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Tangible Avatar : Enhancing Presence and Embodiment During Seated Virtual Experiences with a Prop-Based Controller

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ABSTRACT

We investigate using a prop to control human-like avatars in virtual environments while remaining seated. We believe that manipulating a tangible interface, capable of rendering physical sensations and reproducing the movements of an avatar, could lead to a greater virtual experience (presence) and strengthen the relationship between users and the avatar (embodiment) compared to other established controllers. We present a controller based on an instrumented artist doll that users can manipulate to move the avatar in virtual environments. We evaluated the influence of such a controller on the sense of presence and the sense of embodiment in 3 perspectives (third-person perspective on a screen, immersive third-person perspective, and immersive first-person perspective in a head-mounted display). We compared the controller with gamepad controllers to control the movements of an avatar in a kick-in-a-ball game as illustration. The results showed that the prop-based controller can increase the sense of presence and fun in all three perspectives. It also enhances the sense of embodiment in the immersive perspectives. It could therefore enhance the user experience in various simulations involving human-like avatars.

Index Terms: Prop, Controller, Tangible, Avatar, Virtual environments, Presence, Embodiment

1 INTRODUCTION

Users are increasingly represented by human-like avatars in virtual environments that they can control with diverse controllers. These controllers have different levels of mapping between user inputs and avatar outputs, ranging from “arbitrary (unrelated to the function being performed) to natural (related to the function being performed)” [33].

For instance, controllers based on body movements (e.g., Nintendo Wiimote, walk-in-place controllers [2, 6]) induce a natural mapping between user and avatar movements while joysticks, buttons, or hand gestures (e.g. [3, 20]) lead to high abstraction. Controllers that map natural body actions tend to enhance the users’ experience in virtual environments, previous works suggesting that they increase the sense of presence (e.g [28, 29, 34–36]) related to the feeling of “being in the virtual world” [27], and the sense of embodiment [7] related to the feeling of “being inside, controlling and having a virtual body” [17]. However, controllers with natural mapping tend to generate fatigue [35], so they cannot be used for long or by disabled users (e.g., people undergoing rehabilitation, older people). They are also not suitable for desktop use.

In this paper, we investigate using a prop-based controller consisting of a small-scale model of the avatars that can be manipulated directly by hand (Figure 1). Such a controller could be considered a trade-off between arbitrary and natural controllers: it allows one to

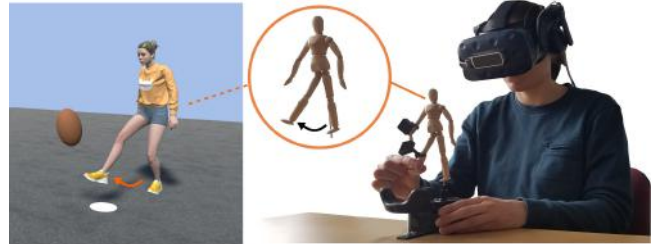


Figure 1: We propose to use a tangible prop to control a human-like avatar during seated virtual experiences. By manipulating the prop, users perform kinematics similar to those of the avatar and experience physical interactions with it. We show that such controllers can enhance the sense of presence and embodiment compared to traditional gamepad controllers.

control various movements in miniature so it does not generate fatigue while having kinematics similar to the avatars. It also conveys physical interactions that could enhance the user’s virtual experience [14, 21]. With immersive Virtual Reality, the prop can even be co-located, i.e., share the same physical location, with an avatar in a third-person perspective for a potentially improved user experience.

Prop-based controllers have been used in the past to control the off-line pose or motion capture of virtual characters (e.g., [4, 15, 16]); as users perform more efficiently, these tasks with prop-based controllers than with a computer mouse [15, 38]. However, the interest in using prop-based controllers for real-time control of avatars in virtual environments has not been studied. In particular, the influence on the sense of presence and the sense of embodiment, important factors in users’ virtual experiences, has not been explored.

