGB-D camera to the HMD to integrate the visual representation of the physical keyboard into the virtual environment. However, the employed hardware devices may become burdensome and expensive. In contrast, our method allows mobility without requiring additional hardware devices but only handheld controllers.

Mid-air techniques [12, 19, 39, 46, 51] are popular and provide reasonable text entry speed and accuracy. A limitation of these approaches is that they often require additional devices or sensors, which can be challenging when the user needs to interact with virtual environments via other input devices, such as handheld controllers. Recently, researchers have investigated the performance of touchscreen-based text entry methods [17, 18, 26, 38]. These methods achieve adequate text entry speed and accuracy, but it is occasionally difficult for users to sense where their hands are before pressing the initial character [18].

Various other VR text entry techniques do not employ handheld controllers. Meier et al. [34] developed "TapID," which is a wristband device for detecting rapid touching events on surfaces and identifying the tapping finger using a machine learning classifier. The detected taps and finger identification can be further combined with tracked hand poses to trigger input events at the correct fingertip locations in virtual environments. Lu et al. [29] introduced two alternatives for hands-free text entry, namely NeckType and BlinkType, which utilize eye blinks and forward/backward neck movements of the user as the selection mechanism of keys. While TapID, NeckType, and BlinkType may require a substantial learning curve, our CrowbarLimbs is instead an intuitive and user-friendly text entry metaphor.

The head-directed text entry interface [52] is a relatively cheaper solution that employs the built-in head-tracking capability of numerous existing VR hardware devices, such as HTC Vive, Oculus Rift, and PlayStation VR. The head- and gesture-based approaches can also be combined to improve text entry speed. Gaze typing [40] is another efficient text entry approach in VR. It employs an eye-tracking unit integrated with the HMD to recognize the eye movements of a user and demonstrates the potential for practical applications.

2.2 Controller-Based Approaches

Another major category of VR text entry methods with mobility is based on handheld controllers [4]. For example, DrumKeyboard [9] uses controllers as drumsticks such that a user can strike keyboard buttons like playing drums, which is entertaining and achieves satisfactory typing speed (24.61 WPM) [5]. Raycasting [27] relies on a laser beam emitted from the corresponding position of a controller in the virtual environment to specify a character, and the final selection is made by pressing the trigger button of the controller. However, the large physical movements of the striking action of DrumKeyboard can quickly result in fatigue [17]. The laser metaphor of raycasting can also easily cause finger fatigue owing to the repeated pressing action of the same finger.

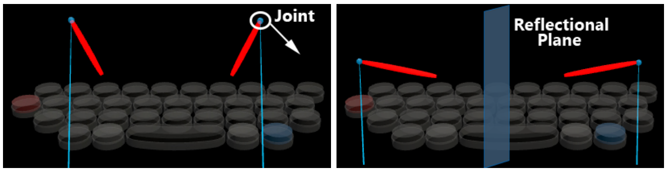
Yu et al. [53] introduced PizzaText, which combined a handheld game controller with a circular virtual keyboard for text entry. For rapid search of characters, the circular keyboard is further divided into slices, each of which contains several characters. The final selection is then achieved by using thumbsticks of the controller, resulting in acceptable typing performance for both novices (8.59 WPM) and experts (15.85 WPM). To facilitate one-handed text entry, Jiang et al. [23] leveraged a circular touchpad with a virtual circular keyboard and examined the typing performance of various key layouts. Yao et al. [50] proposed Punch Typing that asks a user to make a hand movement like punching for text entry. Punch Typing may be a fun way of text input, but it requires large physical movements that may lead to a higher level of fatigue in user's arms.

In summary, controller-based text entry techniques are often inexpensive solutions, because they do not need additional hardware devices. However, most of them struggle to provide competent text entry speed to physical keyboards owing to the lack of tangible feedback, which is also a limitation of CrowbarLimbs. Moreover, previous controller-based approaches may quickly cause fatigue due to large physical movements [9] or repeated pressing action of the same finger [27]. By contrast, we designed CrowbarLimbs in a way that helps users to avoid large physical movements and maintain a comfortable posture while typing.

2.3 Keyboard Design

Rajanna and Hansen [40] studied the impact of keyboard design, selection method, and motion in the virtual environment. They found that users performed well in the within-view keyboard condition, but a larger-than-view keyboard design often led to fatigue owing to frequent head movements. Moreover, motion in the virtual environment negatively affects typing performance, and a multimodal selection method that combines gaze and clicking on an external button is preferred and more efficient.

Circular keyboards [49, 53] may also offer additional advantages when engaging with input devices [53], such as joysticks. Xu et al. [49] proposed a hands-free text entry method called RingText that combines a circular keyboard with gaze typing. Although RingText has potential, it is unsuitable for a person who cannot rotate their head, and frequent neck movements may increase the risk of motion sickness [23, 53].



(a) Before (b) After

Fig. 2: (a) Shape of CrowbarLimbs before the joint of a virtual limb is moved in the specified direction. (b) After the joint has been moved, the lengths of (and angle between) the front end and bar of the virtual limb change accordingly. Note that the other limb simultaneously changes its shape symmetrically with respect to the reflectional plane of CrowbarLimbs.

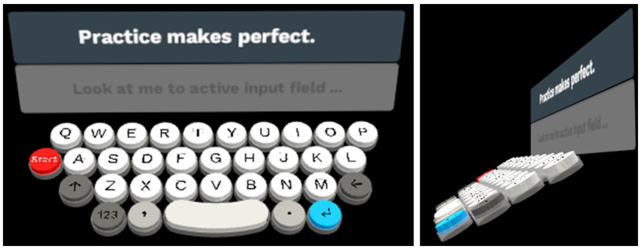


Fig. 3: Virtual keyboard employed in our user studies.

The split keyboard design [47] was introduced to force users to type with both hands by wearing touch sensitive gloves that enable thumb-to-finger interactions. The virtual keyboard is split into two parts. One is assigned to the right-hand fingers and the other to the left-hand ones. In this way, the user can tap on a certain part of their finger using their thumb to select the corresponding keyboard button.

