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Giant Finger: A Novel Visuo-Somatosensory Approach to Simulating Lower Body Movements in Virtual Reality

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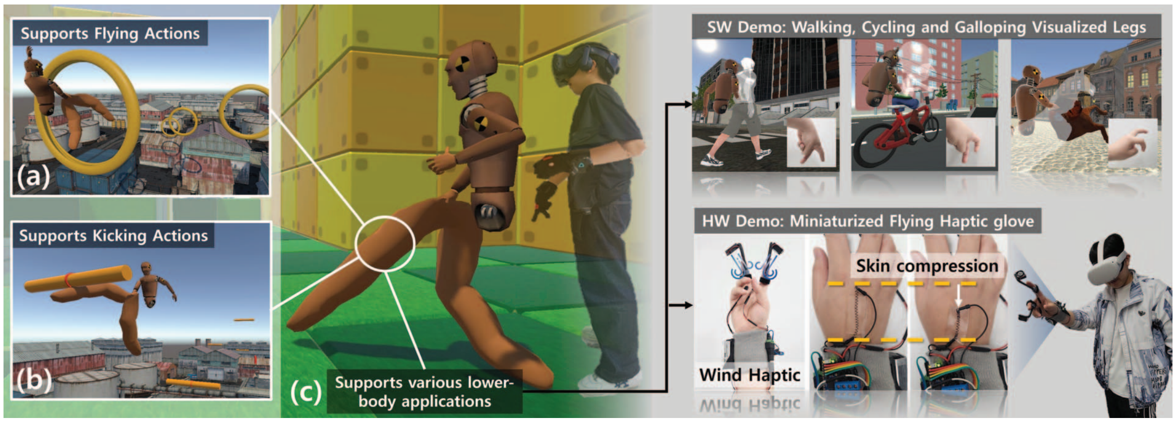

Figure 1: Giant Finger method employs enlarged fingers that replace the legs and become a part of the virtual body. (a) Users can fly and (b) kick a high target that exceeds the capabilities of human legs. It supports hyper movements that are difficult to perform with two legs while providing a congruent somatosensory experience with the two fingers. (c) Based on the research results, we present software and hardware demonstrations that can be integrated into Giant Finger for wider applications.

Abstract

Surreal experience in virtual reality (VR) occurs when visual experience is accompanied by congruent somatosensation. Thus, VR contents that require physical actions are often bounded to our physical capabilities to maintain somatosensory consistency. Alternatively, users often choose less immersive but safer interfaces that offer a wider action variability. In either case, this situation compromises the potential for a hyper-realistic experience. To address this, we introduce "Giant Finger," a concept that replicates human lower body movements through two enlarged virtual fingers in VR. Through a user study, we affirmed Giant Finger's ownership using proprioceptive drift and questionnaire responses. We also compared Giant Finger's capability to perform a variety of tasks with existing methods. Despite its minimalistic approach, Giant Finger demonstrated a high level of efficacy in supporting lower body movements, with ownership and presence comparable to those of the body-leaning method with whole-body motion. Giant Finger can replace the sensations of real legs or support locomotion in confined spaces by providing proprioceptive illusions to the virtual lower body. The applications showcased in this paper suggest that Giant Finger can enable new forms of movement with high action variability and immersion in various fields such as gaming, industry, and accessibility.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction techniques—Gestural input

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1 Introduction

Virtual reality (VR) allows users to explore virtual scenarios beyond the constraints of the physical world. However, as our bodies are still bound to physical reality, interacting with the virtual environment often requires bodily movement. Thus, the sense of immersion and presence in the virtual simulation is enhanced when the movements of the virtual avatar align with those of the user in the real world [44, 45, 53]. A distinct example of this is when users observe their virtual hands and arms move in synchronization with their physical actions, enriching their immersive experience [35, 46, 56].

However, certain visual experiences in VR may not offer this level of visuo-somatosensory congruity, particularly when they pose safety risks or require movements beyond our physical capabilities. For example, mapping lower body actions, such as walking, jumping, or kicking, to the user's actual movements can be risky. This is due to potential hazards such as colliding or losing balance, as VR obscures the visual perception of the physical surroundings. Furthermore, actions that exceed our physical abilities - whether these are individual limitations or inherent human constraints such as running faster in VR or flying and levitating - cannot be accurately represented through the user's body movements. These restrictions confine the VR experience within the boundaries of our physical capabilities, thereby limiting its potential to provide surreal experiences.

Some methods attempt to circumvent these limitations by lessening the need for physical movement, as seen with the use of a joystick or other hand-held controllers. However, this often results in limited immersion and presence due to the restricted somatosensory experience [16, 26]. To offer unrestricted scenarios in VR without compromising immersion, it is crucial to provide a comprehensive somatosensory experience that accommodates a wide range of movements. However, this doesn't necessarily require an exact mirroring of physical movements in the virtual environment. While walking with our actual legs provides most authentic walking somatosensory sensations, the concept of virtual body ownership suggests that peo-

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ple can experience the somatosensory illusion being attributed to virtual bodies or virtual body parts [4, 23].

Inspired by the concept of virtual body ownership, we propose the Giant Finger - a VR movement technique that enables various lower body movements such as walking, flying, and kicking using finger-mapped virtual lower body. The method allows users to control their lower body in VR by wiggling their fingers in the air. By assigning virtual body ownership to the finger-like virtual legs, the method also facilitates more efficient movements by requiring the use of only two fingers rather than engaging the entire lower body. We believe that this method could be effectively integrated into VR scenarios involving walking, jumping, and other motions, particularly when there's a need to balance motion flexibility with the sense of presence due to its visuo-somatosensory congruity. In this paper, we delve into the design of the Giant Finger method and present user studies to assess the virtual body ownership it induces, as well as the user experience and performance in various application.

2 RELATED WORK

2.1 Flying and Kicking Support Techniques

VR input technologies offer the potential for actions that are either challenging or unfeasible in the real world. In the context of flying movements, controller-based methods, such as those implemented by Perusquía-Hernández et al. [38] using Xbox controller joysticks, offer a wide range of motion options as they are not constrained by human limitations. However, these methods risk inducing motion sickness or reducing immersion due to visuo-somatosensory mismatches [7, 26]. As a response, alternative methods incorporating bodily movements for VR actions have emerged, providing a realistic visuo-somatosensory congruence for flying actions using full body motions, such as wing flapping-based control [31, 32, 42, 60], body-leaning-based control [34, 38, 47, 61], and Superman-style locomotion [39]. Some studies have even added the sensation of floating through additional hardware like cables [24, 38], or air currents provided by propellers [40]. Nevertheless, these methods often either maintain a sensation of groundedness or pose challenges in precise control due to the reliance on full body movements [5]. Additionally, they may not be suitable for VR scenarios requiring additional movements, such as kicking, as they use the entire body for locomotion.

