Embodying Physics-Aware Avatars in Virtual Reality

Yujie Tao
Stanford University
Stanford, CA, USA
yjtao@stanford.edu

Cheng Yao Wang
Cornell University
Ithaca, NY, USA
cw776@cornell.edu

Andrew D. Wilson
Microsoft Research
Redmond, WA, USA
awilson@microsoft.com

Eyal Ofek
Microsoft Research
Redmond, WA, USA
eyalofek@microsoft.com

Mar Gonzalez-Franco
Microsoft Research
Redmond, WA, USA
margonzalezfranco@gmail.com

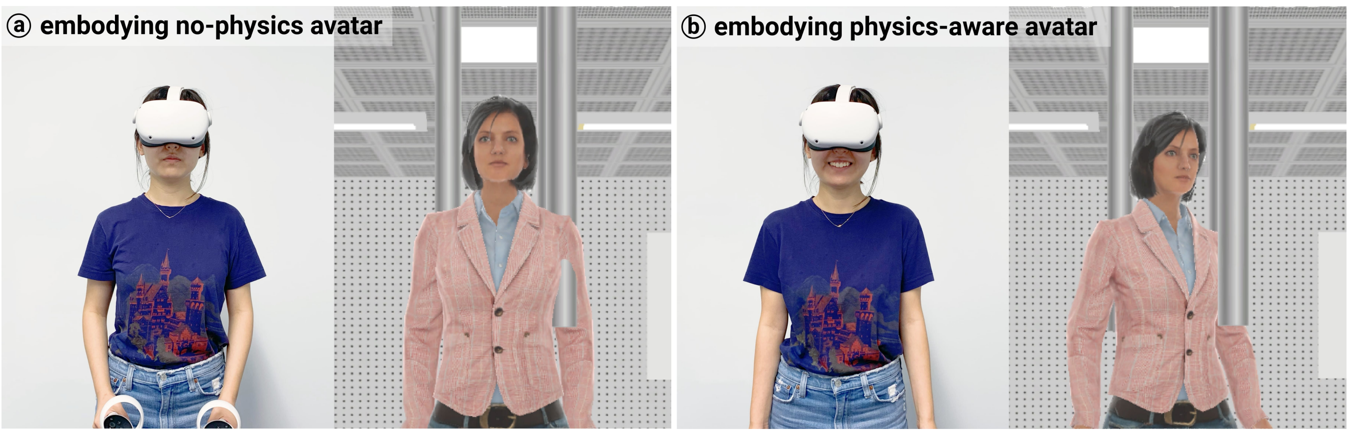

Figure 1: (a) When a user is embodying a self-avatar in virtual reality, it usually follows a one-to-one mapping of their motion. While this preserves visual-proprioceptive congruence, a determining factor for embodiment, it also leads to unnatural behavior, such as the body passing through objects in the VR environment. (b) With physics correction, the self-avatar developed motion that didn't match the user input: in this case, avoiding the poles when contacting. We find that rather than compromising the sense of virtual body ownership, these types of small deviations improve the embodiment of users in VR.

ABSTRACT

Embodiment toward an avatar in virtual reality (VR) is generally stronger when there is a high degree of alignment between the user's and self-avatar's motion. However, one-to-one mapping between the two is not always ideal when user interacts with the virtual environment. On these occasions, the user input often leads to unnatural behavior without physical realism (e.g., objects penetrating virtual body, body unmoved by hitting stimuli). We investigate how adding physics correction to self-avatar motion impacts embodiment. Physics-aware self-avatar preserves the physical meaning of the movement but introduces discrepancies between the user's and self-avatar's motion, whose contingency is a determining factor for embodiment. To understand its impact, we conducted an in-lab study (n = 20) where participants interacted with obstacles on their upper bodies in VR with and without physics correction. Our results showed that, rather than compromising embodiment level, physics-responsive self-avatar improved embodiment compared to no-physics condition in both active and passive interactions.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interaction paradigms**; • **Virtual reality**;

KEYWORDS

Embodiment, Physics Avatars, Virtual Reality

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1 INTRODUCTION

Virtual reality (VR) enables the user to embody a virtual body beyond their physical one. With the proliferation of portable VR hardware that tracks user's head and hand positions, one can easily control a virtual body when they put on a head-mounted display and look down to see their body being substituted by an avatar [85]. The illusory ownership of an avatar is known to improve presence in VR [43, 90], foster implicit learning [82], and influence emotional response [83, 95]. Embodiment can also reduce implicit biases [65] and empower behavioral change [80]. To achieve the embodiment, visual-sensorimotor contingencies (i.e., synchronizing the user and self-avatar motion, which can be felt as having control over the avatar), visual perspective (i.e., first-person point of view), and appearance (i.e., visual features) of the virtual body are all important contributing factors [25, 43, 57, 84].

Past work uncovered determinants for embodiment in virtual reality, but the relationship between the self-avatar and the environment is often under-explored. Rather, we argue that the interaction between virtual body and the environment remains an important reason why the embodiment illusion might break. In the physical world, our senses can inform us of any interaction (wanted or unwanted) of our body with objects around us, and we develop an awareness of the environment through manipulating objects and observing the physical interactions. In VR, our avatar is a sense-less robot, and our understanding of interaction with the environment is heavily dependent on visual and audio cues rendered from the headset. Thus, in our interaction with a VR environment, one-to-one mapping between the user's and self-avatar's motion often leads to behavior that lacks physical meaning, such as an unmoved virtual body when hit by obstacles or objects penetrating into the virtual body, as shown in Figure 2.

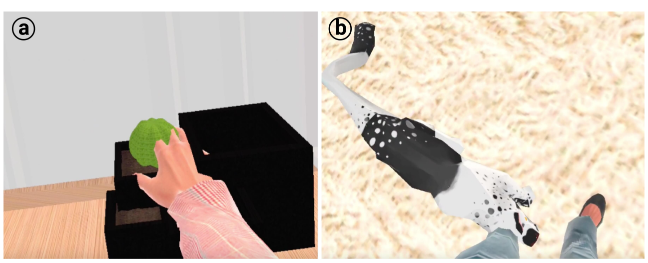

Figure 2: Examples of unnatural behavior due to one-to-one mapping of user's motion. (a) Hand penetrating into objects when contacting. (b) Body unmoved when being hit, such as by a pet.

While haptics is great way to augment the physical experience of our body inside VR and ultimately improve embodiment [33], we argue that adding physics correction to self-avatar motion visually could already improve the embodied experience. The space of physics simulations for VR and graphics has been widely explored for cloth [42], fluid [14] and non-player characters [21]. There is also a growing interest in industry and beyond to add physics to self-avatars, such as Hand Physics Lab [2] and Boneworks [1]. However, its impact on embodiment is still under-explored. In fact, correcting self-avatar motion when in contact with objects in VR, though preserving the physics relationship between the virtual body and the environment, creates a discrepancy between user input and the self-avatar behavior. We know that avatars do not need to be in perfect alignment with the self-motion, and users might try to match with the avatar motion [31], but too much divergence could trigger body semantic violations [62]. Do users still feel embodied with physics-responsive self-avatars that develop physically correct behavior but go beyond user input? What is the users' preferred range of physics correction for their self-avatars?

To investigate those questions, we conducted a within-group user study (n = 20), where participants' upper bodies interacted with obstacles in VR, both passively (hit by a ball) and actively (walking toward obstacles). Participants experienced each interaction type with physics-aware and no-physics self-avatar respectively. The results showed that participants developed a higher embodiment level with physics-aware self-avatar in both passive and active interactions. We also uncovered the preferred level of physics correction for the passive interaction task.