Furthermore, Dube and Arif. [11] investigated the effects of key dimensions and shapes on text entry performance. According to their findings, key dimensions influence accuracy, shapes affect text entry speed, and both impact the user experience.

In this paper, we conducted a user study on different virtual keyboard locations for CrowbarLimbs. Our keyboard follows the within-view design [40] and is located at the line of sight height to allow less physical movements and comparable text entry speed and accuracy to previous selection-based methods.

3 Design Rationale

The proposed metaphor was designed with specific objectives:

- Less fatigue: Reduce the physical fatigue in body parts for medium- or long-term text entry tasks.
- Standing postures: Focus on standing postures during typing.
- Efficiency: Provide satisfactory text entry speed and accuracy.
- Mobility: Enable user mobility in the real world.
- Privacy: Protect private user information.
- Customizability: Allow adaptivity to the physical stature of an individual user.

3.1 Less Fatigue and Standing Postures

While sitting and typing on a physical keyboard for a medium/long period of time, a user tends to maintain a natural posture that causes less strain on their body, for example, looking straight forward and keeping arms relaxed [20]. We assume that a similar tendency exists when a user stands and types on a virtual keyboard in virtual environments.

To keep a user relaxed, we refer to rapid upper limb assessment (RULA) [32], which can evaluate the muscular effort associated with different postures of body parts based on the orientations of the arms and upper body. According to RULA, a typing posture with minimal effort (or minimal risk factors) involves placing the hands in front of the body at the waist level and keeping the wrists in a neutral position, with the trunk straight, elbows slightly bent, shoulders unraised, and upper arms not abducted. Thus, we designed CrowbarLimbs to effectively reduce the physical movements of various body parts and assist the user in maintaining a comfortable posture during typing.

3.2 Efficiency, Mobility, and Privacy

In virtual environments, an efficient text-entry method with adequate speed and accuracy is essential for mid- and long-term tasks. Considering these two factors, using a physical keyboard may be the most preferred method [42]. Unfortunately, this often restricts user mobility and causes physical fatigue for a medium/long period of time.

Speech-based approaches [2, 37] are another popular choice for achieving efficient text entry. Their entry rates are adequately fast, perhaps even currently higher than those of physical keyboards, and their accuracy is comparable to that of traditional methods. However, privacy and security issues [48] are major concerns when a user has to input some personal information, including their name, phone number, and account/password. In quiet public places, such as workplaces and libraries, speech-based approaches are also inappropriate.

As for selection-based methods [42], their text entry rates in VR (3-15 WPM) are generally slower than those of physical keyboards (24-40 WPM), but still at an acceptable level. Furthermore, system usability is another important factor for efficiency. A virtual keyboard with a layout familiar to physical keyboards can often lead to a gentle learning curve for VR novices. Therefore, we followed selection-based methods and developed CrowbarLimbs by employing the common QWERTY layout for virtual keyboards. From our user studies, the WPM and error rate of CrowbarLimbs were more than 21 and less than 6.5% on average, respectively, showing its potential for efficient text entry. Participants could also easily and intuitively learn to use CrowbarLimbs efficiently within a few minutes and shared voluminous positive feedback on system usability.

3.3 Customizability

One of the most apparent reasons for customizing a system is to provide an environment specifically tailored to an individual user. They can interact with the system in ways different from "normal/default use" through customization [30], which may improve performance, productivity, and user experience. As for CrowbarLimbs, we found that a single configuration is unsuitable for each user, because users have unique bodies, for example, heights, arm lengths, and shoulder widths. To explore the customizability of CrowbarLimbs in more depth, we designed and conducted two additional user studies to investigate the impact of changes in the shape of CrowbarLimbs and virtual keyboard location. Therefore, our method can automatically suggest a user-oriented configuration based on the physical stature of an individual user, and allow them to fine-tune the lengths of (or angle between) the front end and bar of a virtual limb, and the keyboard location.

4 System Design

Our system is divided into two main parts:

- CrowbarLimbs: A metaphor that extends the arms of a user;
- Keyboard: A virtual keyboard at the line of sight height;

4.1 CrowbarLimbs

We designed the metaphor "CrowbarLimbs" to achieve a comfortable posture based on RULA [32]. As Fig. 2(a) illustrates, CrowbarLimbs comprises two crowbar-like deformable virtual limbs that extend the arms of a user. The front end of a virtual limb is bent toward the virtual keyboard and allows the user to place their hands at the waist level without raising their shoulders and abducting their upper arms. This special design can also decrease the RULA score (thus, lower muscular effort) by preventing unnecessary bending of wrists or large flexion angles of elbows. The user can also drag the joint of a virtual limb to simultaneously change the shapes of both limbs, specifically the lengths of the front end and bar, as well as the angle between them.

4.2 Keyboard

Fig. 3 demonstrates an example of our keyboard design that comprises three major parts: the text box (top gray rectangle), input field (middle light gray rectangle), and key buttons. The text box (size: 35×5 cm) shows the phrases/sentences that a user needs to type during the user studies. The input field (size: 35×5 cm) shows the current content that has been typed by the user and can be modified by pressing the "Backspace" button. As for the key buttons, we employ a standard QWERTY keyboard layout (with alphanumeric and punctuation keys) with which numerous users are familiar. The size of the spacebar is 9×3 cm, and the radius of the other keys is 1.5 cm. Moreover, the height of each key button is 2 cm.

To fit in with the user's field of view, the keyboard size (33×11 cm) was determined based on the within-view design [40]. By default, our system adapts the keyboard location to the line of sight height, so that the user can maintain a comfortable posture while typing with CrowbarLimbs. Nevertheless, the user can further relocate or resize the keyboard as preferred, often based on their shoulder width and height from our experience.

5 User Study I: CrowbarLimbs Versus DrumKeyboard

To evaluate the potential of CrowbarLimbs, we conducted the first user study to compare its performance with that of DrumKeyboard [5, 9], especially focusing on physical fatigue.