This paper aims to fill this gap by evaluating the influence of a prop-based controller on users’ virtual experiences (presence, embodiment, and fun). A prop has been designed and implemented to control an avatar from 3 different perspectives—a classic third-person perspective on a desktop screen. Using a head-mounted display (HMD), we propose co-locating the prop with a third-person avatar to transmit co-located haptic sensations (immersive third-person perspective). The controller was also implemented with an avatar observed from a first-person perspective in an HMD (immersive first-person perspective). In the three perspectives, the prop was compared with arbitrary mapping controllers (buttons or Dpad) in a scenario of kicking in a ball. The results show that the prop enhances the virtual experience of users from all perspectives.

2 RELATED WORK

In the following, we discuss existing prop-based controllers (also known as dolls) and their influences on virtual experiences.

2.1 Existing prop-based controllers

Different prop-based controllers have been proposed in the past to control virtual characters. For instance, rigid elements (e.g., objects [12] mobile phone [37], Vive controller [9]) can be manipulated by hands and tracked to control the movements of virtual

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objects. However, with these interfaces, users can only control global motions, not local ones (e.g., arm or leg).

Other interfaces have been proposed to control local motions (e.g., [1, 4, 5, 13, 15, 16, 19, 22, 24, 32]). For instance, Knep et al. [19] designed instrumented dolls representing dinosaurs to perform motion capture for movies. Esposito et al. [4] proposed an interface called "the monkey" representing a virtual human model, assuming that pose capture would be easier with the 3D device than with a 2D mouse input. A commercial controller lighter and smaller than the monkey and therefore easier to manipulate was suggested by *celsys QUMARION*. To represent other types of characters and overcome the fixed topology of classical props, researchers also proposed to use reconfigurable systems, in which users assemble components to achieve different shapes (e.g., [15, 24]). Going a step further, Yoshizaki et al. [38] proposed an actuated interface to simulate specific poses automatically.

However, all these interfaces have to be built from scratch. Other works then suggest tracking the movements of existing artist dolls using vision and markers to perform motion capture [5, 13]. Our prop-based controller draws on these works, consisting of an artist's doll tracked with accelerometers but provides built-in tracking that is not sensitive to occlusion that is likely to happen during the manipulation of the interface.

2.2 Influence on virtual experiences

The benefits of using a prop-based controller over arbitrary mapping controllers have been investigated in some studies [15, 16, 38]. Jacobson et al. [15] compared mouse and prop-based controllers for pose capture. They asked participants to perform a 3D targeting task with both controllers, and results show that they moved fewer parts with the prop than with the mouse for the same result. Yoshizaki et al. [38] also compared prop and mouse interfaces in a 3D targeting task and found that participants were significantly faster with the prop than with the mouse and that the prop was easiest to learn, easiest to use, and least fatiguing. Prop-based controllers are then helpful for pose or motion capture.

In the context of real-time control of virtual characters, Johnson et al. [16] asked some users to test a chicken plush interface mapped with a virtual chicken on a screen and asked for feedback on the usability of the controller. Users gave positive feedback, even if they did not make a comparison with other input systems. This work suggests that prop-based controller dolls can be used with real-time simulations. In this paper, we are interested in the influence of prop-based controllers on the sense of presence and the sense of embodiment, which are important factors during virtual experiences. The prop has a kinematic similar to one of the avatars, which may increase the user experience. Active control is more positively associated with presence than arbitrary mapping control [28–30, 34–36]. Props also convey haptic feedback that is considered an important factor for the sense of presence [21, 31]. Getting haptic feedback from virtual objects also seems to positively impact the embodiment of users (e.g., [8, 25]).

Controlling avatars with a prop-based controller could then enhance users' virtual experiences. As avatars are more likely to be present in virtual environments than other virtual objects, such a result would be interesting for future applications. But it has to be demonstrated, and this in different perspectives. In the case of an immersive first-person perspective, for instance, the avatar and prop have different scales, which can negatively affect virtual experiences.