Our key contributions are the following: (1) We made the first step to study how physics-aware avatars impact on subjective embodiment level in virtual reality; (2) We compared physics correction with one-to-one mapping of user's motion in both active and passive interactions; (3) We uncovered the thresholds of user preference to physics corrections in passive interaction; and (4) We discussed implications of our findings and suggested directions for future work.

2 RELATED WORK

In this work, we move beyond one-to-one mapping between user and self-avatar motion and remap user input with consideration of the surrounding virtual environment. This means our interaction with the self-avatar aims to have both body awareness, and environment awareness, according to the framework from Reality-Based Interaction [39]. Thus, our research draws inspiration from prior work on embodiment in VR, motion remapping, and physics simulations.

2.1 Embodiment and Illusion of Virtual Body Ownership

The sense of "embodiment" has often been described as a somatic form of self-consciousness [52]. The sensorimotor state of the body plays an instrumental role in information processing [32, 47]. To manipulate body ownership, a classic example is the so-called "rubber-hand illusion" [13]. When a rubber hand is brushed synchronously with the participant's own hand, they perceive the prosthetic hand as part of their body [52, 77, 89]. In a virtual environment, the illusory ownership of an avatar can modulate the user's perceptual experience of their own body, changing their body image [70, 95], their distance perception, [29] and even their haptic accuracy [30, 56, 58]. Active self-avatars were also found to improve cognitive performance such as letter recall [86]. Moreover, users are able to embody self-representations with drastically different body shapes, such as giants [6] or even non-humanoid avatars [48, 69, 94].

To induce the sense of embodiment toward an avatar in VR, there are three determining factors: sense of location (i.e., visuospatial perspective), sense of agency (i.e., synchronous visuomotor correlations), and sense of body ownership (i.e., self-attribution of a body) [43]. The visual appearance of an avatar is a crucial contributing factor to sense of body ownership [50]. The match of clothing and skin tones between user's and self-avatar's body influences the strength of virtual body ownership [57] while a replica of human likeness that is close but not good enough could lead to the uncanny valley effect [53]. However, when investigating into relative contributions of the appearance of the avatars in inducing embodiment to a virtual body, avatar appearance was found of less importance than the other two factors, control and point of view [25]. It was shown that with a high degree of spatial overlap between real and virtual bodies, the sole effect of congruent visuo-proprioceptive cues is sufficient for inducing embodiment in VR [57, 84]. Beyond boosting embodiment, synchronizing body movement between participants and avatars also result in sense of presence, while reducing simulator sickness [45].

2.2 Remapping of User Movement in VR

While mirroring user movement to avatar movement helps preserve embodiment, breaking the mapping, or remapping, could introduce new interactive experiences. Powered by the dominance of vision over proprioception [15], researchers developed re-targeting techniques to convert daily objects [10, 38], robot-actuated physical props [28], or even user's own body [22] to serve as haptic proxies in VR. Varying the displacement of visual representation of the hand could also induce pseudo-haptics such as force and weight perception [20, 40, 74–76]. By amplifying or miniaturizing user motion [46], remapping further allows users to interact with distant objects [41, 71, 92] or enjoying haptics on a miniature scale [91]. Remapping [19, 24] or stylizing [7] user movement also allows users to reduce fatigue while preserving embodiment. Remapping user motion in VR has unlocked various applications.

When considering the discrepancy between the user and self-avatar motion due to remapping, we can summarize its impact into three categories: (1) When the discrepancy is small (e.g. less than 14 centimeters), users do not notice/can tolerate the difference and its impact on embodiment is limited [92]. (2) The discrepancy generates a self-avatar follower effect, by which the users try to reduce the distance between the two bodies by changing their own body position and thus correcting to match the avatar motion [31]; (3) When discrepancy is too large, it creates a strong disembodiment response, and even a body semantic violation [62]. Li et.al [49], for instance, investigated how user-avatar movement inconsistency affects its noticeability and sense of body ownership in VR.

2.3 Introducing Physics to Self-avatar Motion Beyond User Input

Physics-simulated characters have been widely explored in 3D graphics community [9, 93]. Different from kinematic control, which heavily relies on motion capturing data, physics-based character develop motions from the result of physics simulation processes [27]. Rag-doll physics is commonly used in video games to simulate death animation for non-player characters [78]. More recently, researchers explored leveraging deep reinforcement learning to render physics characters that imitate diverse behaviors while preserving response to environmental stimuli [11, 51, 67, 68].

We see a growing interest in adding physics to self-avatar in VR. An early implementation by Peinado et.al. [66] combined both inverse kinematics constraints and damping constraints created dynamically by the collision-avoidance system. More recently, physics correction has been added to full-body tracking systems for VR [87] as well as commercial games such as Boneworks [1] and Hand Physics Lab [2]. While physics-aware self-avatar enables more naturalistic behavior, its impact on embodiment is still under-explored. Particularly, in order to preserve its physical relationship with the surrounding environments, the physics correction breaks the synchronization between user and avatar motion, which could be detrimental to user's embodied experience.

Therefore, our work is also grounded in prior research that investigated different visual representations of the virtual hand when grasping objects in VR [16, 44, 72, 73]. Canales et.al. [16], showed that when the virtual hand did not penetrate into the objects (i.e., preserving physical meaning), the participants found higher ownership of the virtual hand. However, the small discrepancy between visuals and proprioception of the hand is not comparable to what users might experience when they embody a full-body avatar with physics correction and receive physical impact on other parts of the body (e.g., hit by a ball on the shoulder).

In our work, we specifically focus on the impact of physics correction while users embody a full-body avatar. We also investigate both active and passive interactions and how users respond to different levels of physics correction.

3 METHODS AND MATERIALS

To evaluate the impact of physics-responsive self-avatar on embodiment and other critical aspects of the VR experience, we conducted a with-in group user study. Each participant was asked to interact with virtual objects while embodying a physics-responsive avatar and a no-physics avatar respectively. We studied this duality in both active and passive interactions, correspondingly with and without voluntary movement from the participants [17]. In both interaction types, we focused the experiments on upper body of the avatars, which are better tracked in commercial VR systems. Embodiment questionnaire [64] was followed after each task.

We hypothesized that (**H1**) embodying physics-aware self-avatar would improve the embodiment level in active interaction; (**H2**) participants would prefer physics-aware self-avatar over no-physics self-avatar in passive interaction; (**H3**) physics-responsive self-avatar would be regarded as more embodied than no-physics one but over-reaction in the physics on the self-avatar motion could drop embodiment level in passive interactions.

This study was approved by our Institutional Review Board at Microsoft Research.