5.1 Research Questions

Two research questions were investigated in this user study:

- **RQ1:** Will CrowbarLimbs have lower physical fatigue than DrumKeyboard? It is hypothesized that Drumkeyboard may easily cause fatigue in various body parts of the user, because Drumkeyboard requires relatively larger physical movements than CrowbarLimbs to press keyboard buttons.
- **RQ2:** Will CrowbarLimbs have comparable text entry speed, accuracy, and system usability to DrumKeyboard?

5.2 Participants

We recruited 16 participants (6 females and 10 males) for this user study. All were university students with engineering backgrounds, between the ages of 20-30 ($M = 25.13$, $SD = 3.24$), and none had suffered an arm/shoulder injury. Twelve participants were novices to VR, three had some experience, one was a regular user, and none had ever participated in any prior VR-related text entry experiments.

5.3 Interface and Apparatus

The testing system was developed using Unity 2017.4.28f1 and C# and deployed on an HTC VIVE Pro headset with handheld controllers. The user study was conducted using a PC (with an Intel Core i7 processor, 32GB RAM, and an NVIDIA GTX 1080 Ti graphics card) running on Windows 10.

5.4 Evaluation Metrics

5.4.1 Fatigue

It is difficult to accurately measure the low-level physical fatigue of a user, particularly in various body parts. To overcome this problem, we employed the Borg CR10 scale [6] ranging from 0 to 10, where 0 indicates no fatigue and 10 indicates extremely strong fatigue. The Borg CR10 scale shows a fine resolution for low-level fatigue and has been widely adopted to measure perceived exertion, fatigue, and pain [2, 13]. It has also been reported to be strongly correlated to and more reliable than electromyogram-based metrics [8, 35, 43], especially for low levels of physical exertion, such as keyboard typing.

5.4.2 Other Metrics

The WPM and total error rate (TER) [3] were used to evaluate typing performance, including speed and accuracy. Moreover, the subjective usability of CrowbarLimbs and DrumKeyboard was measured using the system usability scale (SUS) [7].

5.5 Experimental Design and Procedure

Before the user study, the demographic information of the participants was collected through a questionnaire. Subsequently, each participant was briefed regarding the experimental protocols, required to carefully read and sign the informed consent form, acquainted with VR, instructed to move the virtual keyboard to their line of sight height, given 10 minutes to practice both metaphors, namely CrowbarLimbs and DrumKeyboard, encouraged to fine-tune the keyboard location for both metaphors, and asked to especially maintain a comfortable posture (mentioned in Section 3.1) based on RULA while typing.

In addition to the default shape of CrowbarLimbs, participants could further fine-tune its shape to fit their preferences. A demo video on how to change the shape was first shown. The participants were then instructed to move the joint of the right-handed virtual limb (Fig. 2) to change the lengths of (and angle between) the front end and bar of each limb.

Following a brief intermission of 10 minutes to avoid any residual fatigue from the practice, the experiment was divided into two sessions, each of which evaluated only a single metaphor: one for CrowbarLimbs and the other for DrumKeyboard, and their order was counterbalanced across participants. Before each session, the participants were reminded again to maintain a comfortable posture based on RULA while typing. Each session lasted approximately 10 minutes with a rest interval of 10 minutes. Following each session, the participants were required to remove the HMD, rate the perceived fatigue in their hands, wrists, forearms, elbows, upper arms, and shoulders using the Borg CR10 scale, and complete the system usability questionnaire. After evaluating both metaphors, we encouraged participants to make further comments.

Note that in each session, participants were instructed to type the same 30 phrases (a total of 134 words with 672 key presses, manually selected from the MacKenzie phrase set [31]) as quickly and accurately as possible using CrowbarLimbs or DrumKeyboard. They were also allowed to use the backspace to correct errors.

5.6 Results

The one-way repeated measures analysis of variance (ANOVA) was performed to analyze the collected data. To control the familywise error rate, a significance threshold of 0.005 was used for p values.

5.6.1 Fatigue

Fig. 4(a) illustrates the mean fatigue ratings in the hands, wrists, forearms, elbows, upper arms, and shoulders for CrowbarLimbs and DrumKeyboard. Figs. 4(b)-(g) also compare the fatigue ratings in the six body parts in detail. On average, CrowbarLimbs can effectively reduce the overall fatigue rating by 2.93 when compared to DrumKeyboard, which is a moderate to strong difference according to the Borg CR10 scale.

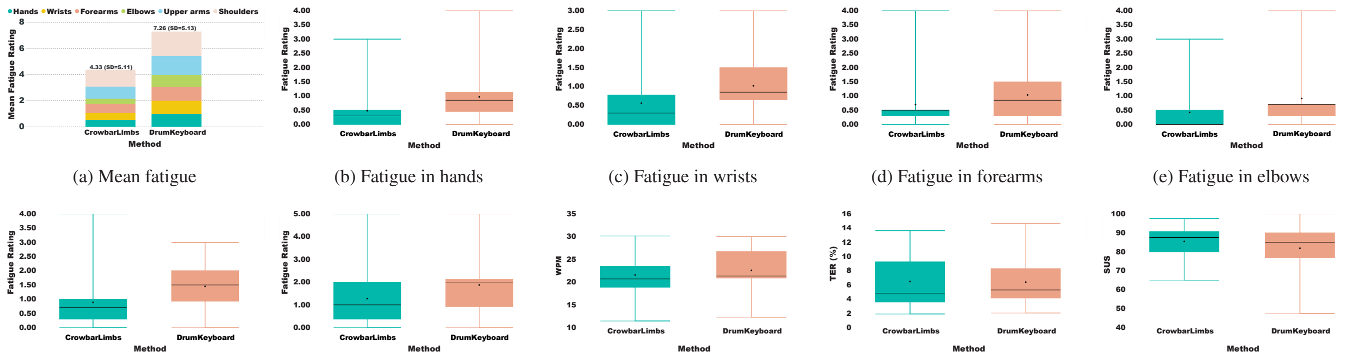
Moreover, ANOVA showed significant differences in the fatigue ratings in the hands ($F_{1,15} = 20.10$, $p = 0.0004$), wrists ($F_{1,15} = 12.68$, $p = 0.0028$), elbows ($F_{1,15} = 12.74$, $p = 0.0028$), upper arms ($F_{1,15} = 11.20$, $p = 0.0044$), and shoulders ($F_{1,15} = 22.15$, $p = 0.0003$, but no significance for forearms ($F_{1,15} = 4.34$, $p = 0.0547$). This suggests that participants can feel a decrease in the physical fatigue in various body parts using CrowbarLimbs, especially hands, wrists, elbows, and shoulders.