In the case of lower body actions such as kicking and jumping, some studies have employed physical movements to facilitate realistic yet amplified actions. For instance, Lehtonen et al. [27] boosted the user's jumping ability using a trampoline, and Hayashi et al. [17] and Wolf et al. [58] enhanced the height of jumps beyond the actual leap. Other works exaggerated the angle of a kick to simulate a higher kick [14]. While these methods enable the simulation of heightened human abilities with greater distance coverage [17, 58], the variety of possible actions and the degree of motion flexibility remain limited to offer a more realistic experience [17, 58]. Due to their reliance on the physical movements of actual legs, these methods can be inherently constrained by the physical abilities of individual users. Furthermore, the extent to which the actions can be enhanced or modified remains capped to ensure compatibility with the user's somatosensory experience [14, 17, 27, 58].

Striking a balance between motion flexibility and realism, we propose a novel method for controlling lower body movements in VR using fingers, which are presented in an enlarged, leg-like format. This approach bridges the gap between controller-based and full body motion-based methods in that it directly maps the motion of body parts to VR while enabling locomotion with manipulation-based input. We adopted this technique to provide an immersive experience by mapping our body parts for interactions within VR while mitigating the variability and challenges associated with individual physical capabilities, especially when compared to methods requiring full lower body engagement.

2.2 Rubber Hand Illusion (RHI)

The Rubber Hand Illusion (RHI) is a phenomenon where individuals perceive a rubber hand as part of their own body when their actual hand is concealed and synchronized visual-tactile stimuli are given to both hands [4]. This illusion is rooted in the visual-proprioceptive integration mechanisms of our brain, where the sensory information is combined [9, 48]. Predominantly, visual information tends to override other sensory modalities, often preceding when there's a conflict between visual and proprioceptive data [9]. This dominance of visual perception within our multi-modal sensory experience means that when a virtual body is visually presented, we can experience proprioception for it, even if it doesn't exist in reality.

Beyond just tactile synchronization, the RHI can also be elicited by synchronizing joint movements between actual and virtual fingers [8, 43, 49]. Moreover, when individuals undergo the RHI due to this visual-proprioceptive integration, they tend to adjust their positioning to be closer to the virtual body or even perceive the length of their own body parts as being in line with those of the virtual representation [4, 43, 48]. This spatial reorientation towards the virtual body, termed as proprioceptive drift, acts as a robust marker of the presence of the RHI.

With this understanding of the RHI, we drew inspiration for our system, aiming to overlay this illusion onto the finger-based lower body movement in VR. Our goal was to enhance user immersion and presence by fostering a sense of ownership over virtual legs, depicted as enlarged fingers. To verify the effectiveness of our approach, our initial user study focused on assessing the induction of the RHI by examining the results of a proprioceptive drift experiment.

2.3 Finger Walking In Place (FWIP)

Our approach builds upon the concept of Finger Walking in Place (FWIP) [20], a technique that facilitates navigation in a CAVE display by sliding fingers across a touchpad. This technique has evolved with the integration of modern technologies. For instance, Ouzounis et al. [36] demonstrated the feasibility of using finger to control virtual environment characters by mapping detected finger gestures to the movements of these characters using skeletal tracking data. Recent studies have suggested the potential for fostering a sense of virtual body ownership by utilizing finger haptic stimuli, detected through the finger walking metaphor, which can be perceived as whole body stimuli [55]. Furthermore, participants walking on finger-scale floor tiles using the finger-walking metaphor perceived the size of the floor tiles on a body-scale order [52]. This suggests that achieving visuo-proprioceptive congruence through finger sensations can provide a sense of ownership for the virtual body.

Despite the potential of the finger-as-legs metaphor to induce virtual body ownership, FWIP techniques have primarily been implemented in screen-based VR environments [20, 29, 36, 51, 55]. Yan, Z. et al. [59] compared their finger-based metaphor in HMD-based VR environments with conventional gamepad movement interfaces and found no significant differences in terms of presence, usability, or enjoyment. Our method aims to enhance presence by enabling locomotion synchronized with the user's finger movements within an HMD-based VR environment from a first-person perspective.

3 GIANT FINGER DESIGN

Synchronizing the position and orientation of virtual body parts with real counterparts is crucial to generate virtual ownership [8, 48]. To achieve this, we designed the Giant Finger method to originate from the real hand's position. The independent control of the user's head pose by HMD and FWIP can lead to conflicting inputs, potentially causing negative experiences such as sickness. Our approach distinctly controls the torso via HMD and the lower body through Giant Finger, optimizing it for HMD VR. Additionally, the inherently limited field of view in HMDs can pose a challenge for continuously observing synchronized leg movements. Giant Finger addresses this

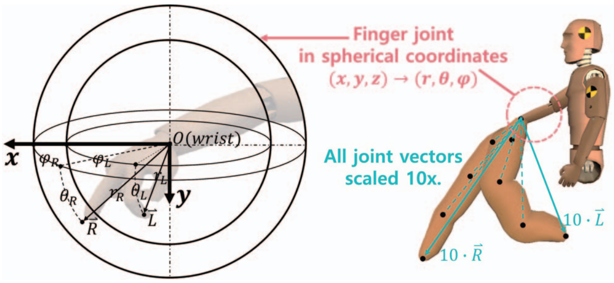

Figure 2: Position of the finger joint expressed in spherical coordinates. Each finger joint position is scaled 10 times to create Giant Finger.

by using representations that can be more easily observed within the constraints of HMDs, instead of the realistic proportions or angles of human legs, thereby facilitating visuo-proprioceptive integration.

We incorporated Hi5 VR gloves into our system to track the finger joint movements and translate them into VR locomotion. Each finger joint's position relative to the wrist was then linearly scaled 10 times to create Giant Finger (Fig. 2). The linear operation preserves the relative kinematics of each joint and maps the hand motion to the motion of the Giant Finger in VR. Algorithm 1 outlines how the wiggling motions of the index and middle fingers in the air are translated into walking motions. We set the timing of locomotion step updates based on human gait motion mechanisms involving pivot and push. The finger with the lowest fingertip position becomes the pivot finger (lines 5, 7), and the distance traveled by the pivot finger's tip is reflected in the body's movement (lines 9, 10, 13).