3.1 Study Design

We adopted a within-group study design, where all participants underwent the same conditions but in a counterbalanced order. Participants stood in front of a mirror in VR, and after a short period of free interaction to get familiar with the self-avatar and generate embodiment [37], they interfaced with two conditions: physics-aware self-avatar and no-physics self-avatar (*baseline*). We designed two different interaction types to investigate the impact of physics correction. In the active interaction, participants were asked to walk through poles. In the passive interaction, participants were

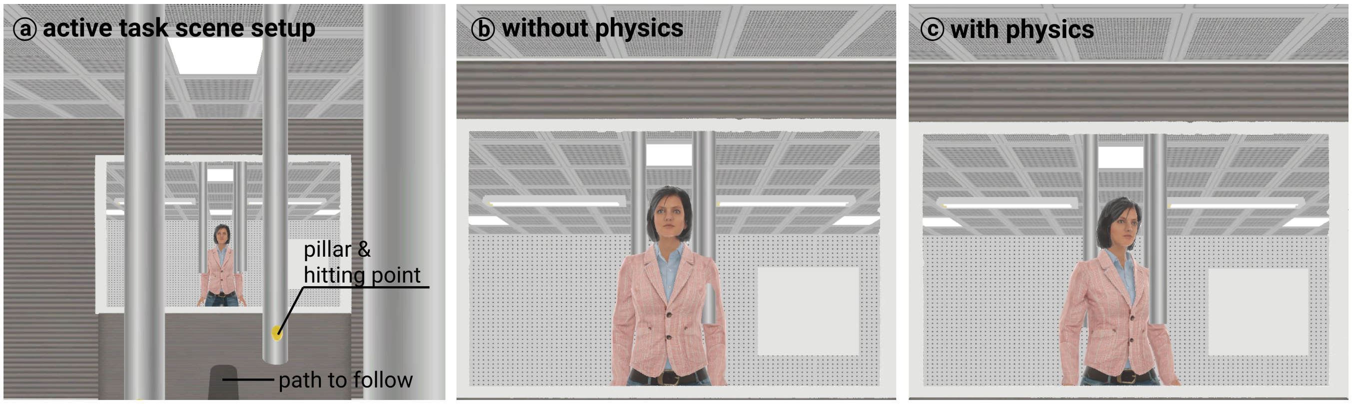

Figure 3: Active interaction tasks in our user study. (a) Participants started off standing towards three pillars and followed the grey path in front of them to walk to the other end. They were instructed to ensure their body was in contact with the pillar on the hitting point marked in yellow. (b) No physics condition. The self-avatar's motion was mapped one-to-one to the participant's motion, and the pillars penetrated into the participant's virtual body. (c) With physics condition. The self-avatar's body developed physical behavior that the participant did not input and reacted to the metallic pillar.

hit by a ball. The design is inspired by prior research on the nature of our body being both sentient (activity) and sensible (passivity) in daily interactions [54]. It's also inspired by the importance of touche-touchant interactions, as well as motor control models that show the impact of efferent signals on how we interpret the sensory feedback [12, 32].

Active interaction. In the active interaction task, participants were instructed to walk following a straight path (length: 2m) from a position remote from the mirror, and proceed toward it while looking at the reflection of their avatars in the mirror, as shown in Figure 3 (a). In the meantime, obstacles in their way, in the form of poles hanging from the ceiling, would hit their self-avatar's upper body. Participants were asked to follow the path, and pass through the poles where a yellow contact point is marked, ensuring the contact of the self-avatar and each pole. When the participants reach the end of the path, the pillars vanished, enabling a obstacle-free return of the participants to the path starting position, and then poles would re-appear. For each interface condition (*active physics*, *active no physics*), participants repeated this walking task five times.

Passive interaction. Participants stood still in front of a mirror while a ball hit them on the upper body in VR. Each ball stimuli was 8 kg in mass and was spawned from a location that's 1.4 m away from the participants, targeting the self-avatar's left clavicle with a speed of 10m/s. While all the ball properties were controlled in this task, participants were blind to the exact values and only saw the ball flying to hit them. This design aligns with how we normally interact with sudden stimuli in the physical environment.

In the passive interaction task, beyond embodying both physics and no-physics self-avatar, we also want to study how participants react to different levels of physics correction. This is in essence a threshold evaluation: what is a good enough body response to the stimuli presented? Thus, we presented participants with a virtual slider, which allowed them to control the reaction of their self-avatar to the stimuli. The slider settings enabled participants to set the response all the way from no physical effect (*passive no physics*), gradually increasing the body reaction, to fully knock down the avatar after hit (*passive physics fall*).

Each muscle of the self-avatar could be simplified as a spring system, with x being displacement, k being spring constant, and F being the spring force:

$$F = -kx$$

In essence, since the force is constant, the changes on the spring will make the avatar motion change, from an over-reaction and ensured fall to the floor to not moving at all. Thus, we can represent each physics correction on the slider as the offset between the virtual body and the actual user pose. The offset is calculated by the displacement between the inverse kinematics (IK) skeleton (α_1) and physics skeleton (α_2) given L joints of the avatar's upper body, following prior work [49]:

$$offset(\alpha_1, \alpha_2) = \max_{\{1 \le i \le L\}} \sqrt{\sum_{d \in x,y,z} (\alpha^i_{d,1} - \alpha^i_{d,2})^2}$$

Figure 4 shows the corresponding offset at each position of the slider for a standard skeleton (1.65m in height). The slider contains 100 physics-corrected self-avatar motions ranging from 21.0 cm to 203.0 cm offset and one no-physics motion (0 cm in offset). Note that as we calibrated the self-avatar of each participant, the exact offset between physics self-avatar and user pose will vary across participants but follow the same trend.

Using the slider, participants were asked to vary the self-avatar's response to the ball impact and chose the response they felt as the most embodied. They did this twice and started from each of the two end points of the slider for the selection: (1) starting from the "completely fall down" side of the slider (*passive select #1*); (2) or starting from the "completely still", no physics movement endpoint (*passive select #2*). While the sliding starting point was determined each round, participants could control the slider in two directions (i.e. increasing or decreasing their avatar's response to the ball) during the selection process. There was no time limit we put on

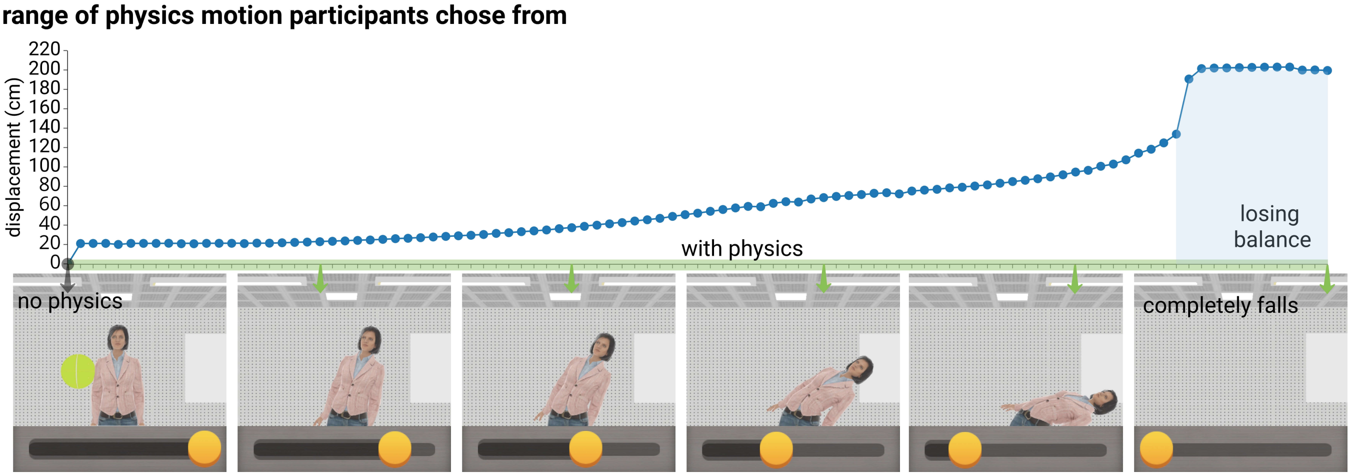

Figure 4: Range of motion that the participants could slide in the passive interaction task. The self-avatar pose ranges from no movement when being hit by a ball (no physics) to completely falling after the hit. In total, the slider includes 101 different motions. We sampled 6 of them and visualized them in the figure. Please see the supplementary video for better visualization of the reactions.

participants for completing the selection task. Participants were free to experience every physics levels on the slider one-by-one or skip certain range of avatar reactions through continuous sliding.