5.6.2 Typing Performance

Figs. 4(h) and 4(i) compare the typing performance of CrowbarLimbs and DrumKeyboard in terms of the WPM and TER. The mean text entry rates were 21.57 WPM ($SD = 4.88$) for CrowbarLimbs and 22.58 WPM ($SD = 4.84$) for DrumKeyboard, and ANOVA revealed no significant differences ($F_{1,15} = 5.24$, $p = 0.0369$). On the other hand, the mean TERs of CrowbarLimbs and DrumKeyboard were respectively 6.49% ($SD = 4.07\%$) and 6.39% ($SD = 3.37\%$), and ANOVA yielded no significant effects ($F_{1,15} = 0.03$, $p = 0.8659$).

5.6.3 System Usability

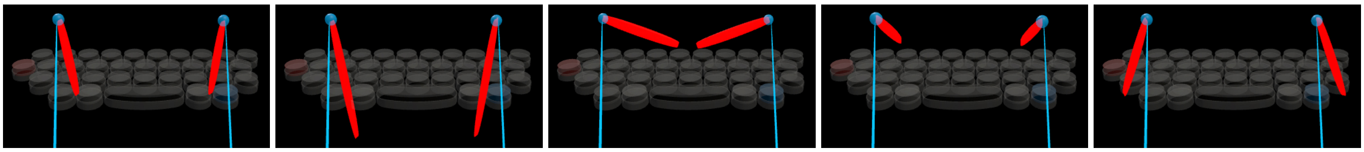
As illustrated in Fig. 4(j), the mean SUS scores were 85.47 ($SD = 8.28$) for CrowbarLimbs and 81.88 ($SD = 13.28$) for DrumKeyboard,



(a) Mean fatigue (b) Fatigue in hands (c) Fatigue in wrists (d) Fatigue in forearms (e) Fatigue in elbows

(f) Fatigue in upper arms (g) Fatigue in shoulders (h) WPM (i) TER (j) SUS

Fig. 4: User study results for CrowbarLimbs and DrumKeyboard. (a) The mean and standard deviation of the accumulated fatigue ratings in six body parts are shown at the top of each stack. (b)-(j) For each box, the three horizontal lines indicate the maximum, median, and minimum (from top to bottom). The top and bottom edges of each box are the third and first quartiles, and the black dot shows the mean.



(a) S1 (b) S2 (c) S3 (d) S4 (e) S5

Fig. 5: Five tested shapes of CrowbarLimbs in User Study II: (a) S1: the default shape; (b) S2: a longer (red) front end of each limb; (c) S3: the front end bent toward the other limb; (d) S4: a larger angle between the front end and the (blue) bar of each limb; (e) S5: the front end bent away from the other limb.

indicating that both metaphors had good system usability, and ANOVA results showed no significant differences ($F_{1,15} = 2.76$, $p = 0.1176$).

5.7 Discussion

Based on this user study, CrowbarLimbs is an effective metaphor for reducing fatigue ratings and achieves comparable text entry speed, accuracy, and system usability scores to DrumKeyboard. Although the mean WPM of CrowbarLimbs is slightly lower than that of DrumKeyboard, no significant differences between them were reported by ANOVA. A rate of 21.57 WPM remains satisfactory and outperforms numerous controller-based selection approaches [23, 42].

Furthermore, six participants stated that CrowbarLimbs was more intuitive to use and easier to press keys on the virtual keyboard than DrumKeyboard. CrowbarLimbs also allowed them to retain their hands and arms in a comfortable posture. Five participants mentioned that fewer physical movements were required when typing with CrowbarLimbs. In contrast, two participants could barely maintain a comfortable posture based on RULA while using DrumKeyboard, and other participants also had similar issues (but relatively moderate). This can be further validated by our quantitative results, in which CrowbarLimbs generally had lower fatigue ratings.

Moreover, one participant indicated that dividing CrowbarLimbs into two parts was an effective design to quickly customize the shape of CrowbarLimbs. During the experiment, we also observed that participants often placed the keyboard near them and at half their height. These two findings inspired us to conduct User Studies II and III to further investigate the effects of different shapes of CrowbarLimbs and keyboard locations.

6 User Study II: Shapes of CrowbarLimbs

Based on User Study I, we discovered that participants preferred specific shapes of CrowbarLimbs. To explore a more ergonomically user-friendly metaphor, we identified and studied five representative shapes of CrowbarLimbs (S1∼S5, as shown in Fig. 5) by increasing the length of the (red) front end of a virtual limb or changing the orientation of the front end with respect to the (blue) bar.

6.1 Research Questions

This user study investigated two research questions:

- **RQ3:** Will the shapes of CrowbarLimbs have significant effects on the physical fatigue, text entry speed, accuracy, and system usability?
- **RQ4:** Will S1, S2, and S4 have similar performance and outperform S3 and S5? it is hypothesized that the performance of S3 and S5 may be significantly affected, because users often need to moderately rotate or tilt their hands while typing with S3 or S5.

