The Effects of Body Tracking Fidelity on Embodiment of an Inverse-Kinematic Avatar for Male Participants

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Abstract

Many research studies have investigated avatar embodiment and its effects on self-location, agency, and body ownership. Researchers have also investigated the effects of various external stimuli and avatar appearances during embodiment. However, the effects of body tracking fidelity while embodying an inverse-kinematic avatar are relatively unexplored. In this paper, we present two studies using a set of six trackers that investigate four levels of body tracking fidelity during avatar embodiment for male participants only: Complete (head, hands, feet, and pelvis trackers), Head-and-Extremities (head, hands, and feet trackers), Head-and-Hands (head and hands trackers), and No-Avatar (head and hands trackers; only controllers visible). Our results indicate that tracking the head, hands, and feet significantly increases the sense of embodiment and the sense of spatial presence when embodying an inverse-kinematic avatar for male participants.

Keywords: Embodiment, virtual reality, body tracking fidelity, avatars.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies

1 Introduction

The sense of *embodiment* toward a virtual body is the sense that emerges when the properties of that body are processed as if they were the properties of one's own physical body [24]. Kilteni et al. [24] have identified three structures underlying embodiment: self-location, agency, and body ownership. *Self-location* refers to localizing oneself within the spatial borders of a body [2]. *Agency* refers to intending and executing actions, including the feelings of controlling one's own body movements and, through them, events in the external environment [60]. Body ownership is the sense that one's own body is the source of sensations [60].

Current embodiment research originated with Botvinick and Cohen's research on what has become known as the "rubber hand illusion" [5]. They investigated the effects of visuotactile stimulation of a rubber hand that was located near the participant's real hand. They found that participants experienced an induced sense of ownership of the rubber hand. The rubber hand illusion has since sparked a large body of research on inducing embodiment of virtual limbs and bodies.

Much embodiment research is now conducted in the virtual reality (VR) domain. Researchers have investigated both *congruent* (i.e., co-located) [48, 49, 58] and *incongruent* (i.e., not co-located like the original Rubber Hand Illusion) [38, 42, 61] virtual bodies in studies of different stimulation techniques. Means of inducing embodiment beyond visuotactile stimulation have been investigated, including threat stimulation [13], avatar fidelity [23], and visuomotor stimulation [56]. Banakou and Slater [4] have shown that visuomotor stimulation alone is effective in inducing embodiment, and many studies have relied on inducing embodiment with body tracking alone [9, 27, 41–43, 46–48, 50]. Other researchers have investigated the effects of body tracking on embodiment beyond simply whether it is provided or not. Prior studies have investigated inverse kinematics (IKs) versus full-body motion capture [11, 53], tracking latency [20, 26, 51, 59], tracking noise [26, 59], and tracking errors [20, 26, 59]. However, different levels of IK body tracking fidelity have not been previously investigated.

In this paper, we present novel research investigating the effects of body tracking fidelity and avatar presence on inducing embodiment of a congruent, full-body IK avatar. We conducted two studies to compare varying levels of tracking fidelity and avatar presence. The results from our studies show that full-body tracking improves embodiment scores for a congruent, IK avatar for male participants. We also found that while a pelvis tracker is not required for high levels of embodiment, foot tracking is essential. We discuss these results and how full-body tracking should be implemented when embodiment is important in dynamic scenarios. We also discuss the limitations of our small, non-representative sample.

2 Related Work

In this section, we discuss several aspects of prior research on embodiment evaluation and their designs in VR, mixed reality (MR), and real-world studies. For those readers interested in a more in-depth discussion of embodiment, we recommend reading the survey work of Gonzalez-Franco and Peck [12].

2.1 Evaluations of Embodiment

To better understand embodiment stimulation techniques and measurement techniques, we have reviewed many studies on inducing embodiment and its effects. These included studies performed in the real world, MR, and VR.