3 PROP-BASED CONTROLLER TO CONTROL AVATARS

3.1 Hardware

The prop was designed to provide an accessible device that could be easily replicated. It consisted in a 20 cm tall commercial artist's doll that we instrumented (see Figure 2). Rotations of the right forearm and right leg were inferred using 2 IMU (Inertial Measurement

Unit) stations (Bosh BNO055, 100Hz), providing absolute rotations along the three axes (360°). BNO055 sensors fused data from an accelerometer, compass, and gyroscope to accurately estimate the angle. We limited the measurements to the right arm and right leg since these body parts are involved in most actions right-handed people perform. The detection process is simple enough to extend to other prop parts if necessary (e.g., torso, head, etc.).

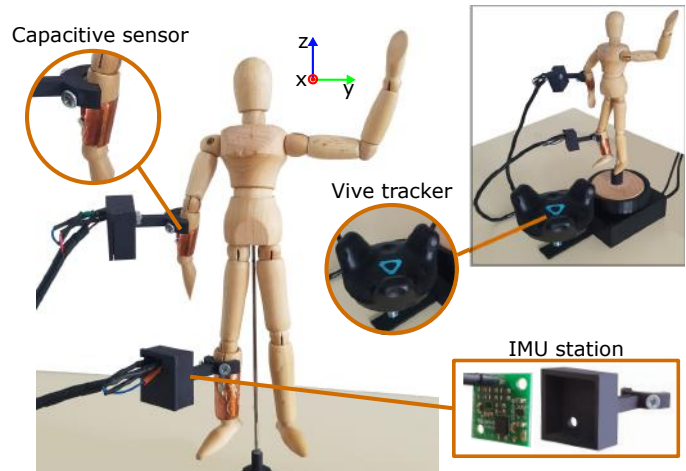


Figure 2: Overview of the prop-based controller including IMU stations, capacitive sensors and a Vive tracker.

Capacitive sensors were added on the right leg and arm to detect the user grip (copper tape and 1 MΩ resistor). The sensors communicate with the computer through 2 Arduino Micro boards at 38400 Bauds. The Arduino boards were placed in a base so that the interface was only connected to the computer by two USB wires.

The controller rested on a table thanks to a base made of 3D printing material and the doll was attached to it by a pillar (10 cm, Ø2mm). The pillar was grounded such that no rotation was allowed between the doll and the base, however, the base was free to move on the table. Global motions (3 rotations and 3 translations of the overall system) were inferred using a Vive tracker attached to the base, detected by 2 HTC Vive 2.0 stations. Users moved the prop's body part with 2 hands to control local movements only. The interface (including the base and tracker) weighed 380 g and could be easily moved.

3.2 Mapping with avatar motions

The virtual environment was implemented with Unity 3D on a computer equipped with an Intel(R) (Xeon(R) CPU E5-1603 V4, (2.80GHz)) processor and an NVIDIA (GeForce GTX 1080) graphic card. The simulation ran at frequencies above 90 HZ. In the simulations, users controlled human-like avatars downloaded from Adobe Mixamo website ¹.

The avatar's movements could have been mapped directly to the movements of the prop's body parts. However, Johnson et al. [16] noticed that some users complained about this mapping because the virtual character's movements seemed unnatural. Glauser et al. [10] presented a mapping method based on inverse kinematics methods to render more natural movements. Here we propose an alternative mapping, suggesting to drive animation clips of the avatars (pre-recorded actions used in virtual environments to animate the avatar). The method is similar to usual controllers, for example, pressing a button triggers an animation. However, the prop-based controller allows continuous control of the movements, i.e. at each frame the system maps the physical and virtual body motion to guarantee

¹<https://www.mixamo.com>

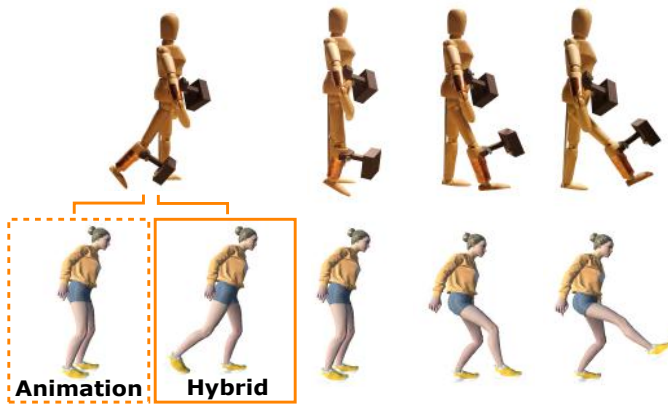


Figure 3: With the animation mapping alone, the avatar does not kick backward like the prop’s leg because it is not part of the animation. With hybrid mapping, the avatar follows the prop’s movement.

smooth movement. The speed can also be controlled intuitively compared to button inputs.