Algorithm 1 Giant Finger Walking

Input: *Current finger tips' coordinates* $(r_L, \theta_L, \varphi_L)$, $(r_R, \theta_R, \varphi_R)$
Previous finger tips' coordinates $(r_L^*, \theta_L^*, \varphi_L^*)$, $(r_R^*, \theta_R^*, \varphi_R^*)$
Output: *Distance the whole body translates the x-y plane* $(\Delta x, \Delta y)$

The procedure is performed 60 times per second

1: **procedure** GIANT FINGER WALKING $(\vec{L}, \vec{R}, \vec{L^*}, \vec{R^*})$
2: $\vec{L} \leftarrow 10\{r_L, \theta_L, \varphi_L\}$, $\vec{R} \leftarrow 10\{r_R, \theta_R, \varphi_R\}$
3: $\vec{L^*} \leftarrow 10\{r_L^*, \theta_L^*, \varphi_L^*\}$, $\vec{R^*} \leftarrow 10\{r_R^*, \theta_R^*, \varphi_R^*\}$
4: **if** $|\vec{L}| \cdot |\sin\theta_L| > |\vec{R}| \cdot |\sin\theta_R|$ **then**
5: $\vec{P}, \vec{P^*} \leftarrow \{\vec{L}, \vec{L^*}\}$
6: **else if** $|\vec{L}| \cdot |\sin\theta_L| \leq |\vec{R}| \cdot |\sin\theta_R|$ **then**
7: $\vec{P}, \vec{P^*} \leftarrow \{\vec{R}, \vec{R^*}\}$
8: **end if**
9: $\Delta x \leftarrow 10\, r_P \cdot \cos\theta_P \cdot \cos\varphi_P - 10\, r_P^* \cdot \cos\theta_P^* \cdot \cos\varphi_P^*$
10: $\Delta y \leftarrow 10\, r_P \cdot \cos\theta_P \cdot \sin\varphi_P - 10\, r_P^* \cdot \cos\theta_P^* \cdot \sin\varphi_P^*$
11: $\{r_P^*, \theta_P^*, \varphi_P^*\} \leftarrow \{r_P, \theta_P, \varphi_P\}$
12: **if** $((\Delta x)^2 + (\Delta y)^2)^{1/2} < 0.5$ (cm) **then**
13: **return** $(\Delta x, \Delta y)$ // *Walking Reflection Threshold*
14: **else**
15: **return** *null*
16: **end if**
17: **end procedure**

Whereas prior works [20, 55] required constant touchpad contact, we designed Giant Finger to move using finger movements in the air. This approach provides greater flexibility in finger position and orientation, which can be influenced by how users pose their hands, wrists, elbows, and shoulders. This degree of freedom enables the simulation of body movements while floating above the ground, extending the applicability of flying actions. However, there has been minimal research into finger-based control of flying actions, prompting us to test mechanisms for flying direction and velocity.

We presented the Giant Finger concept to five VR developers (age: M=24.8, SD=1.64, years of experience: M=1.8, SD=0.81)and solicited their ideas for designing control mechanisms for flying. Through 10-minute interviews with each developer, we explored methods to control the direction and speed of flight through the Giant Finger, using poses of fingers, wrists, and arms. From the ideas gathered, we distilled three direction control methods (Fig. 3(a)-(c)) and two speed control methods (Fig. 3(d),(e)). We implemented the six possible combinations of these controls and evaluated them with the same group of developers. This evaluation sought to establish consensus on the tool's intuitiveness and ease-of-use based on their experience, rather than numeric responses from predefined questionnaires. As a result, all VR developers evaluated the wrist-based direction control (Fig. 3(a)) and the head-wrist-based speed control (Fig. 3(d)) as being the most suitable. Consequently, we integrated this as the flying method for the Giant Finger.

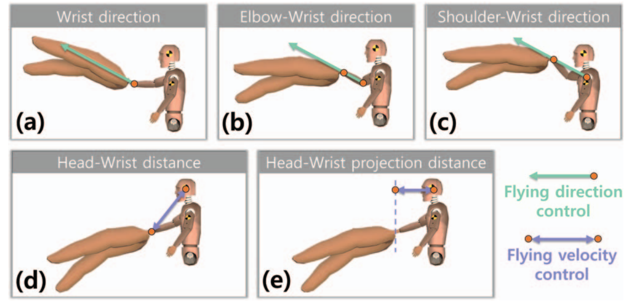

Figure 3: Visual representation of the six proposed flying control methods for the Giant Finger. The methods include three direction control techniques: (a)-(c) and two speed control techniques: (d),(e).

4 STUDY 1: VIRTUAL OWNERSHIP VERIFICATION

The Giant Finger method allows for VR locomotion using enlarged and "legified" fingers. Given that virtual ownership allows users to experience visuo-proprioceptive congruence with the virtual body, ownership of the virtual, enlarged fingers should be guaranteed to deliver an immersive experience. Without this sense of ownership, potential conflicts between visual and proprioceptive information could disrupt immersion, regardless of its support for various movements. User Study 1 is designed to verify the ownership that users can have when using the enlarged virtual fingers. In alignment with the standardized objective and subjective methods for verifying virtual ownership from prior studies [4, 22, 28, 43, 48], we conducted an evaluation with 23 participants (female: 5, age: M=21.3, SD=2.0) on 1) proprioceptive drift and 2) ownership illusion questionnaires, with some modifications made to adapt to our specific system.

4.1 Study Procedure

4.1.1 Ball Kicking Task

Before evaluating virtual ownership, participants performed a ball-kicking task using Giant Finger to familiarize themselves with the method. The task environment comprised a 60 m × 80 m virtual space with blue balls appearing at predetermined locations, ensuring that all participants experienced the same ball positions and distances. Participants were instructed to walk using Giant Finger to the ball and kick it to remove it (Fig. 4(a)). Each participant experienced Giant Finger for 90 s, regardless of the number of balls removed.

4.1.2 Measurement

After completing the ball-kicking task, we measured the proprioceptive drift. Specifically, a 2 m × 2 m yellow wall was presented 3 m in front of the participant in a new VR environment. Participants were instructed to raise their right arm in front of them while forming a "V" with their fingers. They were then asked to walk towards the virtual yellow wall and halt when they believed their fingertip would touch it, although the wall did not physically exist in the real world (Fig. 4(b)). The experiment was repeated three times, and

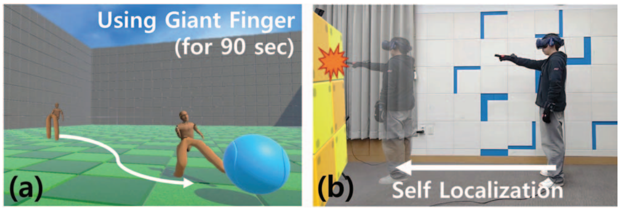

Figure 4: Overview of Study 1. (a) Environment for the ball-kicking task, (b) Setup for measuring proprioceptive drift

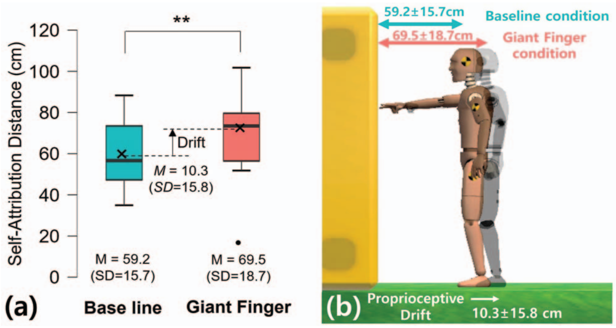

Figure 5: Results of Study 1. (a) Boxplot and (b) Visualization of proprioceptive drift in the Giant Finger Condition

during the task, their bodies and hands were not visible in the VR environment. Consequently, participants would stop at a greater distance from the wall if they perceived their fingers to be longer than their body proprioceptive sensations. We also measured the stopping distance under a normal finger condition as a baseline. The order of measuring the baseline condition was counterbalanced to be either before or after the ball-kicking task.

