2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Embodiment in VR Avatar with Haptic Sensations and Its Control by Subtle Input Interface

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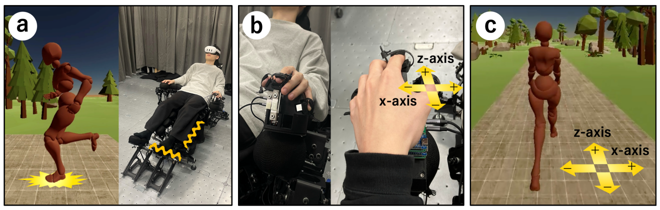

Fig. 1. VR locomotion interface that allows seated users to experience the sensation of walking or running by combining thumb-force input with a full-body haptic chair. (a) Left: Visualization of the avatar making foot contact with the ground. Right: A participant wearing an HMD, seated in the Synesthesia X1 chair, and experiencing vibrations propagating from the lower limbs to the calf in sync with each virtual footfall. (b) Left: Close-up of the participant's thumb-mounted force sensor. Right: Visualization of the finger interface and how its input is mapped to locomotion. (c) The avatar moves across a 2D plane, with speed continuously modulated by the direction and magnitude of the thumb press.

I. Introduction

Virtual Reality (VR) experiences that can be enjoyed while lying down or remaining almost motionless eliminate the need for a large play area and help reduce user fatigue. Consumer head mounted displays (HMDs) such as the Meta Quest series already support this mode of interaction through an optional lying down mode. However, when users control an avatar with minimal bodily movement, the mismatch between visual motion cues and the absence of kinesthetic feedback has been shown to reduce both the sense of body ownership (SoO) and the sense of agency (SoA) [1]. Importantly, this reduction in embodiment is not merely subjective; it has been associated with increased symptoms of cybersickness (e.g., nausea, disorientation), a weakened sense of presence and reduced motor accuracy during goal-directed tasks [7].

Research on multisensory integration suggests that individuals can perceive a virtual body as their own; even when its configuration differs from the user's physical body, provided that temporally congruent external stimulation is provided [2]. Likewise, fingertip force input interfaces can maintain a sense of agency (SoA) even with minimal gross-body movement by translating applied fingertip pressure into avatar motion [3]. Moreover, delivering vibrations to the soles and shins in synchrony with a locomotion rhythm can evoke a "walking sensation" while the user remains seated, simultaneously enhancing SoO and SoA [4], [5].

In this study, we used a fingertip force input device to control walking motion while the user lies down. The Synesthesia X1 full-body haptic chair (Enhance Experience Inc., Synesthesia Lab) provided somatosensory feedback corresponding to each movement step. The strength of fingertip pressure is linearly mapped to walking speed to preserve the action–reaction relationship, while sequential vibrations propagate upward from the heels to the calves, reproducing proprioceptive cues of walking and running. Previous work has shown that vibrations confined to the soles or the seat are sufficient to convey ground texture and locomotion cues; building on these findings, we introduce a lower-limb vibration pattern, an upward-traveling vibration to the lower limbs, from the heels to the calves, to examine whether it enhances the sense of immersion and produces a more full-bodied walking and running experience.

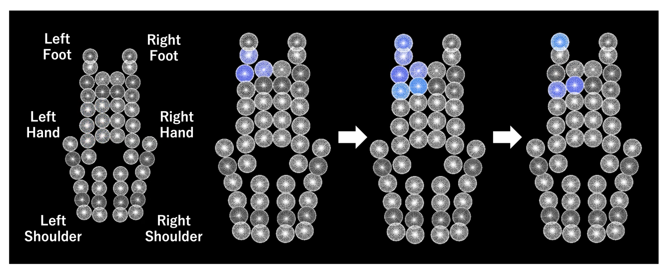

Fig. 2. A spatiotemporal map illustrating haptic flow during the simulated gait cycle (left foot phase). The activation sequence begins with synchronous stimulation of the heel and lower calf, followed by concurrent activation of the upper calf and toes.