The animation clips were managed with the Mecanim animation system of Unity. The time of the animation clip was modified based on the information about the rotations of the prop’s body parts. The mapping was calculated to achieve maximum synchronization between the avatar’s and the prop’s movements. In the example in Figure 3, when the prop’s leg rotation was maximum, the motion parameter was set to the animation time when the leg was higher and vice versa for the low position. We used a linear relationship to achieve continuous motion between these positions. The same method can be applied to various animations (punch, pick, etc.).

We noticed in a pilot experiment that users sometimes made additional movements that were not simulated in the animation. For example, some users tend to put the prop’s leg back much higher than in the animation when kicking. We then implemented a hybrid mapping, extending the animation mapping with direct mapping to simulate these extra movements (Figure 3).

3.3 Avatar perspectives

The prop-based controller was implemented with 3 avatar perspectives (see Figure 4). In the third-person perspective ([3PP]), the virtual scene was displayed on a desktop screen in front of the user.

In the immersive third-person perspective ([3PPI]), the avatar is observed from a third-person perspective in an HMD. The avatar and the prop were co-located using an HMD (HTC Vive pro eyes²), with the prop and the avatar having the same size and location. The co-location gave users the impression that the avatar was truly tangible. The pose of the HMD was calibrated for each user using SteamVR software. The prop’s pose was calibrated using a Leap Motion³ attached to the HMD and capable of detecting the user’s right hand (see Figure 5). Users were asked to place their index finger on the prop’s head, and the avatar’s head was placed in the same location.

In the immersive first-person perspective ([1PPI]), users saw the virtual scene through the eyes of the avatar thanks to a HMD. Users then saw a full-size avatar while the prop was small, which may explain why it has never been paired. We hypothesized that users would be able to overcome this difference. The virtual camera was placed at virtual eye level, and the avatar’s head orientation was updated to follow the user’s head orientation.

Extra features were implemented to increase the connection between users, the prop, and the avatars. In 3PP, the avatar was trans-

²www.vive.com/fr/product/vive-pro-eye/specs

³www.ultraleap.com/product/leap-motion-controller



Figure 4: The different perspectives : (Top) Desktop third-person perspective [3PP]. (Bottom Left) Immersive third-person perspective [3PPI]. (Bottom Right) Immersive first-person perspective [1PPI].

parent and became opaque after a “magic” outline effect appeared for 3s when users grabbed the prop, detected by the capacitive sensors. In 1PPI, the same features were implemented, except for the outline effect. The avatar was also placed in front of a virtual mirror at the beginning of the simulation to help with appropriation. During the simulations, the avatar’s shadow was displayed in front of the avatar.

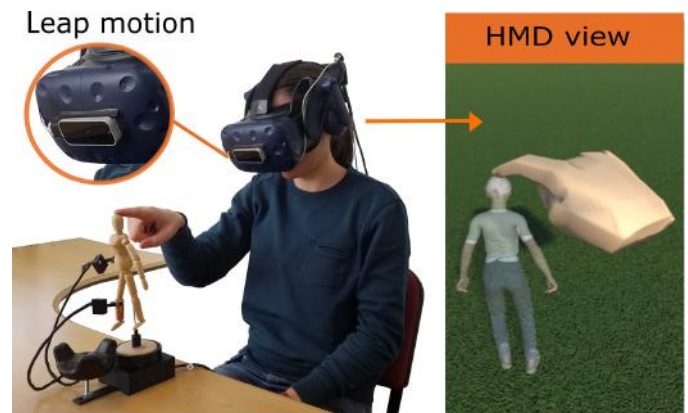


Figure 5: Calibration to co-locate the prop and the avatar.