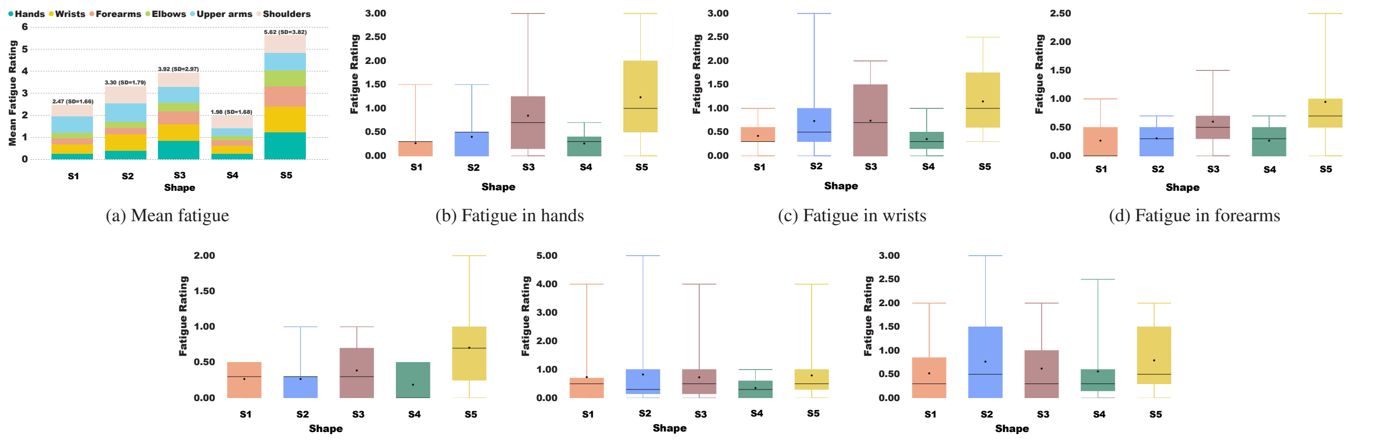
6.2 Participants, Interface, and Apparatus

We recruited 15 participants (6 females and 9 males) for this user study. All were university students with engineering backgrounds, between the ages of 21-30 ($M = 24.47$, $SD = 3.46$), and none had suffered an arm/shoulder injury. Eleven participants were novices to VR, two had some experience, and two were regular users. Two participants had joined from User Study I, but others were first-time participants of VR-related text entry experiments. The same interface and apparatus were utilized as in User Study I.

6.3 Experimental Design and Procedure

The participants were required to fill out the demographic questionnaire, read the protocols and consent form, and sign the form. For each participant, the experiment was split into five sessions, each of which evaluated only one shape of CrowbarLimbs. To counterbalance the order of shapes, the 15 participants were randomly divided into three groups, each of which contains 5 participants. In each group, the same 5×5 Latin square design was employed to determine the order of shapes for the 5 participants.

In each session, the participants were first acquainted with the current shape and given 5 minutes to practice. After a brief intermission, the participants were required to type the same 30 phrases as quickly and accurately as possible and to correct errors using the backspace. Following each session, we instructed the participants to rate the fatigue in six body parts based on the Borg CR10 scale, fill out the SUS



(a) Mean fatigue (b) Fatigue in hands (c) Fatigue in wrists (d) Fatigue in forearms

(e) Fatigue in elbows (f) Fatigue in upper arms (g) Fatigue in shoulders

Fig. 6: Fatigue ratings in various body parts for the five tested shapes of CrowbarLimbs. (a) The mean and standard deviation of the accumulated fatigue ratings are shown at the top of each stack. (b)-(g) Refer to Fig. 4 for the meanings of the horizontal lines, box edges, and dots.

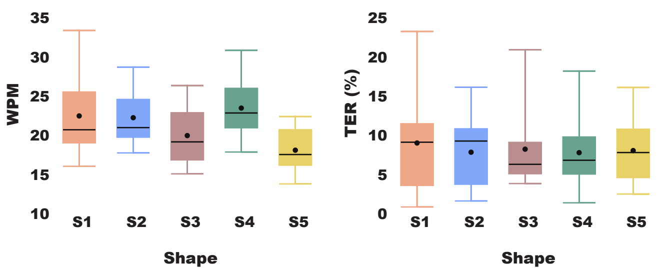


Fig. 7: Text entry speed (left) and accuracy (right) for the five tested shapes of CrowbarLimbs. Refer to Fig. 4 for the meanings of the horizontal lines, box edges, and dots.

Table 1: Mean WPM, TERs, and SUS scores as well as ANOVA results for the five tested shapes of CrowbarLimbs. The best shape per metric (or scale) is highlighted in bold text, while the second is underlined. The order for each metric (or scale) is also shown in Roman numerals.

Shape	WPM	TER (%)	SUS
S1	II: 22.55	V: 9.10	**I: 89.83**
S2	III: 22.33	II: 7.92	III: 80.00
S3	IV: 20.04	IV: 8.31	IV: 60.83
S4	**I: 23.56**	**I: 7.86**	II: 86.83
S5	V: 18.18	III: 8.13	V: 46.00
$F_{4,56}$	19.70	0.42	25.47
p	1.22×10^{-7}	0.7921	9.43×10^{-8}

questionnaire, and then rest for at least 10 minutes before the next session started. After completing all five sessions, the participants were instructed to rank the five shapes and encouraged to comment.

6.4 Results

In addition to one-way repeated measures ANOVA, post-hoc comparisons were performed using pairwise t-tests with the Bonferroni correction. The Mauchly's test was applied to detect sphericity violation and the Greenhouse-Geisser adjustment was used for correction when needed. A threshold of 0.005 was employed for statistical significance.

6.4.1 Fatigue

Fig. 6(a) shows a stacked chart of the mean fatigue ratings in body parts for the five tested shapes, and Figs. 6(b)-(g) illustrates the box charts of the fatigue ratings in detail. On average, S4 provided the lowest overall fatigue rating (1.98), whereas S5 had the highest rating (5.62). Most of the mean fatigue ratings for the five shapes were below 1.0 (very weak fatigue), except that the ratings in hands and wrists for S5 were slightly higher than 1.0.

ANOVA yielded significant effects of shapes on the fatigue ratings in the hands ($F_{4,56} = 13.13$, $p = 0.0001$) and forearms ($F_{4,56} = 8.62$, $p = 0.0019$), but no significance for wrists ($F_{4,56} = 6.28$, $p = 0.0064$), elbows ($F_{4,56} = 5.77$, $p = 0.014$), upper arms ($F_{4,56} = 0.74$, $p = 0.4422$), and shoulders ($F_{4,56} = 0.92$, $p = 0.4578$).