Of the studies, several involved passive observation from the participant without moving (e.g., [5, 19, 35, 55]). A number of these studies did not allow the user to move their head. The majority of the studies are direct evolutions of the original rubber hand illusion study [5], while the other research evaluate embodiment using other techniques. Two other methods are used to elicit an embodiment response, visuomotor stimulation and threat stimulation. It has been shown that visuomotor stimulation is enough to induce embodiment and often improves the sense when compared to just visuotactile stimulation [28]. Threat stimulation has been shown to induce embodiment when

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presented without visuotactile or visuomotor stimulation [13]. First-person perspective may be a major factor in full-body embodiment [38, 47, 56]. Table 1 compares the studies that we reviewed to our current work, in terms of the perspectives and factors investigated.

Table 1. Comparison of related work and our work in terms of the user's perspective and factors affecting embodiment.

	Perspective		**Embodiment Factors**				
Studies	**Third-Person**	**First-Person**	**Visuotactile**	**Threat**	**Visuomotor**	**Avatar Fidelity**	**Tracking Fidelity**
[7, 17, 33]	X		X				
[8]	X		X	X			
[54]	X		X		X		
[58]	X				X	X	
[38]	X	X	X				
[46, 56]	X	X	X	X			
[6]	X	X	X	X	X		
[9, 27]	X	X			X		
[11]	X	X			X	X	X
[10]		X					
[5, 19, 35, 40, 55]		X	X				
[47, 49]		X	X	X			
[28, 29]		X	X	X	X		
[25]		X	X		X		
[34, 37]		X	X		X	X	
[18]		X	X			X	
[13]		X		X			
[14]		X		X	X		
[1, 36]		X		X	X	X	
[4, 41, 42, 45, 48, 50]		X			X		
[3, 15, 21, 23, 30, 31, 43, 52, 61]		X			X	X	
[51]		X			X	X	X
[20, 26, 53, 59]		X			X		X
Our Work		**X**			**X**	**X**	**X**

2.1.1 Embodiment Perspectives

Most studies seem to focus on first-person perspectives as a result of the greater prevalence of VR head-mounted displays (HMDs) in recent years. Third-person perspective studies grew out of the original rubber hand illusion study [4] investigating the effects of visuotactile stimulation on an incongruently located limb. Most of the third-person perspective studies investigate visuotactile stimulation on an entirely separate mannequin or virtual body. Our current studies focus on first-person perspectives, using an HTC Vive Pro.

2.1.2 Common Embodiment Factors

There are four main factors of embodiment stimulation that prior studies have investigated: visuotactile, visuomotor, threat, and avatar visual fidelity. The majority of early research focuses on visuotactile stimulation with visuomotor stimulation tending to be evaluated later in immersive VR studies. Threat-induced embodiment research has had intermittent combined investigation with other stimulation techniques, and one study has investigated the effects of threat independently [13]. Most investigations into the effects of avatar fidelity on embodiment have been more recently evaluated, but some initial embodiment research investigated the effects of avatar fidelity early on [34].

2.1.3 Tracking Fidelity Factors

Some researchers have investigated the effects of body tracking on embodiment, beyond simple visuomotor stimulation. Roth et al. [53] compared a five-point (head and extremities) IK tracking solution to a full-body motion capture system and found no significant differences between the two tracking conditions in terms of agency and body ownership. In a recent study, Fribourg et al. [11] found that users significantly preferred full-body motion capture to a six-point (complete) IK tracking solution. However, it is important to note that they implemented their IK condition using an inertial motion tracking system, which is prone to drift (i.e., error accumulation) [32]. In our study, we used the HTC Vive Pro tracking system, which relies on optical tracking.

Aside from IK tracking versus full-body motion capture, researchers have also investigated tracking issues related to latency, noise, and errors. Jeunet et al. [20] found that separately inducing both tracking latency and errors caused agency scores to significantly decrease. In a similar study, Koilias et al. [26] found that tracking noise, latency, motion jumps, and offset rotations all significantly reduced agency during self-observations and mirror-based observations, but not observations during locomotion. In another study, Toothman and Neff [59] found that latencies greater than 300 ms significantly reduced embodiment, but they did not find any significant effects of tracking errors alone. Roth and Latoschik [51] have found that increased latency significantly reduces both agency and body ownership.