4 USER STUDY

We conducted a user study to evaluate the influence of the prop-based controller on the users’ virtual experience. We chose a kick in a ball play as an illustration. The ethics committee of Inria Rennes approved the protocol.

4.1 Overview and hypotheses

Seated participants controlled an avatar shooting balloons in the virtual environment (see Figure 6). They used either the prop-based controller or buttons to control the movements. Buttons were chosen because they are popular controllers with arbitrary mapping. Since the prop allows for movements related to those of the avatar and conveys physical interaction, we expected that the prop would increase the sense of being in the virtual scene, the relationship with the avatar, and the fun. Therefore, we made several hypotheses:

- **(H1)** The sense of presence is higher with the prop-based controller than with the button controller.
- **(H2)** The sense of embodiment is higher with the prop-based controller than with the button controller.
- **(H3)** The fun would be higher with the prop-based controller than with the button controller.

To test several configurations, participants performed the prop/buttons comparisons in the three perspectives: third-person [3PP], immersive third-person [3PPi], and immersive first-person perspectives [1PPi].



Figure 6: (Left) Screenshots of the avatar shooting balloons in the user study. (Middle) The scene from the third-person perspective and (Right) from the immersive first-person perspective [1PPi].

4.2 Details on the experimental set up

During the experiment, participants were represented by a male (visible in Figure 6) or female avatar (visible in Figure 5). They shot at 25 virtual balloons placed in front of them. To keep the task from being too repetitive, they had to kick slowly if the ball was yellow and faster if the ball was orange, the orange balloons going farther. Participants controlled the avatar's action by pulling with the prop's right leg. They did not control the global movement to assess the prop system's interest only. From a third-person perspective, we chose the buttons on a PS4 game controller as the input, as this is a popular input with the screen display. Participants pressed the cross button to control slow kicks and the circle button to control fast kicks. In both immersive third-person and immersive first-person perspectives, the D-pad of the Vive controller was used as the button. Participants clicked in the center to control slow kicks and up to control fast kicks. In the immersive first-person perspective, they observed the avatar in a virtual mirror for one minute before beginning.

4.3 Measures and Participants

Presence, embodiment, and fun were measured using questionnaires. Presence was self-reported by the IPQ questionnaire (final scores from 0 to 100) [26]. The embodiment was self-assessed by the Peck et al. questionnaire (final scores from 0 to 6) [23]. These two questionnaires refer to the users' experience in the virtual environment (e.g., "I felt that I could control the virtual body as if it was my own body") to ensure that they assess their presence and embodiment, not the one of the prop. The fun was measured on a 5-point Likert scale, with participants answering the question: "I had fun while

using the interface.". All of these data were measured after each controller/perspective configuration.

A sample of 36 volunteers (mean age = 24.65 years; SD = 3.13 years; 25 men) participated in the experiment. They were students from our research center at Inria-Rennes. In total, only two participants reported being left-handed. They were all naive about the purpose of the experiment and had normal or correct-to-normal vision. They were not compensated for their participation.

The experiment had one between factor (Perspectives) that had three levels ([3PP],[3PPi], and [1PPi]) and one within factor (Controllers) with two levels (Prop and Button). The controllers' presentations were counter-balanced across participants. After each simulation, participants filled in questionnaires. Overall, the experiment lasted 25 minutes.

4.4 Results

The results of the user study are shown in Figure 7. The assumption of normality and homogeneity of variance were tested with Shapiro-Wilk and Bartlett tests. If these hypotheses were satisfied, Student's t-tests for paired samples were performed, otherwise Wilcoxon signed-rank tests were performed. In both cases, Holm-Bonferroni correction was applied.