After selecting the preferred physics level starting from each direction, participants were asked to rate the embodiment toward the self-avatar motion at that point. Finally, they were asked to re-experience and rate the two end points of the slider (*passive no physics* and *passive physics fall*).

Additional design considerations. For both active and passive interaction tasks, we focused on physical impact happening to the upper body (e.g., shoulder). We made this decision as mainstream consumer-level VR systems (e.g., Oculus Quest 2, VIVE Focus 3) track only the orientation of the user's head and hands. Moreover, the view direction of users commonly aims at the height of faces. In our pilot studies, we experimented with physics reactions on the lower body too, and we can anecdotally report that the lack of reliable tracking was the major limiting factor that prevented us from studying the lower body. Compared to hand-oriented tasks, the upper body interactions also allow the virtual avatar to develop a wide range of physics responses (e.g., no movement to completely fall after the ball hits on shoulder). Past work has shown that visual-proprioceptive mismatch on hand only could go unnoticed or does not impact embodiment if the offset is small [92].

Furthermore, the use of virtual mirror allows participants to have a clear and constant view of their virtual body. It is equivalent to scenarios that require high attention from the users to their virtual body. Such design decision ensures participants to notice any physical impacts on their virtual body and focus on evaluating how physics correction impacts on embodiment.

3.2 Procedure

We invited the participants to the lab, where they filled out consent forms and demographic questionnaires, following the Declaration of Helsinki ethical protocols. The study started with a calibration procedure with the participant performing a T-pose. The calibration procedure resized the avatar dimension based on participants' body height and arm length. A 5-minute warm-up session followed to get participants familiarized with VR and their virtual body [37]. They were asked to perform simple gestures such as practicing boxing and self-touch.

The full trial always began with participants completing the active interaction tasks, followed by the passive interaction tasks. The conditions were counterbalanced *within* each interaction type. In active interaction, participants walked through poles with/without physics correction. We counterbalanced the order of self-avatar conditions (*active physics, active no physics*) to avoid sequence and learning effects. In passive interaction, participants first familiarized with how to control the virtual slider to adjust the physics response of avatars. Then, in the preferred physics level selection task, we counterbalanced the slider starting endpoints (*passive select #1, passive select #2*). We also counterbalanced the order of embodiment rating for the two avatar response endpoints (*passive no physics, passive physics fall).*

After each task (2 active and 4 passive), participants were asked to rate their embodiment level using the embodiment questionnaire [64]. At the end of each interaction type (i.e., active, passive), we conducted a short interview to understand the participants' general experience.

3.3 Apparatus

Figure 5 (a) shows the setup of our study. Participants wore an Oculus Quest 2 headset, which tracks their head and hands positions. The baseline of self-avatar control was achieved by the state-of-the-art Inverse Kinematics (IK) from partial body tracking rather than full-body motion capture. For our IK baseline, we chose Unity's RootMotion Final IK [4], following prior work [6, 7, 63]. The physics response of self-avatar was achieved by a state-of-the-art active ragdoll physics controller: Unity's RootMotion PuppetMaster [5]. Note that while the physics stimuli contacting the upper body might influence the self-avatar's head location, we did not shift the user's point of view to avoid motion sickness.

The avatars used in the study were selected from Microsoft's Rocketbox avatar library [34], as shown in Figure 5 (b) and (c). We assigned the avatar to each participant based on their self-identified gender, following prior work [79]. While we did not personalize the avatar appearance for each participants, past works showed that embodiment could be elicited with avatars of different appearances [60, 95]. In Section 5.4, we further discuss the decision of avatar customization in this study.

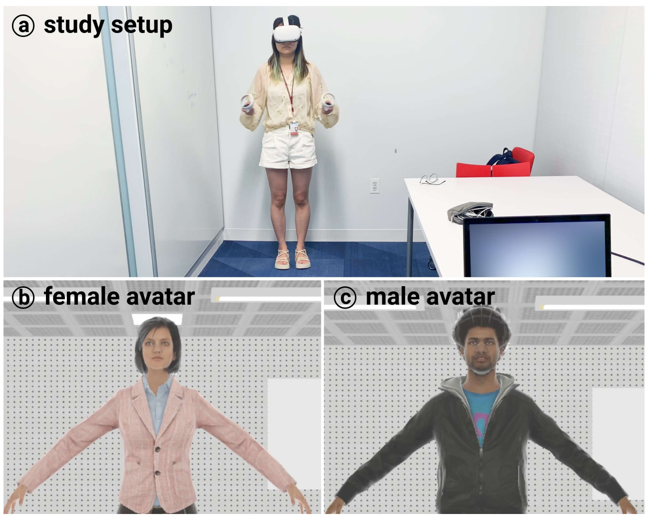

Figure 5: Setup of our user study. (a) A participant is completing a study task. (b) and (c) Avatars used in our study for female and male participants, respectively.

3.4 Participants

To determine the sample size for our study, a priori power analysis was conducted using G*Power [23], based on embodiment rating data from pilot study (n = 8) on active interaction task (walking through poles when embodying a physics-aware and no-physics avatar correspondingly). The effect size in pilot study is 0.93, which considered to be large using Cohen's [18] criteria. With a significance criterion of $\alpha = 0.05$ and power = 0.95, we found that the minimum total sample size needed for Wilcoxon signed-rank test with two tails is 18.

We recruited 21 participants (10 self-identified females, 11 self-identified males) between the ages of 18 to 65 years old (M = 23.3, SD = 4.9). The level of experience in VR and gaming differed widely across participants, from first-time users to VR experts. The study took approximately 45 minutes and all participants were compensated $20 for their time. One participant was excluded from the following analysis as they reported that they could not find any visual difference between physics and no-physics avatar conditions. Thus, the final sample size is 20 participants.

3.5 Measures

To understand the effects of physics-aware avatars on user experiences, we used the embodiment questionnaire designed by Peck et al. [64], which includes 16 Likert scale questions under the sub-scales of Appearance, Response, Ownership, and Multi-Sensory. Participants rated each statement on a scale of 1 to 7, with 1 being "never" and 7 being "always". We adopted questionnaires as the main evaluation metric due to its versatility and ease to use [35]. It did not put burden on the participants to wear extra hardware devices for physiometric sensing. Past works also have showed that subjective measures embodiment levels collected by questionnaires are correlated with objective measures, such as electroencephalogram [36, 62]. Therefore, the adoption of a comprehensive embodiment questionnaire is our first step to uncover the impact of physics-aware avatar on embodiment.

To compute the final embodiment ratings, we first calculated 4 sub-scale scores by averaging questions within each sub-category (appearance, response, multi-sensory, ownership). Then, we averaged the sub-scale scores for the final rating. The computation followed the instructions provided by Peck et al. [64].

Embodiment is closely tied to many other factors, such as presence [61], perception [8, 30] and ultimately behavior [29]. Therefore, it can be a useful metric that also help discuss physics correction's impact on other critical aspects of the VR experience.