After experiencing Giant Finger, the participants completed a virtual ownership illusion questionnaire on a 7-point Likert scale, from -3 to 3; Q1-6 and Q8-9 were adopted and modified from Botvinick and Cohen (1998) [4] (see Table 1. for full list).

4.2 Results

Given that all data satisfied both the skewness and kurtosis prerequisites, we conducted a paired t-test for the proprioceptive drift and a 1-sample t-test for the questionnaire. The perceived location of the fingertips, when participants raised their arms, was found to increase after experiencing Giant Finger (M = 69.5 cm, SD = 18.7 cm) compared to the baseline condition (M = 59.2 cm, SD = 15.7 cm), $t(22) = 3.108$, $p = 0.003$ (Fig. 5). The observed proprioceptive drift (M = 10.3 cm, SD = 15.8 cm) suggests that participants perceived their actual fingers as enlarged after using Giant Finger, indicating that users experienced virtual ownership of Giant Finger.

Along with the proprioceptive drift, subjective reports for the ownership illusion questionnaire also supported the creation of ownership due to Giant Finger. Participants reported their ownership for items Q1 ($t(22) = 5.7$, $p < 0.001$), Q2 ($t(22) = 5.7$, $p < 0.001$), Q3 ($t(22) = 4.3$, $p < 0.001$), Q4 ($t(22) = 4.5$, $p < 0.001$), and Q7 ($t(22) = 3.2$, $p = 0.002$) according to the results of the one-sample t-test (Table 1.). While certain questionnaire items contradicted the result (Q5), albeit without statistical significance, the summed rating indicated that the method offered virtual body ownership, Total ($t(22) = 3.7$, $p < 0.001$).

5 STUDY 2: USER EXPERIENCE WHILE CONDUCTING WALKING, FLYING, AND KICKING ACTIONS

We recruited 35 participants (females: 14, age: M=22.0, SD=2.6) to evaluate Giant Finger in its application scenarios. Our study comprised three tasks: walking, flying, and kicking, each chosen to provide insights into the visuo-proprioceptive experience and presence in VR. In this evaluation, we compared Giant Finger method against the body-leaning (BL) and joystick (JS) based approaches.

Table 1: Ownership Illusion Questionnaire Results

Questionaire (ranging from -3 to 3)	M±SD	t	p
Q1. There were times when I felt like I was walking on my big finger.	1.44±1.20	5.73	**<.001*** **
Q2. There were times when I felt like my whole body was being moved by a large finger.	1.48±1.24	5.72	**<.001*** **
Q3. There were times when my big fingers felt like mine.	1.35±1.50	4.32	**<.001*** **
Q4. There were times when it felt like my fingertips had moved to larger fingertip positions.	1.22±1.28	4.57	**<.001*** **
Q5. There have been times when I felt like I had more than one right hand.	-1.83±0.83	-10.50	1.000
Q6. There were times when I felt like I was moving my fingers somewhere between my real fingers and my big ones	0.30±1.55	0.94	0.178
Q7. There were times when I felt that my fingers were getting bigger.	1.04±1.55	3.22	**0.002** **
Q8. There were times when my big fingertips felt like they were moving to the actual fingertip position.	0.35±1.75	0.95	0.175
Total	0.67±0.85	3.76	**<.001*** **

5.1 Design of each VR movement control method

Our within-subject study designates the VR control method as the independent variable and compares three conditions: body-leaning (BL) based, joystick (JS) based, and the Giant Finger method. The BL method was chosen for its full-body engagement, allowing both walking [16,21] and 3D locomotion [47]. In contrast, the JS method, requiring minimal physical exertion, was selected for its proficiency in both 2D and 3D movements [38]. We chose JS over handheld controllers, which, while common in VR, often limit 3D movement since the free motion of both hands complicates directional movement. Giant Finger, positioned between these two in terms of physical exertion, allows the other two conditions to serve as a comparative benchmark for performance, immersion, and presence.

BL based control BL based control supports walking and flying by leaning the body (Fig. 6(a)). We achieved this by tracking the foot position using a VIVE tracker on shoes and the head position with a VIVE Pro HMD. The tilt angle of the entire body, measured through the difference in distance between the center of the two feet and the head's perpendicular position on the ground, was used to control the walking and flying speed. A 30 cm distance difference was translated to a walking speed of 3m/s and a flying speed of 4m/s. This transfer gain was established through a pilot experiment, noting the 30 cm distance difference as the maximum body tilt while maintaining balance. The maximum speed was set based upon Perusquía-Hernández et al. [38] who set the walking speed of BL method as 2.5m/s and Hashemian & Riecke. [16] 's 3m/s, with a consideration that the task we pose involves exertional work to move promptly to gather balls swiftly. Upward and downward flying movements were controlled by the head angle; it idled within the range of -20° to +20°; it mapped linearly to an upward flying speed with a maximum of 4 m/s between 20° and 80°; and conversely, it induced downward flying within the range of -20° to -80°. We defined these head angle ranges to allow participants to adequately view and navigate the environment during flight. The VIVE tracker on the top of the foot also functioned as an end effector to control the movement of the lower body using the inverse kinematics algorithm. This design allows the entire leg to exhibit a natural movement during the kicking action.