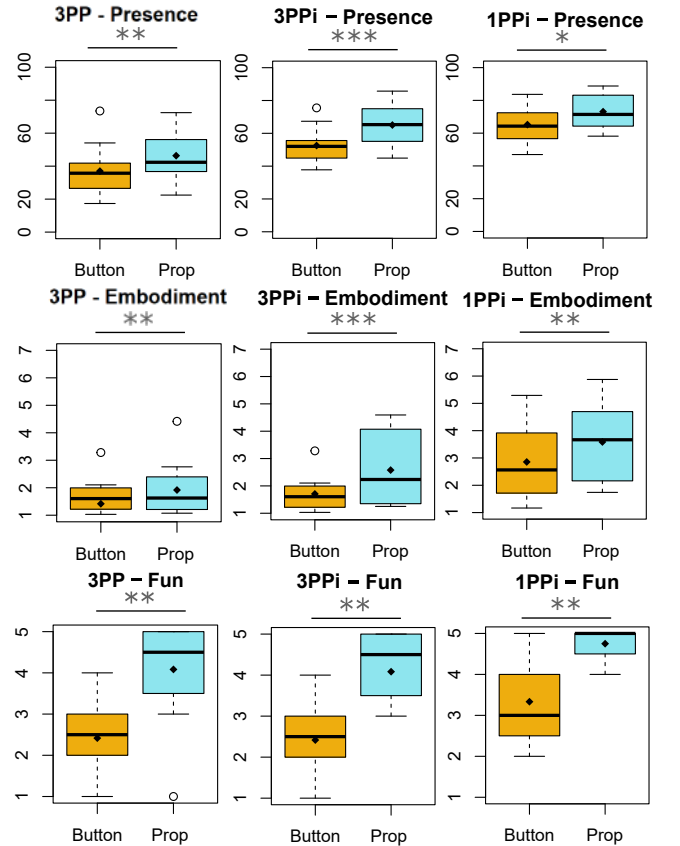


Figure 7: Presence, embodiment and fun scores in the different perspectives. Higher is better for all these measures.

For the presence scores, the normality assumption was met in all perspectives. The participants' sense of presence was significantly higher (+ 10%) with the prop ($m = 46.3, std = 14.7$) than with the button interface in 3PP ($m = 36.9, std = 15.2, p = 0.002, d = 0.6$). It was significantly higher (+ 13%) with prop ($m = 65.1, std = 10.7$)

than with the button interface in 3PPi ($m = 52.5, std = 13.3, p = 0.001, d = 0.92$). It was also significantly higher (+11 %) with the prop ($m = 73.1, std = 10.3$) than with the button interface in 1PPi ($m = 65.2, std = 10.8, p = 0.028, d = 0.71$).

For the embodiment scores, the normality assumption was met in 1PPi but not in 3PP and 3PPi. The embodiment was significantly higher (+ 7%) with the prop ($m = 1.9, std = 0.6$) than with the button interface in 3PP ($m = 1.4, std = 0.9, p = 0.003, r = 0.8$). It was significantly higher (+ 13%) with the prop ($m = 2.6, std = 0.6$) than with the button interface in 3PPi ($m = 1.7, std = 1.3, p = 0.001, r = 0.78$). It was also significantly higher (+11 %) with the prop ($m = 3.6, std = 1.4$) than with the button interface in 1PPi ($m = 2.8, std = 1.4, p = 0.003, d = 0.5$).

The normality assumption was not met in all the perspectives for fun. Participants had significantly more fun (+ 48%) with the prop ($m = 4.8, std = 0.9$) than with the button interface in 3PP ($m = 2.4, std = 1.2, p = 0.006, r = 0.86$). It was also significantly higher (+ 45%) with the prop ($m = 4.75, std = 0.5$) than with the button interface in 3PPi ($m = 2.5, std = 1.0, p = 0.002, r = 0.89$). Finally, It was significantly higher (+28%) with the prop ($m = 4.7, std = 0.4$) than with the button interface in 1PPi ($m = 3.3, std = 1.1, p = 0.007, r = 0.77$).

5 DISCUSSION

5.1 Influence of the prop on users' experiences

Previous studies demonstrated that users' performances were increased when controlling the pose of a virtual character with prop-based controllers when compared to arbitrary controllers [15, 38]. Our study extends these results, showing that prop-based controllers can increase the users' virtual experiences.