Moreover, post-hoc pairwise comparisons showed significant differences in the hand fatigue ratings between S1-S5 ($p = 0.0034$) and S4-S5 ($p = 0.0042$). There were also significant differences in the wrists between S4-S5 ($p = 0.0038$) and forearms between S4-S5 ($p = 0.005$). This indicates that S1, S2, and S4 were similar to each other based on the fatigue ratings in all six body parts. However, S5 was significantly different from S1 and S4, because users felt more fatigue in the hands, wrists, and forearms.

6.4.2 Typing Performance

Fig. 7 and Table 1 show the typing performance for the five tested shapes. The mean text entry rates ranged between 18.18 and 23.56 WPM. ANOVA tests revealed significant effects of shapes on the WPM $F_{4,56} = 19.70$, $p = 1.22 \times 10^{-7}$). In addition, post-hoc pairwise comparisons indicated significant differences between S1-S3 ($p = 1.0 \times 10^{-6}$), S1-S5 ($p < 2.0 \times 10^{-16}$), S2-S3 ($p = 1.8 \times 10^{-13}$), S2-S4 ($p = 0.0003$), S2-S5 ($p < 2.0 \times 10^{-16}$), S3-S4 ($p < 2.0 \times 10^{-16}$), S3-S5 ($p = 9.3 \times 10^{-11}$), and S4-S5 ($p < 2.0 \times 10^{-16}$).

As for text entry accuracy, ANOVA yielded no significant effects of shapes on TER ($F_{4,56} = 0.42$, $p = 0.7921$). We found that the shape with the highest mean WPM, namely S4, also had the lowest mean TER.

6.4.3 System Usability

As shown in Fig. 8 and Table 1, S1 had the highest mean SUS score (89.83, $SD = 6.58$), followed by S4 (86.83, $SD = 9.56$). ANOVA showed significant differences among the shapes of CrowbarLimbs ($F_{4,56} = 25.47$, $p = 9.43 \times 10^{-8}$). Post-hoc pairwise comparisons revealed significance between S1-S3 ($p = 0.0037$), S1-S5 ($p = 2.4 \times 10^{-5}$), S2-S5 ($p = 0.0004$), and S4-S5 ($p = 6.9 \times 10^{-5}$).

6.4.4 Shape Rankings

Fig. 8 visualizes shape rankings in detail, which indicates that many participants (9 out of 15) preferred S1 over others, while S5 was generally

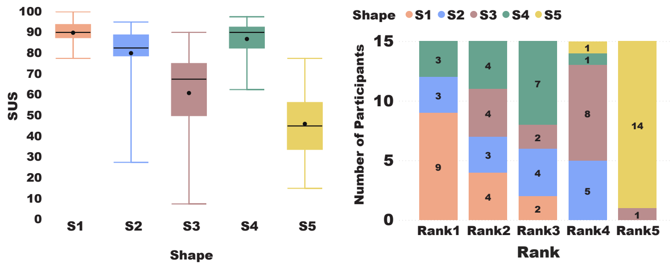


Fig. 8: SUS scores (left) and shape rankings (right) for the five tested shapes of CrowbarLimbs. Refer to Fig. 4 for the meanings of the horizontal lines, box edges, and dots.

the least preferred shape. The Friedman rank sum test revealed significant effects of shapes ($\chi^2 = 38.88$, $p = 7.376 \times 10^{-8}$). Moreover, post-hoc pairwise comparisons using the Wilcoxon signed-rank test showed significant differences between S1-S5 ($Z = -2.81$, $p = 0.0050$).

6.5 Discussion

By our statistical findings, S1, S2, and S4 can be generally regarded as one group with similar performance in terms of all metrics and scales. S5 may be the worse shape, which is significantly different from S1 and S4, with higher fatigue ratings in three body parts (hands, wrists, and forearms), slower text entry speed, and lower SUS scores. However, no significant effects on the TERs were found among all five shapes, and the fatigue ratings for S3 were not significantly different from those for the other shapes.

Moreover, shape rankings showed that S1 was the most preferred by many participants, but we observed that user preference for a particular shape might not substantially affect the fatigue ratings. Specifically, although nine (out of fifteen) participants ranked S1 as their favorite shape, no significant differences in the fatigue ratings in all six body parts between S1 and S4 were found. We also noticed that the shape with the highest mean SUS score (S1) was ranked as the favorite by many participants, whereas the lowest (S5) was ranked as the least preferred by almost all participants.

During our experiments, we found that while typing with S5, participants often tilted their hands toward the ulnas (hand adduction), which was not a comfortable posture based on RULA. Two participants mentioned that it was difficult and uncomfortable to hold the VR controllers using S5. As for S3, a similar (but less serious) issue was observed. While holding the VR controllers, participants usually rotated their hands to keep their palms up (hand supination) for typing. Although no significant differences in the fatigue ratings in all six body parts were found, there were significant effects on the WPM and SUS scores.

Because the employed incomplete counterbalancing method (Sec. 6.3) was based on a Latin square design, the carryover effects may remain a problem. The comparisons between a shape and its subsequent shape, including S1-S2, S2-S3, S3-S4, S4-S5, and S1-S5, should be carefully interpreted. To recruit enough participants for a better counterbalancing solution, such as a balanced Latin square or complete design, is left as our future work.

In summary, we suggest customizing the shape of CrowbarLimbs as S1 or S4. Users can also follow S4 to try an even larger angle between the front end and bar of each limb according to their preferences.

7 User Study III: Keyboard Locations

During User Study I, we observed that participants could more easily maintain a comfortable posture based on RULA by customizing the virtual keyboard location as per their preference. To investigate this observation in greater depth, we identified and studied five representative locations (L1∼L5, as shown in Table 2) by varying the keyboard height (based on the physical stature of the user) and distance (from the user).