4 RESULTS

Figures 6, 7, and 8 depict the main results of our study. We found that physics-aware self-avatar improved the sense of embodiment in active interaction (Figure 6), confirming **H1**. In passive interaction tasks, all participants chose physics-aware self-avatar over no-physics one, confirming **H2**, and physics correction was also shown to improve the level of embodiment (Figure 8). Moreover, we uncovered the range of physics correction participants found as most embodied in our passive interaction task, which is 32.2 to 35.5 centimeters from their physical body positions (Figure 7), whereas the use of strong physics correction undermined and ended up disembodying participants, confirming **H3**.

4.1 Active Interaction

H1 (embodiment) We analyzed our data using a two-sided Wilcoxon signed-rank test and found a significant difference between physics-aware and no-physics self-avatar on overall embodiment rating in the active condition (p = 0.017). The results showed that physics-aware self-avatar (M = 4.1, SD = 1.2) improved sense of embodiment in active interaction compared to non-physics self-avatar (M = 3.5, SD = 1.3), which confirms H1.

Looking into the sub-scales of the embodiment ratings, we also performed a two-sided Wilcoxon signed-rank test. We found significant differences on appearance (p = 0.02), response (p = 0.009) and multi-sensory (p = 0.006) scales between physics-aware and no-physics self-avatar. It showed that participants felt a stronger attachment to the external appearance of the virtual body when embodying a physics-aware self-avatar (M = 4.2, SD = 1.3) than a non-physics self-avatar (M = 3.5, SD = 1.3). Moreover, participants developed a stronger response to external stimuli when embodying a physics-aware self-avatar (M = 3.7, SD = 1.4) than no-physics

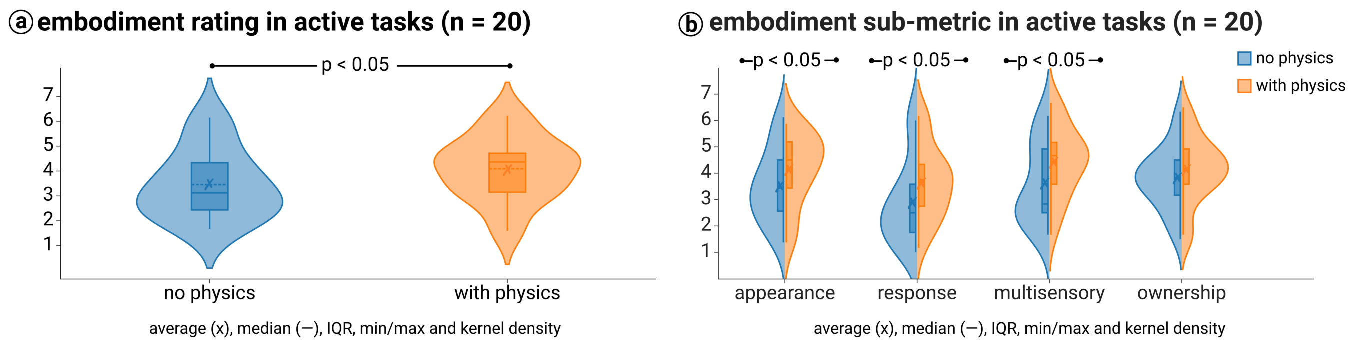

Figure 6: Embodiment in active interaction for physics and no physics conditions. (a) overall ratings, (b) embodiment sub-measures.

self-avatar (M = 2.9, SD = 1.6). Physics-aware self-avatar (M = 4.4, SD = 1.3) were also found to increase multi-sensory experience than no-physics self-avatar (M = 3.6, SD = 1.5). No significant difference ($p = 0.3$) was found between physics-aware (M = 4.1, SD = 1.2) and no-physics (M = 3.8, SD = 1.1) self-avatar in the ownership sub-measure.

4.2 Passive Interaction

H2 (preference). In passive interaction tasks, participants were asked to select with a slider of possible self-avatar motions: from no visible movement (*passive no physics*) up to the avatar falling down as a result of the hit (*passive physics fall*). Participants had to find the point on the slider where they felt most embodied. Using this type of test, we can detect the sensitivity of users as well as better understand the thresholds of perception.

All participants chose self-avatars that developed some physics motions. In other words, none of the 20 participants chose no-physics self-avatar as most embodied in either of the selection trials. This confirms our H2, where participants preferred physics-aware self-avatar over no-physics one in passive interaction. Figure 7 plots the distribution of selected physics correction in our passive interaction tasks. We omitted data from one participant (P19) whose selection of preferred physics correction is regarded as an outlier (above two standard deviations from overall distribution). The offset between physics self-avatar response and user input was calculated with the formula introduced in Section 3.1.

For the task to maximize embodiment, participants' chosen physics correction was 35.5 cm (SD = 10.0 cm) in *passive select #1* (selecting started from the self-avatar completely falls when hit) and 32.2 cm (SD = 10.0 cm) when in *passive select #2* (selecting started from no physics at all). No significant difference was found between the two selection trials. The difference between the selected average values was barely perceptible by participants and indicated sensitivity. On average, participants spent 95 seconds making one selection, indicating that they have a clear preference and found the task easy to complete (after initial familiarization with the slider operation and its corresponding avatar response).

H3 (embodiment). Figure 8 showed the result of embodiment rating in passive interaction tasks. We first performed a Friedman test and found a significant difference ($p < 0.05$) among the four

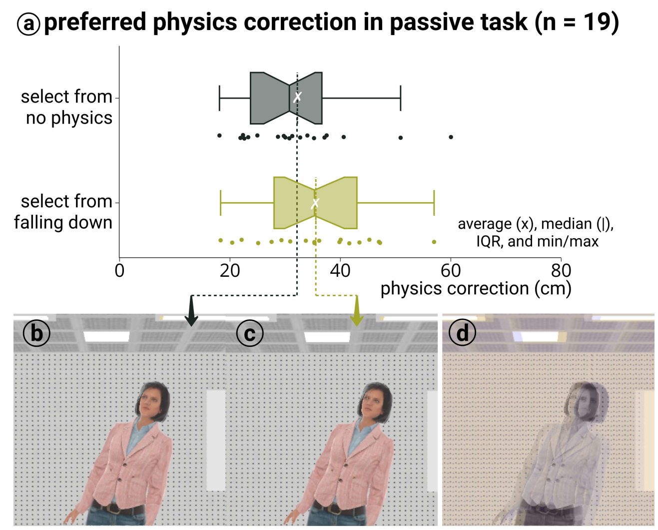

Figure 7: Preferred physics correction selected in passive tasks using the slider. (a) Distribution of selections with an outlier excluded. (b) and (c) Visualization of average preferred physics behavior that participants selected from the two ends. (d) Visualization of difference between the two preferred physics corrections.

tasks in overall embodiment score (*passive no physics*, *passive select #1*, *passive select #2*, *passive fall down*). Thus, pair-wise Wilcoxon rank sum tests with Bonferroni correction were conducted.

Specifically, we found a significant differences between *passive no physics* and *passive select #1* ($p = 0.01$), *passive no physics* and *passive select #2* ($p = 0.004$). This indicates physics-aware self-avatar (*passive select #1*: M = 3.8, SD = 1.2; *passive select #2*: M = 3.9, SD = 1.2) improved the sense of embodiment in passive interaction compared to *no physics* (M = 3.3, SD = 1.1).