Giant Finger Giant Finger uses the walking algorithm and flying method designed in Section 3 (Fig. 6). Similarly, the flying speed is mapped to 0-4 m/s. As Giant Finger was synchronized with

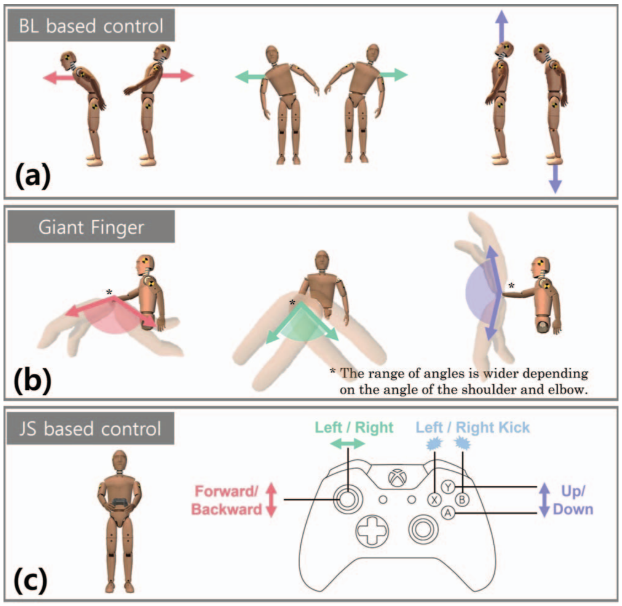

Figure 6: Illustrations of the control methods designed for each VR technology. (a) BL based control method, (b) Giant Finger control method, and (c) JS based control method.

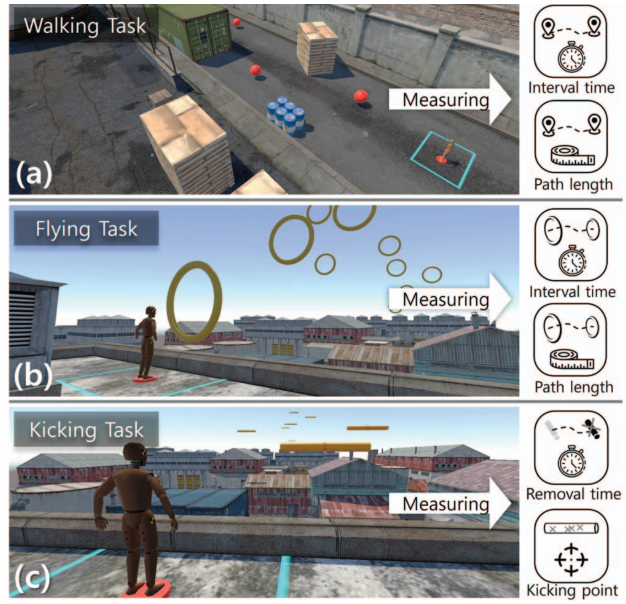

Figure 7: Unity scenes for the three tasks. (a) Walking: move towards and remove red balls. (b) Flying: navigate through yellow rings. (c) Kicking: kick and eliminate bar targets.

the actual finger movements, kicking was possible by reproducing the kicking action with the finger.

JS based control The JS-based approach was set using the X box controller method used in Perusquía-Hernández et al. [38]. Users can move along the plane using the left JS of the X box controller and ascend and descend using the Y and A buttons. The input values of the JS and buttons were linearly mapped to walking and flying speeds of 3m/s and 4m/s, respectively. For kicks, the X and B buttons were set for left and right kicking (Fig.5(c)).

Each operation method was automatically controlled such that the walking and flying movement speeds did not exceed 3m/s and 4m/s, respectively, in any situation to facilitate a comparison with each other. For example, even in a situation where the speed should exceed 4m/s because the straight speed is added to the ascent speed in the flying task, the speed is maintained at 4 m/s.

5.2 Study Procedure

We tested user performance under the three aforementioned VR control conditions through walking, flying, and kicking tasks. The walking task primarily gauges the tool's feasibility for standard VR locomotion. In contrast, the flying and kicking tasks evaluate the tool's capacity to support hyper-realistic actions, especially under scenarios demanding complex aerial movements. The particular emphasis of the kicking task is on mid-air movements, which, while often incorporated in action games, pose challenges in ensuring safe body ownership experiences within VR. User performances for walking and flying actions were assessed based on the time of arrival taken for the entire path or specific places, such as flying through a series of rings [34] or checkpoints [38, 60]. Kicking actions were evaluated based on target elimination time, hit accuracy [14, 60], and specific spatial or angular measurements (angle of the kick) [14].

5.2.1 Tasks and Performance Measures

Walking Task This task was conducted in a 60 m × 80 m virtual space, with ten checkpoints placed at various locations on the floor (Fig. 7(a)). Each participant was instructed to walk quickly through each checkpoint to reach the final destination. In the meantime, the subjects' checkpoint-passing trajectories and the time interval required to pass each checkpoint were recorded.

Flying Task This task was conducted in a 60 m × 300 m virtual space, wherein 10 ring hurdles (1 m in diameter) were placed at different locations and heights (Fig. 7(b)). Participants were requested to fly quickly through the rings to reach the last ring. During the experiment, flying trajectories to pass through the checkpoints and the time interval to pass through each checkpoint were recorded.

Kicking Task This task was conducted in a 60 m × 300 m virtual environment, wherein there were 10 cylindrical bars with a diameter of 30 cm and a length of 3 m located at various points (Fig. 7(c)). Participants were instructed to fly to the cylinder bars and quickly remove the target by accurately aiming at its red center. Throughout the test duration, the region of the target that each participant kicked and the time between each strike were recorded.

Each participant completed the three tasks (walking, flying, and kicking) in sequence using the three different locomotion methods (BL based, JS based, and Giant Finger). The order of the locomotion methods was balanced using a Latin square experimental design.

5.2.2 Subjective Measures

After each task, participants answered a post-experiment questionnaire regarding their sense of body ownership and presence. We adjusted the RHI questionnaire to encompass a whole-body perspective, inspired by Lenggenhager et al. [28] who modified the RHI questionnaire to gauge body ownership from a whole-body standpoint; the items were organized as follows: Q1, Q2, and Q3 were used as separate items, while Q4, Q5, Q6, and Q8 were combined into a single item (a detailed description of the modification is explained below). Participants responded to the questionnaire using a 7-point Likert scale ranging from -3 to 3. To measure the sense of presence, the Slater, Usoh, and Steed (SUS) questionnaire [54], comprising six 7-point Likert scale items, was used.

- Q1. I felt like I was moving through my body in VR.
- Q2. When moving, there were cases in which sensations were felt in the body parts in the VR.
- Q3. There were times when my body felt real in VR.
- Q4. There were times when it felt like my real body was changing like a body in VR.