7.1 Research Questions

Two research questions were explored in this user study:

Table 2: Height and distance configurations for the five tested keyboard locations.

Location	Height	Distance
L1	High (Chest)	Medium (45cm)
L2	Medium (Belly)	Medium (45cm)
L3	Low (Waist)	Medium (45cm)
L4	Medium (Belly)	Far (60cm)
L5	Medium (Belly)	Near (30cm)

- **RQ5:** Will the keyboard locations significantly affect the physical fatigue, text entry speed, accuracy, and system usability?
- **RQ6:** Will L5 outperform the other four keyboard locations?

7.2 Participants, Interface, and Apparatus

All 15 participants from User Study II participated in this study. Moreover, we employed the same interface and apparatus as in User Study I.

7.3 Experimental Design and Procedure

The participants were asked to fill out the demographic questionnaire, read the protocols and consent form, and sign the form. As in User Study II, there were five sessions in the experiment for each participant, and the order of sessions was counterbalanced using the same Latin square design. In each session, only one keyboard location was evaluated. The keyboard distance was fixed and automatically determined by our system according to the tested location (Table 2). The participants were instructed to relocate the virtual keyboard only vertically at a height with respect to one of their body parts. By connecting the HMD to a display, we examined the keyboard height and required the participants to move the keyboard vertically until the target height was reached. The participants were then given 5 minutes to practice the current location.

Following a brief intermission, we asked the participants to type the same 30 phrases and correct errors using the backspace. At the end of each session, the participants were required to rate their perceived fatigue, fill out the SUS questionnaire, and take a rest of at least 10 minutes. After testing all five sessions, the participants were instructed to rank the five locations and encouraged to comment.

7.4 Results

We applied the same statistical techniques as in User Study II to analyze the collected data, and a significance threshold of 0.005 was used.

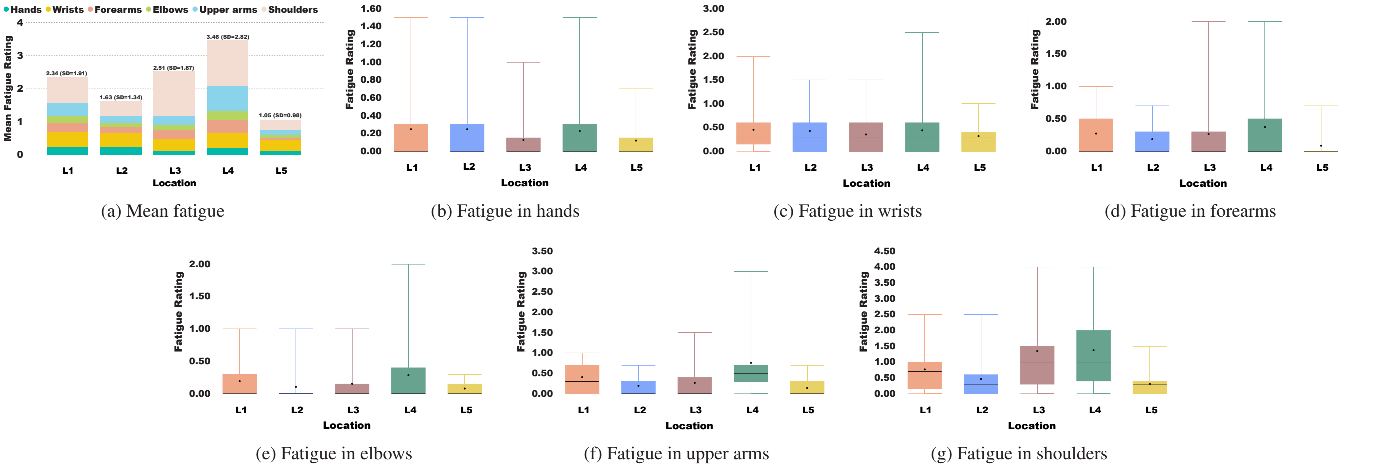
7.4.1 Fatigue

Fig. 9 illustrates the mean fatigue ratings in various body parts for the five tested locations using a stacked chart, and Figs. 9(b)-(g) shows the box charts of the fatigue ratings in detail. Our results revealed that the overall mean fatigue rating of L5 was the lowest (1.05), while that of L4 was the highest (3.46).

ANOVA results indicated no significant effects of locations on the fatigue ratings in the hands ($F_{4,56} = 0.72$, $p = 0.5198$), wrists ($F_{4,56} = 0.30$, $p = 0.7512$), forearms ($F_{4,56} = 1.46$, $p = 0.2451$), elbows ($F_{4,56} = 1.51$, $p = 0.2349$), upper arms ($F_{4,56} = 5.51$, $p = 0.0126$), and shoulders ($F_{4,56} = 5.89$, $p = 0.0096$). Post-hoc pairwise comparisons also yielded no significant differences between each pair of the five locations for all six body parts.

7.4.2 Typing Performance

The typing performance for the five tested locations is shown in Fig. 10 and Table 3. The mean text entry rates ranged from 22.62 to 28.37 WPM. ANOVA tests revealed significant effects of locations on the WPM ($F_{4,56} = 27.34$, $p = 1.33 \times 10^{-12}$). Furthermore, post-hoc pairwise comparisons indicated significance between L1-L2 ($p = 9.2 \times 10^{-8}$), L1-L3 ($p = 3.6 \times 10^{-10}$), L1-L5 ($p < 2.0 \times 10^{-16}$), L2-L4 ($p = 0.00093$), L2-L5 ($p < 2.0 \times 10^{-16}$), L3-L4 ($p = 3.0 \times 10^{-6}$), L3-L5 ($p < 2.0 \times 10^{-16}$), L4-L5 ($p < 2.0 \times 10^{-16}$).



(a) Mean fatigue (b) Fatigue in hands (c) Fatigue in wrists (d) Fatigue in forearms

(e) Fatigue in elbows (f) Fatigue in upper arms (g) Fatigue in shoulders

Fig. 9: Fatigue ratings in various body parts for the five tested keyboard locations. (a) The values at the top of each stack are the mean and standard deviation of the accumulated fatigue ratings. (b)-(g) Refer to Fig. 4 for the meanings of the horizontal lines, box edges, and dots.