The study first aimed to check if the sense of presence of seated users could be improved by using the prop-based controller. The results show that the prop-based controller induces a higher sense of presence than arbitrary mapping controllers, supporting **(H1)**. The effect was comparable across the perspectives. Overall, the presence was enhanced by 10% on average, a significant amount considering that participants remained seated. These results are consistent with previous work that demonstrate a higher sense of presence when introducing a physical object in virtual environments [21, 31]. We show here that a higher sense of presence can be induced by a tangible object representing the avatar that is the entity the more likely to be present in virtual environments. Previous work also suggests that active control is more positively associated with presence than arbitrary mapping control [28–30, 34–36]. The prop-based controller does not strictly induces active control, but our results suggest that it still induces a better sense of presence than arbitrary mapping controllers, supporting the use of controllers based on miniaturized motions (e.g., hand gestures [18], smartphone-based motion control [37]).

Our results also indicate that the sense of embodiment increases with the prop-based controller, supporting **(H2)**. The effects are stronger in immersive perspectives [3PPi] and [1PPi], with an increase of more than 0.7 points, which is significant considering that participants remained seated. While a higher sense of embodiment was demonstrated with haptic feedback displayed on specific objects (e.g [8, 25]), we show that the haptic feedback can be displayed on the avatar itself. Besides haptic feedback, the kinematics similar to the avatar could have helped the process, but further research should be led to investigate its influence. The embodiment enhancement is particularly interesting in the case of the immersive first-person perspective [1PPi] because this configuration is widely used to maximize the embodiment. Users also seem able to link the miniature prop-based controller with a life-scale avatar, suggesting that scale changes are supported between real and virtual environments. The sense of embodiment is higher in the first-person perspective [1PPi] than in [3PP] and [3PPi] perspectives for the button controller, con-

sistent with previous work that demonstrated a greater embodiment in this perspective [7, 11].

The perceived fun was also investigated. The results show that it was significantly higher in all perspectives, supporting **(H3)**. It suggests that the prop-based controller could be used to motivate users to use virtual environments, which could be interesting for some applications (e.g., video games, rehabilitation, etc).

5.2 Future Directions of Research and Use cases

This study shows that a prop-based controller can increase users' virtual experiences. As it limits fatigue while keeping interesting virtual experiences, it could interest all seated users. It could also benefit users with disabilities and older people, so it would be interesting to replicate our study with these populations.

Seated users used the interface but could be used by standing users by attaching it with a harness [22]. Natural mapping controllers are more likely to be used in this situation. Still, we think the prop-based controller could be a good way to limit user fatigue while preserving the user experience. We may make comparisons with natural mapping controllers in future work.

Extending the results to other actions could also be interesting in the future. Many local actions can be explored with the prop's current design, and the IMU concept can also be extended to other body parts to perform even more actions. Actions related to global movements like jumping or flying are also possible, as they can be detected with the Vive Tracker.

Some use cases are presented in Figure 8. Our first example involves locomotion with a virtual visit to a museum. Users moved the prop's leg to control forward motion. Moving one leg with each hand makes it difficult to control the rotation, and since the leg movements are antagonistic, controlling one leg is enough. The rotation of the base was used to manage the rotation of the avatar directly. The second and third examples show a rugby game, with users kicking a ball between rugby posts, and a sword game, where fruits were thrown at a ninja who had to cut them with a sword. These scenarios illustrate the value of controlling a continuous action. The impact forces can be computed from the prop's leg velocity in the rugby game. In the sword game, the prop allows good timing to interact with the dynamic objects.

6 CONCLUSION

In this paper, we explored the use of a prop-based controller for real-time control of human-like avatars. We proposed a prop-based controller based on an artist's doll and accelerometers. We implemented it third-person perspective on a screen, immersive third-person perspective, and immersive first-person perspective in a head-mounted display. Compared to arbitrary mapping controllers, we show that the prop increases the sense of presence and fun in all perspectives, and the sense of embodiment in immersive perspectives. It could then be used to improve the virtual experiences of seated users in many applications.

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Figure 8: Examples of use cases (Left) Virtual visit: users move the prop's leg forward and backward to control a virtual walk. (Middle) Rugby kick: users shoot with the prop's leg. (Right) Sword slash: users move the prop's arm to cut virtual fruits.

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