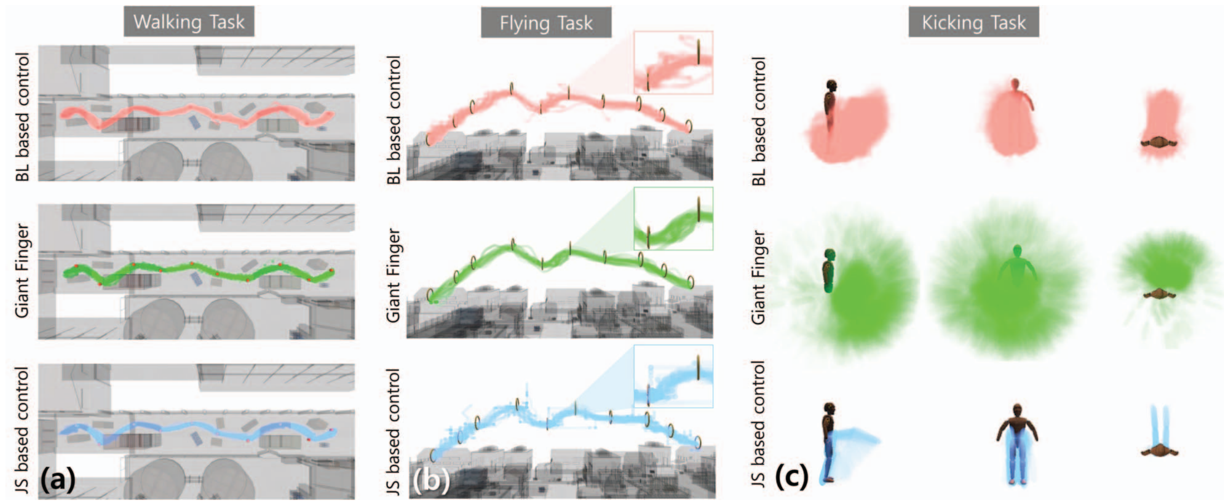

Figure 8: Visualized accumulated trajectories of participants (N = 35): (a) Walking, (b) Flying, and (c) Kicking.

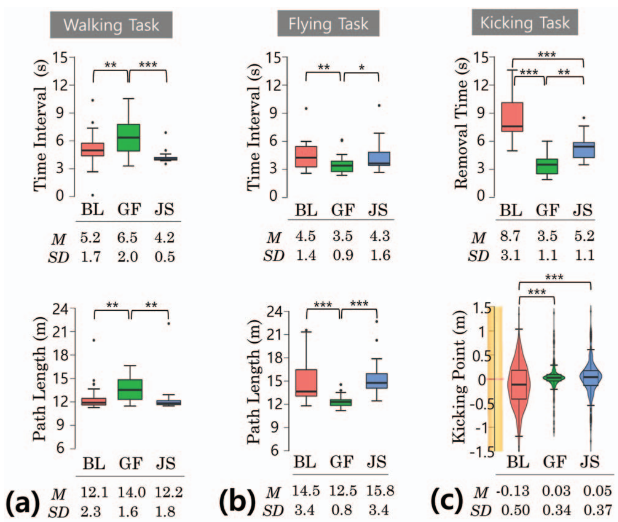

Figure 9: Box plots of performance data (N = 35) from tasks: (a) Walking, (b) Flying, (c) Kicking, including Time Interval, Path Length, and Targeting Distribution. (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

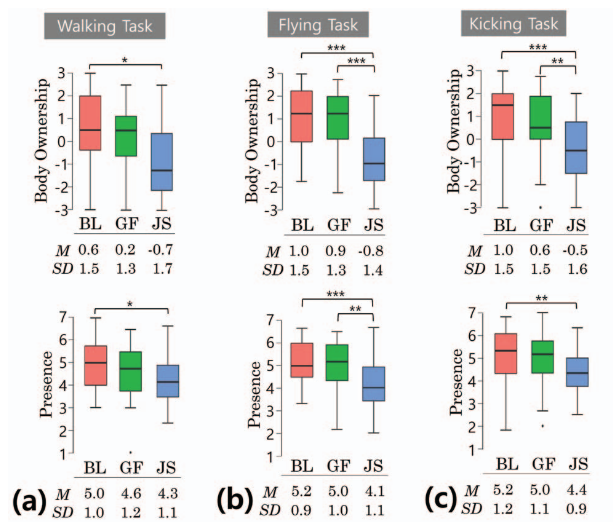

Figure 10: Box plots for subjective data (N = 35) from tasks: (a) Walking, (b) Flying, (c) Kicking, including Body Ownership and Presence. (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

5.3 Results

Our analysis of each task was three-fold: qualitative task trajectories (Fig. 8), quantitative performance metrics (Fig. 9), and subjective questionnaire responses (Fig. 10). All statistical analyses were preceded by normality tests for skewness and kurtosis; all passed the tests. We used repeated measures ANOVA to verify the variable's main effect and the Bonferroni test for a post-hoc analysis.

5.3.1 Walking Task

All three methods, including BL based control, Giant Finger, and JS based control, enabled users to walk in a smooth trajectory to reach the target point (Fig. 8(a)). There were significant differences observed between the methods in both the "Point to Point Time Interval" ($F(2, 68) = 22.335$, $p < 0.001$) and the "Point to Point Path Length" ($F(2, 68) = 7.656$, $p = 0.001$) in the performance measure. In the subjective measure, there were significant differences observed between the methods in "Body Ownership" ($F(2, 68) = 8.228$, $p < 0.001$) and "Presence" ($F(2, 68) = 3.428$, $p = 0.038$).

Giant Finger took a significantly longer time to move between points (M = 6.5, SD = 2.0) than BL based control (M = 5.2, SD = 1.7; $t(34) = 3.710$, $p = 0.001$) or JS based control (M = 4.2, SD = 0.5; $t(34) = 6.669$, $p < 0.001$). In addition, the length of the trajectory moved by Giant Finger (M = 14.0, SD = 1.6) was significantly longer than that of the BL based control (M = 12.1, SD = 2.3; $t(34) = 3.526$, $p = 0.002$) and JS based control (M = 12.2, SD = 2.0; $t(34) = 3.233$, $p = 0.006$), respectively (Fig. 9(a)). The results suggest that Giant Finger may not be ideal for applications that value locomotion efficiency. Regarding measures of subjective experience, including ownership and presence, Giant Finger did not exhibit any statistically significant differences from the standard methods (Fig. 10(a)). Although our technology is primarily designed to facilitate actions that are challenging to execute in the real world, it provides equivalent body ownership and presence with minimal bodily actions while walking in VR compared to the other methods.

5.3.2 Flying Task

While all participants flew on a smooth trajectory with Giant Finger, some had to retrograde to pass through the rings with the BL and JS based control (Fig. 8(b)). The interface type significantly affected the "Ring to Ring Time Interval" ($F(2, 68) = 6.509$, $p = 0.003$) and the "Ring to Ring Path Length" ($F(2, 68) = 15.180$, $p < 0.001$) in the performance measure. For subjective ratings, there was a significant difference among methods in "Ownership" ($F(2, 68) = 19.431$, $p < 0.001$) and "Presence" ($F(2, 68) = 11.464$, $p < 0.001$).