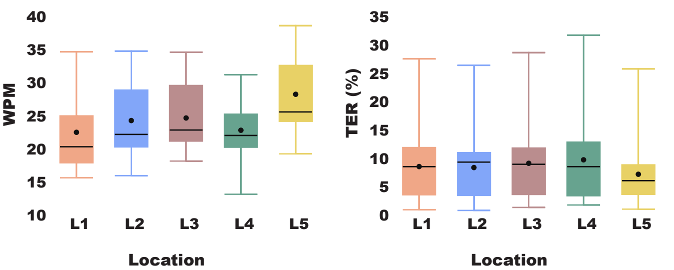


Fig. 10: Text entry speed (left) and accuracy (right) for the five tested keyboard locations. Refer to Fig. 4 for the meanings of the horizontal lines, box edges, and dots.

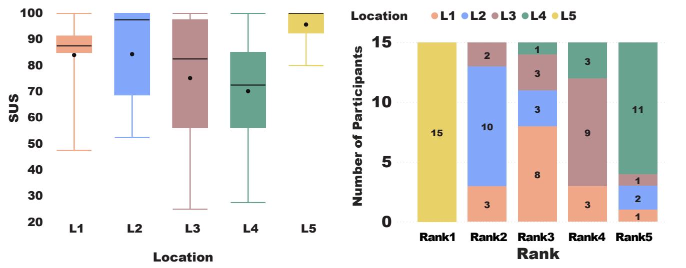


Fig. 11: SUS scores (left) and location rankings (right) for the five tested keyboard locations. Refer to Fig. 4 for the meanings of the horizontal lines, box edges, and dots.

Table 3: Mean WPM, TERs, and SUS scores as well as ANOVA results for the five tested keyboard locations. The best location per metric (or scale) is highlighted in bold text, while the second is underlined. The order for each metric (or scale) is also shown in Roman numerals.

Location	WPM	TER (%)	SUS
L1	V: 22.62	III: 8.69	III: 84.00
L2	III: 24.40	<u>II: 8.51</u>	<u>II: 84.33</u>
L3	<u>II: 24.79</u>	IV: 9.26	IV: 75.17
L4	IV: 22.93	V: 9.88	V: 70.17
L5	**I: 28.37**	**I: 7.33**	**I: 95.67**
$F_{4,56}$	27.34	4.50	6.42
p	1.33×10^{-12}	0.0032	0.0025

For text entry accuracy, ANOVA results showed significant differences in the TERs ($F_{4,56} = 4.50$, $p = 0.0032$). Post-hoc pairwise comparisons revealed significance between L4-L5 ($p = 0.0007$).

7.4.3 System Usability

As shown in Fig. 11 and Table 3, the mean SUS score of L5 was the highest (95.67, $SD = 6.71$), followed by L2 (84.33, $SD = 19.33$) and L1 (84.00, $SD = 14.04$). ANOVA revealed significant effects of locations ($F_{4,56} = 6.42$, $p = 0.0025$), and post-hoc pairwise comparisons revealed significance between L4-L5 ($p = 0.00083$).

7.4.4 Location Rankings

Fig. 11 shows the location rankings in detail. L5 was ranked as the favorite location by all participants, whereas most participants considered L4 the least preferred location. The Friedman test revealed significant effects of locations ($\chi^2 = 43.893$, $p = 6.752 \times 10^{-9}$), and the Wilcoxon test showed significant differences between L2-L5 ($Z = -2.87$, $p = 0.0041$), L3-L5 ($Z = -2.83$, $p = 0.0047$), and L4-L5 ($Z = -2.92$, $p = 0.0035$).

7.5 Discussion

By our study results, L5 not only outperformed other locations in terms of each metric and scale, but was also ranked as the most preferred location by all participants. However, L4 instead was the worst location based on almost all metrics and scales, except that its mean WPM was the second slowest, only slightly higher than the slowest (L1) and no significant differences between them.

We also found that the keyboard distance had greater impacts than the height. By placing the virtual keyboard near users, significant differences in the WPM, TERs, and SUS scores were found, whereas there were only a few significant effects, such as on the WPM, among L1, L2, and L3 (which differed only in their keyboard heights). However, placing the keyboard close to the user may have a negative effect. One participant mentioned that their eyes felt uncomfortable while typing with L5, as the keyboard was overly close.

As discussed in Sec. 6.5, the comparisons between L1-L2, L2-L3, L3-L4, L4-L5, and L1-L5 should be carefully interpreted owing to the possible carryover effects.

In summary, keyboard locations significantly affect text entry speed, accuracy, and system usability, but not fatigue ratings. While using CrowbarLimbs, we suggest placing the virtual keyboard at the belly level and a distance of 30-45 cm from the user.

8 Conclusion

In this paper, we introduce "CrowbarLimbs," a fatigue-reducing VR text entry metaphor with two deformable virtual limbs. CrowbarLimbs allows a user to easily maintain a comfortable posture based on RULA during typing. Our initial user study indicates that the text entry speed, accuracy, and system usability of CrowbarLimbs are comparable to those of previous selection-based methods, such as DrumKeyboard. We conducted two additional user studies to investigate the effects of the shapes of CrowbarLimbs and keyboard locations. The results show that shapes significantly impact fatigue ratings and text entry speed, while the optimal keyboard location may be near the user and at half their height (approximately their belly). In summary, CrowbarLimbs is an ergonomically user-friendly metaphor for applications where users need to type many words over a medium/long period of time. To the best of our knowledge, this work is one of the first few studies to focus on the fatigue issue of text entry in virtual environments.

We expect that the fatigue issue remains a challenge in VR and will explore more different factors, such as keyboard shapes and body poses (sitting, walking, etc.), which may significantly affect fatigue. We are also interested in investigating the relations and interactions among significant factors and in developing novel text entry metaphors.

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