II. System Overview

A. Subtle Input Device

We employed the fingertip force-sensing device developed for the Selfrionette system [3]. The device offers seven degrees of freedom—three for the thumb, three for the index finger, and one for the little finger. In this prototype, forward/backward and left/right thumb presses are mapped to the avatar's translation on a 2-D plane (Fig. 1b,c).

The magnitude of the applied thumb force continuously modulates both the avatar's locomotion speed and the timing

*This research is supported by JST Moonshot R&D Program (Grant number JPMJMS2013), Enhance Experience Inc., and the Synesthesia Lab.
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of haptic feedback, enabling smooth transition across a continuous range of motion, walking and running-like patterns. Rather than treating walking and running as separate modes, the system supports continuous control that reflects subtle variations in user input.

B. Interface Architecture

Stereoscopic 3D imagery is presented through a Meta Quest Pro, and full-body haptic feedback is delivered by a Synesthesia X1 chair. The virtual environment is developed in Unity, and a custom 3D object-collision framework built in TouchDesigner maps the Unity avatar's physical colliders onto the X1 chair's haptic matrix. This architecture allows the system to synthesize arbitrary haptic stimuli and project their three-dimensional representations onto the chair, ensuring that tactile sensations, such as those produced during locomotion or contact with environmental objects, are precisely synchronized with their corresponding visual cues.

Participants were equipped with an HMD, noise-cancelling headphones, the X1 full-body haptic chair, and the fingertip force input device (Fig.1a).

C. Output Feedback

When running, the system generates real-time, pseudo-random camera shake and presents footstep sounds using binaural rendering. The onset intervals of the footsteps are dynamically modulated based on locomotion speed. Fig.2 depicts the propagation sequence of vibrations across the actuator array, and the heel-strike that initiates this sequence is shown in Fig.1a. The system simultaneously activates actuators in two patterns: heel $\rightarrow$ toe and heel $\rightarrow$ calf. The heel actuator is driven by a 130 Hz carrier to highlight the sharp impact sensation, whereas the toe and calf actuators use an 80 Hz carrier to emphasize body-resonant sensations.

The vibration amplitude and delay parameters of the spatiotemporal haptic patterns were further optimized through iterative, perception-driven tuning by the authors while seated in the X1 chair. The drive electronics and firmware follow the same control architecture described in prior work [6].

III. Experience Design

Participants experienced two experimental sequences. In both, the input amplification gain was incrementally increased, allowing the avatar to transition from walking to running in response to minimal thumb force.

A. Forward-locomotion sequence

Pressing the thumb forward propelled the avatar forward, triggering a corresponding vibrotactile pattern through the haptic chair. During operation, participants could toggle between a first-person perspective and a third-person trailing camera view.

B. 2D locomotion sequence

Participants steered the avatar on a 2-D plane by moving the thumb forward, backward, left, or right. The viewing perspective could be switched among first-person, mirror-reflected, and trailing views, allowing participants to observe the avatar's movements from an external vantage point. Because both third-person and mirror perspectives enable objective observation of one's own actions, we hypothesize that these visual cues enhance recognition of bodily movement as in previous related studies.

IV. Conclusion and Future Work

We developed a prototype locomotion interface that employs full-body haptic feedback and subtle input devices to emulate gait sensations, including both walking and running. We are preparing a comparative user study to evaluate the effects of full-body vibration versus sole-only vibration on users' sense of ownership (SoO), sense of agency (SoA), presence, and perceived physical load.

Following the completion of the main experiment, we plan to expand the system's capabilities by incorporating environmental effects such as underwater resistance, sloped or uneven terrain, and varied surface textures. These enhancements are intended to simulate a broader range of physical contexts for future applications. We acknowledge that designing intuitive mappings for locomotion and directional changes remains an important challenge. The fingertip force-sensing device used in this study offers seven degrees of freedom per hand, but our current implementation utilizes only two degrees of freedom from the left thumb. This leaves substantial potential for expanding the input space by involving other fingers and enabling bimanual interaction.

In future work, we aim to explore how full-body haptic feedback could support more dynamic and expressive forms of whole-body movements beyond basic locomotion, including activities such as jumping, sudden directional changes, and even dancing.

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