In our current work, we investigate three embodiment factors: visuomotor, avatar fidelity, and tracking fidelity. We use a full-body IK avatar to provide visuomotor cues. We also vary avatar fidelity, by investigating a controllers-only representation, which is common in many consumer VR applications. Finally, we investigate the effects of tracking fidelity on embodiment of our IK avatar, by varying which trackers control the IKs.

2.1.4 Effects of Embodiment

A number of studies have also investigated inducing embodiment to observe its effects. Researchers have evaluated the effects of embodiment on task performance [34, 42], behaviour [10, 23, 50], size and distance estimation [18], racial bias [3, 43], and self-counselling [9, 41].

2.2 Body Tracking Techniques and Modifications

Though our work is the first to investigate the effects of tracking on embodiment, prior studies have employed a wide range of tracking techniques and tracking modifications. Table 2 provides a summary of these tracking techniques and modifications.

2.2.1 Tracked Body Segments

Some prior studies involved no body tracking and relied on static positions, such as the original rubber hand study [5]. Several VR studies have used only head tracking to provide the user with the capability to look around. Other studies have also only used head and hand tracking. A few studies have used head tracking with some combination of hands, feet, and torso while some studies tracked all four body segments [11, 15, 17]. Finally, many studies used motion capture techniques to provide full-body tracking, as opposed to relying solely on consumer VR tracking technologies.

Table 2. Comparison of related work and our work in terms of body tracking and any tracking modifications.

	Body Tracking					**Modifications**		
Studies	**Head**	**Hands**	**Feet**	**Torso**	**Full-Body**	**Calibration**	**IKs**	**Mirror**
[5, 8, 18, 19, 35, 46, 47, 55]								
[7, 10, 13, 21, 33, 38, 56]	X							
[27, 45]	X							X
[48]	X					X		
[1, 20, 34, 37, 40, 50]	X	X						
[42, 49]	X	X					X	
[14]	X	X					X	X
[25]	X	X				X	X	
[28]	X		X				X	
[6]	X	X	X				X	X
[53]	X	X	X			X	X	X
[54]	X			X				
[23]	X	X		X		X		
[15]	X	X	X	X			X	
[17]	X	X	X	X		X		
[11]	X	X	X	X		X	X	X
[3, 9, 41, 43, 59]					X	X		
[4, 26, 29–31, 36, 51, 52, 58, 61]					X	X		X
[11, 53]					X	X	X	X
Our Work	**X**	**X**	**X**	**X**		**X**	**X**	

More recent research has focused into more immersive systems. This means that more body segments are typically tracked. The real-world studies [5, 35] and some of the MR studies, with large displays [55], projectors [19], and camera feeds [8, 18, 46, 47], track few or no segments and only evaluate a participant's passive observations of an artificial body.

More recently, studies began to start implementing more than just head and hand tracking. Since the introduction of consumer VR HMDs, many studies have implemented more than head and hand tracking. Of these studies, two investigated embodiment effects of just the legs and feet [28, 38], some have investigated partial-body racking involving more than head and hand tracking, and several featured full-body motion capture. Only three studies, to the best of our knowledge, have investigated embodiment effects with head, hands, feet, and torso tracking [11, 15, 17].

In our study, we use the HTC Vive Pro HMD and controllers to track the user's head and hands, respectively. We also used three Vive trackers to track the user's feet and pelvis.

2.2.2 Tracking Modifications

There are three main modifications used in VR to alter the perception of tracking: avatar calibration, inverse kinematics, and virtual mirrors.

Avatar calibration happens when the virtual avatar is scaled to the participant's body segment lengths and sizes. In several studies, researchers discussed that avatars were calibrated to the participants, and only a few did not use full-body motion capture.