Significant differences were also found between *passive no physics* and *passive physics fall* ($p = 0.003$), *passive select #1* and *passive physics fall* ($p = 0.00001$) and *passive select #2* and *passive physics fall* ($p = 0.00003$). It indicates that too much physics correction (e.g., falling down when hit by a ball) would rather drop the embodiment

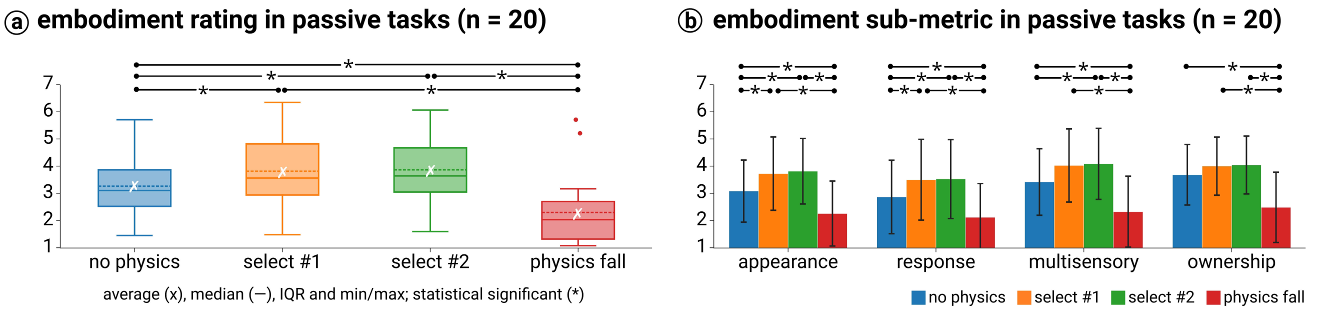

Figure 8: Embodiment in passive interaction for physics and no physics conditions. (a) overall ratings, (b) embodiment sub-measures.

level (M = 2.3, SD = 1.2) than improve it. This confirms our H3, and is aligned with literature on body semantic violations [62]. No significant difference was found between the two selected physics levels regarding embodiment rating (p = 1).

The sub-measures scores were analyzed using the same method as the overall embodiment score. After Friedman tests, significant differences were found in all four sub-scales: appearance ($p < 0.05$), response ($p < 0.05$), multi-sensory ($p < 0.05$) and ownership ($p < 0.05$). Thus, pair-wise Wilcoxon rank sum tests with Bonferroni correction were conducted. Table 1 in Appendix shows the detailed result of the pair-wise test.

In summary, all sub-measures except for ownership followed the trend of overall embodiment score. The physics-aware self-avatar (*passive select #1*, *passive select #2*) was found to increase attachment to the external appearance of the virtual body, develop a stronger response to external stimuli and improve the multi-sensory experience in passive interaction. Same as in active interaction, no significant differences were found between physics and no-physics-self avatar in the ownership sub-scale. Over-correcting the physics response (*passive physics fall*), on the other end, drastically decreased all four sub-scales, compared to the other three conditions. We consider the lack of difference in body ownership score as an indication of the good control that participants felt, even if their virtual bodies did not physically react as they would have expected.

4.3 Qualitative Feedback

Sense of presence. When controlling a no-physics self-avatar, most participants reported feeling less sense of presence and less engaged when they interacted with objects in the virtual environment in active interaction. For example, P3 described the experience as: "There was no sense of me actually going through the pillars because the virtual body didn't have any response to them. It didn't move at all, it walked like nothing was there." Similarly, P15 reported that: "The minute I noticed my body wasn't responding to the pillar in the way my real body wanted to (avoiding the pillar, leaning to the side), I stopped really noticing the pole was there." Such experience disassociated some participants from feeling the VR environment as real or feeling connected to the virtual body. "It doesn't make me feel real in terms of physics. The environment felt less real and interacting with it also felt less real", said P20. P10 added: "The second round [with no physics] I just walked through the pillar... I knew what I was supposed to feel (dodging the pillars), but I didn't feel it. So, it's easier to disassociate myself [from the virtual body]."

These comments all point back to the idea of plausibility [81]. In order to feel presence in an environment, the events in it need to be responding like they would do in reality. As we find in our experiment, this means (1) plausibility needs to include the self-avatar, and (2) it is very much connected to the physics between the environment and the self-avatar.

Similarly, in passive interaction (ball hitting), all 20 participants found the no-physics self-avatar to be less ideal with regards to the embodiment of the avatar, as well as the plausibility and presence. P19 described the experience as: "...there was no movement [from my body], and the only thing that moved was the ball. Physics didn't make sense." Similarly, P7 reacted with less sensitivity to its digital surrounding:" When [my body was] not moving at all, not sure what the ball behavior was. Not sure if it's hitting me." P13 added that "when the body didn't move at all, it's unrealistic." P11 described:"If I am gonna be hit by a big ball, at least I am gonna move. If the avatar didn't move, [it] seems the ball was not affecting avatar at all."

Sense of embodiment. When walking through poles, the physics-aware self-avatar developed avoiding behavior. This behavior matched many participants' expectations, even though their own bodies didn't follow that motion. Such avatar behavior can have different effects on embodiment and how participants integrate their virtual body as their own. P15 for instance, said that:"my first instinct was to avoid the pillar [myself], and my virtual body was also doing so; I felt more so that my virtual body is an actual manifestation of myself." The way self-avatar interacted with the obstacles not only impacted on the perceived embodiment level of some participants, but also created visual-driven haptic illusion: "I felt more embodied in the first trial [with physics] where I dodged the pillar. Because the pillar looks metallic and heavy, the fact that I have to dodge that, it enforces the illusion of touching it and it's a physical thing." said P10. When comparing with the no-physics self-avatar, P1 said:"There were obstacles and my body should avoid them... Even though I didn't do the avoidance, it felt like it's my own movement. The first [no-physics] one is closer to my own movement but I like the second [physics] one more." 3 out of 20 participants (P1, P14, P16) also mentioned that the behavior of the self-avatar influenced their own movement. "I can see the avatar avoiding the pillar... I tried to align my body with the avatars to avoid the pillars", said P14.

While physics-responsive self-avatars develop more natural behavior, some participants pointed out the discrepancy between their input and self-avatar's motion broke their experience. P17, for instance, said:"...the avatar was affected by the pillar, but my own body was not, so there was some disconnectivity there". These discrepancies further lead to self-agency issues in the virtual body: "the avatar has its own autonomy and was avoiding the pillar, even when I was not doing that" said P16. P12 further added that: "When I bumped into the pole, the avatar was no longer in my control and it was in the program control. That's not what I imagined I was moving. There was something else taking over me."

Nevertheless, no-physics self-avatar is not without benefits. Almost half of the participants (8 out of 20) reported that they felt more synchronization between their motion and self-avatar motion with no-physics self-avatar. P5 described it as "the virtual body moved exactly as real body moved" and P26 added that "I felt more of my body. The avatar was more aligned with my own body." As upon the interaction with the pillars, P7 said: "I felt more control of the body. I could move whatever I want, but I couldn't feel the pillar." P11 further elaborated that: "[no physics] one was intuitively not physical because the virtual body can pass through obstacles. But from a user perspective, it felt more natural because there was no deviation between the virtual [movement] and physical input."

This shows a possible duality and trade-off in active interaction, where we need to include physics at some point to increase plausibility and embodiment, but that could decrease the subjective control users might feel over the avatar. Maybe overtime, users will start to compensate this dissociation in the body by unconsciously activating a self-avatar follower effect [31]. However, we did not observe such activation in our current experiments.