Giant Finger took a significantly shorter time to move between rings (M = 3.5, SD = 0.9) than the BL based control (M = 4.5, SD = 1.4; $t(34) = 3.420$, $p = 0.003$). In addition, the length of the trajectory moved by Giant Finger (M = 12.5, SD = 0.8) was significantly shorter than those of BL based control (M = 14.5, SD = 3.4; $t(34) = 4.401$, $p < 0.001$) and JS based control (M = 15.8, SD = 3.4; $t(34) = 5.072$, $p < 0.001$) (Fig. 9(b)). The results reveal that Giant Finger facilitates more efficient flying actions than other techniques. Our method also induced significantly higher ownership (M = 0.9, SD = 1.3) and presence (M = 5.0, SD = 1.0) than those of JS based control (ownership: M = -0.8, SD = 1.4; $t(34) = 5.165$, $p < 0.001$), (presence: M = 4.1, SD = 1.1; $t(34) = 3.759$, $p = 0.001$), respectively (Fig. 10(b)). In subjective ratings, the difference between Giant Finger and BL based control was insignificant. Consequently, despite Giant Finger employing only a portion of the body, its virtual ownership and presence were significantly greater than those of the JS based control, similar to the whole BL approach, while delivering more efficient flying motion trajectories.

5.3.3 Kicking Task

Because each method offers a different degree of motion flexibility, the resulting action trajectories are distinct (Fig. 8(c)). With Giant Finger, participants performed kicking motions with larger pitch and yaw angles, expanding the range of possible actions. In contrast, the BL based control permitted users to kick within the range of their physical capabilities, whereas the JS based control operated within a predetermined range of motion. In addition, there was a significant difference in "Target to Target Removal Time" ($F(2, 68) = 66.059$, $p < 0.001$) and "Kicking Point Distribution" ($F(2, 68) = 17.348$, $p < 0.001$) among different interfaces. Moreover, in the subjective measure value, there was a significant difference between the methods in "Ownership" ($F(2, 68) = 10.671$, $p < 0.001$) and "Presence" ($F(2, 68) = 5.480$, $p = 0.006$).

Giant Finger required significantly less time to complete the kicking task (M = 3.5, SD = 1.1) than BL based control (M = 8.7, SD = 3.1; $t(34) = 11.288$, $p < 0.001$) and JS based control (M = 5.2, SD = 1.2; $t(34) = 3.765$, $p = 0.001$), respectively (Fig. 9(c)). In addition, Giant Finger enabled more precise targeting, as demonstrated by the distribution of the average hit area in the cylindrical target bar (Fig. 9(c)). The mean hit position for Giant Finger was interquartile-ranging (-0.044, 0.090), whereas those of the BL based control (-0.416, 0.181) and JS based control (-0.129, 0.174) were larger. Furthermore, Giant Finger also supported significantly more accurate targeting (M = 0.03, SD = 0.34) compared to the BL based control (M = -0.13, SD = 0.50; $t(34) = 4.795$, $p < 0.001$). While there was no significant difference between Giant Finger and JS based control in performance measures, participants felt a greater sense of ownership with the Giant Finger approach (M = 0.6, SD = 1.5) than with the JS based control (M = -0.5, SD = 1.6; $t(34) = 3.362$, $p = 0.004$) (Fig. 10(c)). The ownership of Giant Finger was comparable to that of the BL based control (M = 1.0, SD = 1.5), without a statistically significant difference. In conclusion, with Giant Finger, users can kick a target faster and more correctly, which is a key hyper movement in VR. The proposed approach facilitates efficient interactions without compromising ownership or presence.

6 DISCUSSION

6.1 Virtual Ownership is Created on Giant Finger

After experiencing Giant Finger, participants in Study 1 perceived their fingers as significantly longer. This study validates, for the first time, the establishment of virtual ownership in fingers that replace the actual lower body. The result aligns with findings from Rubber Hand Illusion (RHI) studies [4,22,28,43,48]. In the study by Lenggenhager et al. [28], participants experienced an average drift of 12.1cm when they viewed a virtual whole body at 2m ahead of them. Similarly, while the observed drift in our study was not as long as the enlarged finger length, the statistical significant proprioceptive indicated metaphorically analogous finger movements can substitute locomotion with establishing virtual ownership and maintaining a comparable visuo-proprioceptive experience.

6.2 Giant Finger Provides Virtual Ownership and Presence without Actual Locomotion

During the walking task, Giant Finger, as a novel method, needed more time and longer routes compared to the other two, more established methods (Fig. 9(a)). Participants in our study tended to move their fingers at a slower pace than the anticipated average finger swing frequency of approximately 3 Hz, with individual differences. Despite these initial observations, it's important to note that Giant Finger showed comparable ownership and presence with the BL approach which requires full body motion. This result is noteworthy considering the inferior ownership and presence of the JS approach, which, like Giant Finger, utilizes the user's hands to emulate leg walking. Therefore, Giant Finger is suitable for scenarios where a sense of ownership in the lower body is required or scenarios in which the sensation of walking needs to be provided utilizing minimal space rather than applications where walking efficiency is particularly important. For example, Giant Finger could offer a highly immersive walking experience in virtual reality for those who face challenges with locomotion. Despite the increasing accessibility of VR environments, people with lower body disabilities can only access them for a restricted range of activities or to a limited degree of immersion and presence, while maintaining their safety. By enabling movement through finger motions and fostering a sense of virtual body ownership, Giant Finger facilitates a more immersive exploration of VR spaces. Furthermore, as VR headsets become increasingly mobile and setup environments continue to be simplified, technologies like Giant Finger—which support immersive exploration anywhere without risk concerns such as obstacles—are needed [50]. Potential applications could include applications in environments where full body movement is restricted, such as inside cars [13,18,33], airplanes [57], or confined office spaces [25].

6.3 Giant Finger Enables Stable Control for Immersive Hyper-Action Experience Beyond Actual Reality

Participants completed the flying task faster with Giant Finger, a result attributable to the degree of motion freedom it provides. Giant Finger maps lower body movements directly to fingers, leading to an intuitive control scheme and increased efficiency compared to the JS and BL methods. Giant Finger offers flexible motion selection, allowing actions such as jumping, flying, and kicking to be executed as a single integrated action, mirroring the nature of the compound movement. For example, a kick, in reality, isn't a discrete sequence of a jump followed by a kick, but a continuous motion. On the other hand, the JS method enables flight by using a combination of buttons, which doesn't resemble our actual movements and requires cognitive processing to translate real-world actions into joystick inputs.