As for passive interactions, all participants chose self-avatar with certain physics corrections to be more embodied. When asked about their criteria for selecting the most embodied physics level, many participants made selections based on how they imagined themselves would react to the ball. P8 described it as: "unconsciously thinking how I will react to it." P13 added: "I envision myself that when I get hit, I would move a little bit but not too much". Similarly, P6 focused on "how in sync my body is compared to the avatar movement". "I tried to move intentionally to see how much movement I would make and then select the closest one to my movement", said P6. How realistic the reaction is also an important factor. "It needs to move but not too much", said P20.

Experiencing over-corrected self-avatar motions. While physics-aware self-avatar improves embodiment, over-correcting the physics behavior could backfire. When participants experienced self-avatars that completely fell down after a hit, participants expressed that the movement was "too exaggerated" (P6, P10) and even "ridiculous" (P19, P20). "I don't expect my body to fall just with a ball", said P13. P2 added:"it feels like my virtual body deviates from my physical body because it fell on the floor and I was still standing." 13 out of 20 participants expressed that they would even favor no-physics self-avatar to the one that over-corrects. "I didn't feel the presence of the ball [with no-physics self-avatar], but at least I felt that I was in the game", explained by P4. For participants that favored the fall-down behavior over no-physics (P1, P8), P1 elaborated that:"Because it at least gave me something. There was a ball, I should at least do something." P8 added: "I might fall like this with this size of the ball." The remaining 5 participants didn't hold a strong preference between the two as they regarded both as sub-optimal.

These comments are in agreement with research reproducing anarchic hand illusions inside VR, where people lose control of their hand while performing a rapid decision motor task [62]. In these experiments, researchers found that the embodiment illusion breaks after body semantic violations.

5 DISCUSSION

In this section, we first discuss the insights derived from our experiment results. Then, we uncover applications that could be benefited from our findings and how our results translate to applications where users might not pay full attention to virtual body. Lastly, we discuss limitations of this paper and directions for future work.

5.1 Embodiment, Presence and Environment Awareness

Embodiment in virtual reality is an illusory body ownership toward an avatar. Past research uncovered multiple factors that drive embodiment illusion, such as visual perspective, sensorimotor contingency, and external appearance [25, 57, 84]. In this work, we extend beyond considering the virtual body as a singular entity isolated from its environment, and introduce physics-driven body reactions to self-avatar. The VR environment is often the key to presence, which is a combination of place illusion (i.e., feeling being there) and plausibility illusion (i.e., the events happening are real).

The joint aspects of embodiment and presence create an intrinsic need to balance the bodily and the environmental factors. On one hand, we need to preserve the agency of our actions and intentions in VR (sensorimotor contingency and motor control loops [26]), and on the other hand, we need to have a sense of "being there", and believing events happening are real (i.e., physics motion that react to the environment stimuli).

Our results showed that adding physics correction to self-avatar motion generally improves embodiment in upper body tasks. We observed improvement in all sub-scales of embodiment except for the ownership measures in both active and passive interactions. The ownership sub-measure is tightly related to the control, location, and visual features of the virtual body. We regard the lack of difference in ownership sub-scale as an indication of a good control that participants felt when embodying both physics-aware and no-physics avatars. While physics-aware avatars introduce a visual-proprioceptive mismatch, decreasing the control of participants on virtual body movement, the ownership sub-scale results showed that physics correction does not compromise virtual body ownership. Rather, participants were able to accept a certain level of visual-proprioceptive mismatch in trade with behavioral realism of their virtual body when encountering physical impacts. Our results also showed that over-correction in physics would backfire and decrease overall embodiment level.

Although we did not have a direct metric for presence, we found a clear preference for the realism introduced by the physics in the passive interactions. Additionally, we see reports of stronger presence feelings when embodying physics-aware self-avatars in the qualitative interview. The increase in presence could be due to the increased embodiment, as it is known to be positively correlated with presence; but it could also be directly associated with the increased plausibility of the interaction with environment stimuli.

In summary, our work shows the importance of preserving environment awareness when embodying a virtual avatar in VR in order to maintain the plausibility of the experience, and ultimately improve user's embodiment and presence. It is another step to push toward the reality-based interaction paradigm proposed by Jacob et.al. [39]. Beyond focusing on factors determining "body awareness" (awareness of own physical body and skills for controlling bodies), physics correction introduces "environment awareness" (sense of the surroundings and skills for manipulating within the environment). Our finding showed that preserving environment awareness through physics-responsive self-avatar does not compromise body awareness but rather improves embodiment.

5.2 Applying Physics Correction to Modify One-to-one Mapping

Our interaction with the VR world heavily relies on sensorimotor loops, in which the sensory afferent feedback, mainly in the form of visual and audio information from the headset, needs to align with the user's motor actions. When adding physics correction to the motion of self-avatars, it could lead to a visual-proprioceptive mismatch, by which one-to-one mapping of motion is disrupted, and the avatar does not completely match with the real body (shown in Figure 9).

This is an increasingly relevant issue in VR as the interaction techniques become more advanced, such as when introducing AI-driven motions to improve the performance of users [7], or when reducing tracking power and relying on inverse kinematics [19]. However, not all the subproducts of modifying one-to-one mapping are negative. In fact, these types of dissociation have been exploited to drive haptic re-targeting techniques and even can generate self-avatar follower effects.

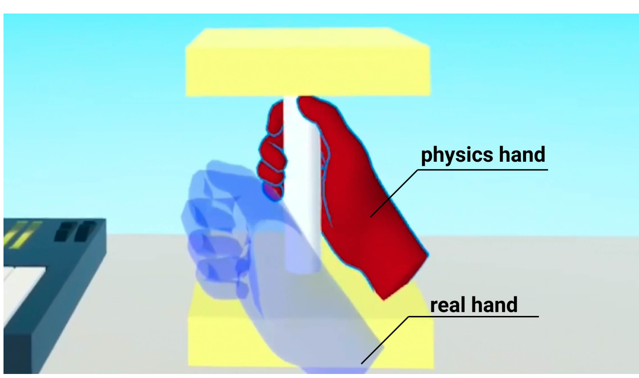

Figure 9: Visual-proprioceptive mismatch created by adding physics correction to avatar motion. Using hands as an example, when a user is grabbing an object, the physics hand leaves on the surface of the object while the actual hand might already penetrate.

As the first step to investigate how physics-aware avatars impact on embodiment, we focused on upper body tasks (i.e., physical impacts happening on the shoulder) in our current study. This decision allows us to study with mainstream consumer-level VR headsets, which only tracks head and palm orientation, as a baseline. More importantly, those upper body tasks lead virtual avatar to develop a wider range of offsets from the actual user input, compared to tasks using hands alone. In our study, we also used a virtual mirror to have a constant and clear display of self-avatar's upper body pose and amplify the user's bodily awareness. We could see the use of a mirror as a proxy for applications that require high attention to the virtual upper body's response in relation to the environment. We imagine our study results maybe be used to enhance upper body embodiment in applications where the user has a good view of their virtual upper body, such as physical training, rehabilitation, or seeing their body reflection on a windshield. In those scenarios, users naturally focus on their upper bodies in relation to the stimuli from the environment. Future work is needed to explore generalization of the findings to other body parts such as lower limbs.

5.3 Awareness of Physics Correction

On some occasions, when the physics motion of the self-avatar are not perceived by the users, the gains on embodiment might be lost. On the other hand, we hypothesize that the negative effects of not providing correct physics would also not be visible when participants do not see their bodies.

Beyond counting on full attention from the VR users, the physics impact on self-avatar body is also likely to be more noticeable when VR hardware advances in its field of view (FOV). The head-mounted display we used in our study is a popular commercial headset (Oculus Quest 2), which has a 104° horizontal FOV and 98° vertical FOV [3]; this is far less than FOV of human eyes (210° horizontal and 150° vertical) [88]. The increase in FOV of head-mounted displays would likely allow users to be more aware of the changes in their bodies after physical impact [59]. As HMDs achieve a larger vertical field of view, we also believe that the issues of not having physics on avatars will become more prominent.

Of course, there are always situations in which the users may absorb themselves into other tasks and not notice the physics impact on their virtual body even when it is visible [55]. We can envision several ways in these cases to extend the reach of physics reaction information to the users through multi-sensory channels and sensory augmentation. (a) Directional audio can guide the attention of the users to the affected body part so that they are aware of the physical impact on the virtual body. (b) Directional visual effects, such as a glow, flying embers from the impact location, or visualized wave, can also guide the user's attention. (c) Augmenting hand or body motions. In general, the hands are the most visible parts of the avatar's body, and the reaction to physical stimuli can be revealed in their movement to make it more visible. While there are many other ways we could possibly remap the virtual body physics reaction to enhance the noticeability, its impact on embodiment is subject to further investigation.

5.4 Limitations and Future Work

As we made the first step to investigate the influence of physics correction on embodying a virtual avatar, in this section, we lay out out some promising opportunities for future work to build upon our findings.

Impact on various body parts. In this study, we focused on investigating its impact on embodiment when the stimuli hit on the upper body. Although we conducted pilot studies on the lower body as well, we found the baseline embodiment was largely compromised by the limited tracking of the selected VR headset, which only provides head and palm orientation. The decision to focus on upper-body tasks allows us to study with mainstream VR headsets and state-of-the-art IK solver as a baseline. However, physics is an interaction between the full body and the environmental stimuli and can happen anywhere on the virtual body, as shown in Figure 10. Future work could look into the sensitivity of different body parts to physics correction and should first guarantee a good tracking of that studied body parts. Moreover, in our experiments examining the effect of physics correction on embodiment, we provided a constant view of the avatar upper body. While some applications, such as training and rehabilitation, may enable such display, users in many other applications might only have a partial view of their self-avatar (e.g. limbs only, or objects held by the hands). We wish to extend the experiments to different partial views of the self-avatar, and examine the possible generalization of this effect to more applications.

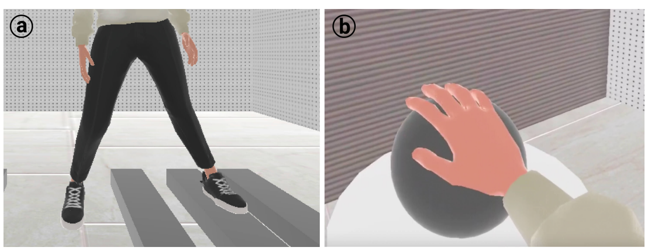

Figure 10: Physics reaction on other parts of the virtual body. (a) Foot when stepping on floors with protrusions. (b) Hand when touching a rigid sphere.

Stimuli properties. Our participants only interacted with one type of object in each interaction type in the current study (i.e., metallic bars in active interaction and balls in passive interaction). Different textures, shapes, or sizes of objects could influence people's expectations of how much their bodies should react. We believe our work provides grounding for future work investigating how different object properties and body's physics reaction influence embodiment.

Avatar customization. In our study, we did not customize the avatar based on each participant's visual appearance and only matched participants with a general humanoid avatar of the same gender. While visual appearance mismatch could impact embodiment, participants in our study underwent all conditions with the same avatar. Considering this within-subject nature, we do not consider the avatar selection affects the relative difference we observed in embodiment between physics and no-physics avatars. Future work could explore better matching self-avatars with users' appearances to further improve the experience when users embody a physics-aware avatar.

User attention. We leveraged a virtual mirror in the study to ensure participants to notice the physical impact on their virtual bodies. This allows us to single out physics correction from other confounding factors. On the other hand, we also acknowledge that there are situations where participants barely pay attention to their virtual bodies. In such cases, users need to be notified about the physical impact of physics-aware self-avatar taking effect to improve embodiment. In Section 5.3, we listed some potential ways to achieve such notification, and future work could explore the full design space and user preference.

Alternative metrics for embodiment. Last but not least, this work focused on subjective measures of embodiment through questionnaires. Objective metrics of embodiment, which past work showed a correlation with subjective rating from questionnaires [36, 62], was not explored. Future work could deepen the evaluation with physiometric measures, such as heart-rate monitors, skin-conductance, and electroencephalogram, to better understand the impact of physics correction. Another promising direction is to investigate how embodying physics-aware avatar impacts on task performance in VR.

6 CONCLUSION

Physics between our body and the surrounding environment is an essential part of our daily interactions. One-to-one mapping between user's and self-avatar's motion in VR, however, often leads to unnatural behavior without physical meaning. Adding physics correction, in turn, creates a discrepancy between the user and self-avatar motion, whose synchrony is a determining factor for embodiment in VR. In this work, we evaluated the impact of physics-aware self-avatar on the embodiment. We conducted a within-group study, where participants engaged in active and passive interaction tasks with and without physics correction on self-avatar's motion. Our results showed that physics correction, while introducing a visual-proprioceptive mismatch, improves embodiment level. The results highlighted the importance of preserving environment awareness while embodying a virtual body. Last but not least, we discussed how to translate our results to VR applications with and without full attention from users on their virtual bodies.

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APPENDIX

		no physics vs select #1	no physics vs select #2	no physics vs physics fall	select #1 vs select #2	select #1 vs physics fall	select #2 vs physics fall
appearance	**M ± SD**	3.1 ± 1.1	3.1 ± 1.1	3.1 ± 1.1	3.7 ± 1.3	3.7 ± 1.3	3.8 ± 1.2
	M ± SD	3.7 ± 1.3	3.8 ± 1.2	2.25 ± 1.2	3.8 ± 1.2	2.25 ± 1.2	2.25 ± 1.2
	p-adj	**0.010**	**0.002**	**0.005**	1	**0.002**	**0.0001**
response	**M ± SD**	2.9 ± 1.4	2.9 ± 1.4	2.9 + 1.4	3.5 ± 1.5	3.5 + 1.5	3.5 ± 1.5
	M ± SD	3.5 ± 1.5	3.5 ± 1.5	2.1 + 1.2	3.5 ± 1.5	2.1 + 1.2	2.1 ± 1.2
	p-adj	**0.029**	**0.034**	**0.007**	1	**0.001**	**0.001**
multi-sensory	**M ± SD**	3.4 ± 1.2	3.4 + 1.2	3.4 + 1.2	4.0 ± 1.3	4.0 + 1.3	4.1 ± 1.3
	M ± SD	4.0 ± 1.3	4.1 ± 1.3	2.3 + 1.3	4.1 ± 1.3	2.3 + 1.3	2.3 ± 1.3
	p-adj	0.103	**0.042**	**0.003**	1	**0.00002**	**0.001**
ownership	**M ± SD**	3.7 ± 1.1	3.7 ± 1.1	3.7 ± 1.1	4.0 ± 1.1	4.0 ± 1.1	4.0 ± 1.1
	M ± SD	4.0 ± 1.1	4.0 ± 1.1	2.5 ± 1.3	4.0 ± 1.1	2.5 ± 1.3	2.5 ± 1.3
	p-adj	0.168	0.27	**0.008**	1	**0.0009**	**0.002**

Table 1: Sub-measures of embodiment rating for passive interaction