Furthermore, the JS configuration on the Xbox controller controls horizontal and vertical movements independently. This is a departure from reality, where movement across the three axes is simultaneous and not controlled by separate buttons. The incongruity is evident in Fig. 8(b), which shows the path of the JS method with intermittent discontinuities in forward, reverse, upward, and downward movements. Conversely, the BL method enables continuous motion by inclining the entire body, yet there is a trade-off in precise control. As observed in Fig. 8(b), users employing the BL method often deviate from the most common paths, reflecting the difficulty in maintaining a stable trajectory. In contrast, Giant Finger method delivers the most consistent flying trajectory due to its enhanced controllability (Fig. 8(b)). Despite only supporting partial proprioceptive experience, the approach achieves comparable

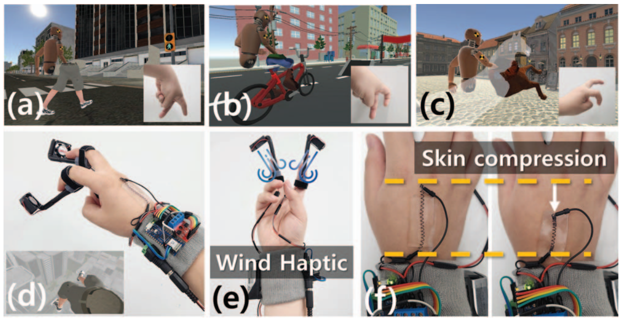

Figure 11: Expanded applications of the Giant Finger method: (a) Visualization based on lower body shape for enhanced ownership. (b) Visualization of a cyclist's pedaling legs and (C) a horse's galloping legs. (d) Haptic systems for flight sensations. (e) Wind haptic feedback from flight. (f) Skin compression feedback from flight acceleration.

levels of body ownership and presence to the BL method, which involves full body motion (Fig. 9). These findings highlight the potential of Giant Finger method as an effective flying technique in VR, delivering high ownership, immersion, and motion efficiency.

6.4 Expanded Applications of Giant Finger

The capabilities of Giant Finger to support complex movements such as flying and kicking in VR open up potential applications for tasks requiring lower body actions. Giant Finger enables individuals, regardless of their physical limitations, to engage with VR sports, altering previously inaccessible activities into enjoyable experiences with a sense of body ownership. Moreover, it provides a congruent visuo-proprioceptive experience with a minimal physical task load. This attribute is particularly beneficial for long-term engagement with intense VR lower body movements, preventing user fatigue.

The applicability of Giant Finger extends beyond facilitating action-oriented and lower body movements. It serves as a technology enabling immersive support for continuous 3D locomotion in VR. VR navigation techniques aim for long-term usage with minimal motion sickness and physical strain, often employing methods such as teleporting and pointing using VR handheld controllers. While these discontinuous movement methods reduce motion sickness [10] and physical strain [30], they compromise location awareness and immersion [11]. Giant Finger allows for immersive and continuous movement in 3D space with minimal body movement. This 3D navigation approach could be incorporated into existing VR applications for industries that require user mobility in 3D spaces, such as manufacturing [1], safety education [2], and telepresence [6].

Additionally, Giant Finger, with its straightforward design and implementation, holds potential for further expansion. Since Giant Finger enables control and visualization of a variety of virtual targets, it can offer increased ownership by aligning the visual representation more closely with the context-specific object. For example, instead of an enlarged finger, Giant Finger could be visually depicted in the form of the lower body (Fig. 11(a)) or a bicyclist's pedaling legs (Fig. 11(b)). Applying the design guideline by Pei et al. [37] and Jiang et al. [19], the method can provide virtual ownership over non-human objects, such as a galloping horse's front legs (Fig. 11(c)). Stemmed from Wang et al. [55], who demonstrated the feasibility of conveying a realistic haptic experience through minimal haptic feedback on a hand-scaled miniature avatar, potential hardware applications could include flight demonstrations using a small propeller or a shape-memory alloy spring-based actuator [15] (Fig. 11(d)). These can provide haptic feedback, such as wind (Fig. 11(e)) or acceleration through skin compression (Fig. 11(f)). Given that haptic stimuli at the finger level can be perceived as originating from the entire body due to virtual ownership [55], the Giant Finger concept may open up possibilities for cost- and space-efficient VR haptic systems.

7 LIMITATIONS AND FUTURE WORK

7.1 Giant Finger Constantly Occupies One Hand

An inherent limitation of the Giant Finger method is the reduced degree of freedom in one hand, a consequence of controlling the virtual lower body with it. To mitigate this, we suggest a mode-switching scenario to dynamically adjust the size of the finger based on the user input and contexts. This will allow both hands to maintain functionality while preserving ownership or enabling one hand to serve as the Giant Finger for lower body movement. Future steps include testing these mode-switching scenarios to broaden their applicability, particularly in contexts with abundant manipulative tasks, thereby enhancing potential for increased industrial use.

7.2 Walking Efficiency Need to be Optimized

While Giant Finger provides efficient flying and kicking movements, its suitability for walking tasks is less clear. For rapid VR navigation, users must swing their fingers with increased amplitude or speed, which is not always intuitive. We propose applying angular or translation gain to the stride as a solution to cover greater distances with smaller finger motion. This concept draws potential insights from other locomotion interfaces like the detection threshold in redirected walking [25]. The gain should be balanced within the trade-offs between locomotion efficiency and immersion [41]. Given the unique motor control properties of different body parts, [12], future work should explore the detection threshold for gained locomotion with the Giant Finger technique, aiming to optimize both efficiency and immersion, and thereby improve system usability across tasks.

7.3 Giant Finger in Broader VR Locomotion Landscape

By comparing Giant Finger with the JS and BL methods, we identified the unique characteristics of each method in terms of performance and user experience. However, the VR movement method landscape extends beyond the single-axis model of required body motion. For example, Boletsis et al [3] defined a VR locomotion typology along three axes: interaction type (physical vs artificial), VR motion type (continuous vs non-continuous), and VR interaction space (open vs limited). Assessing Giant Finger's position within the wider landscape will provide better understanding of its strengths, limitations, and potential applications in relation to other tools.

8 CONCLUSION

We introduced Giant Finger as a technique to facilitate a range of lower body movements, such as walking, flying, and kicking in VR. The creation of virtual ownership in the enlarged fingers was confirmed through proprioceptive drift and questionnaires. Comparative assessments revealed that Giant Finger exhibited flying and kicking movements more precisely and efficiently than either joystick or body-leaning methods, with comparable body ownership and presence to the body-leaning method involving whole body movements. Furthermore, because Giant Finger directly translates finger-wiggling motion to lower body movements, users can perform complex actions without cognitive efforts or physical fatigue. This indicates the potential of Giant Finger for exploration in VR, especially in confined spaces, which extends to enabling virtual walking for individuals with lower body disabilities, complex VR gaming, and 3D industrial navigation. Our demo scenarios suggest that the method is customizable for various context-specific applications by integrating corresponding haptic devices and visual representations.

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