Inverse kinematics (IKs) algorithms are used to approximate the location and orientation of in-between joints given known locations of end joints. Only nine studies talk about implementing some form of IKs for the virtual avatar. Of these studies, two implemented IKs for the arms [14, 42], one implemented the legs [28], two implemented the upper body [25, 49], and four implemented the arms and legs [6, 11, 15, 53].

Virtual mirrors are used in a number of studies to provide an indirect view of the virtual avatar to the participant, and the mirrors work in the same manner as their real-world counterparts. This view allows participants to observe their body being tracked without directly looking down. From our review, we found several studies that implemented a virtual mirror.

3 Experimental Design

The goal of our research was to evaluate the effects of body tracking fidelity on embodiment of an IK avatar. We created our IK avatar by using RootMotion FinalIK and VRIK component, a commercially available full-body solver designed for consumer VR. We used an HTC Vive Pro HMD, controllers, and three additional trackers to provide the head, hand, feet, and pelvis tracking for the solver. We were able to investigate the effects of tracking fidelity by disabling the trackers to force the full-body solver to approximate those missing body segments. Additionally, we also investigated a condition with no avatar and only visual representations of the controllers, which is common in consumer VR applications and prior embodiment studies [45].

3.1 Tasks

We developed a VR application designed to investigate virtual avatar body parameter values and to provide a simple coin-collection game task for virtual avatar observation. The application replicates a small office environment (4m x 4m), in which the participant is able to move around and observe their avatar. In order to avoid potential confounds due to the skin color of the avatar not matching the participant's skin color, we placed a pair of winter gloves on the virtual avatar. We then placed a frosty window with a view of a snowy outdoor scene in our office environment to provide a rational explanation for the gloves.

Figure 1: The virtual office environment used in our research.

Our application involved two tasks completed in succession: adjusting parameters of the virtual avatar body and then collecting coins randomly placed around the environment in a minigame. For the first task, the application presented the user with a floating window of sliders. Each slider was labeled identifying which parameter of the virtual avatar it controlled. For our studies, we investigated the following adjustable parameters: elbow position, knee position, arm length, and leg length. These parameters correspond to the arm `bendGoalWeight`, leg `bendGoalWeight`, `armLengthMlp`, and `legLengthMlp` variables of the FinalIK VRIK solver, respectively. Participants were encouraged to manipulate each slider to experience what each slider changes on the virtual avatar. Once the participant had chosen the body parameter values that they felt were the most realistic, they selected the "Next" button to start the second task.

The second task presented a coin-collection minigame in which the participant was encouraged to collect as many coins as possible in one minute. The coins appeared every five seconds with a spatial audio chime to aid in discovery. Coin placement varied to provide a diverse range of motion to participants during the collection process, and placements were randomly ordered to avoid potential learning effects. Participants had to walk, reach up, lean, crouch, and turn to collect all the coins. The intent of this task was to provide movement tasks for the participant to observe how their virtual avatar moves (see Figure 2).

These two consecutive tasks described above were repeated for a total of three times per tracking fidelity condition. Repeating the tasks allowed participants to refine and reevaluate their virtual avatar body parameters during the repetitions after experiencing movement during the first coin-collection minigame. At the end of the condition, a window was displayed asking the participant to choose the iteration that they thought was the most realistic. This process was repeated three times, once for each condition.

Figure 2: First-person perspective of our coin-collection minigame.

Figure 3: The physical setup used for our two studies.

3.2 Materials

We used an HTC Vive Pro system, including the HMD, two handheld controllers, and three additional Vive trackers, to run our VR application. The Vive Pro HMD provided 110° diagonal field of view with a display resolution of 1440 x 1600 pixels per eye and a 90Hz refresh rate. The additional trackers were attached to participants using straps at the arch of each foot and at the waist (see Figure 3). The application was developed using Unity and maintained a framerate of 90 frames per second (fps) to match the Vive Pro HMD refresh rate. Based on recent research [57], the motion-to-photon latency of our system was approximately 55 ms. The SteamVR plug-in for Unity was used to process the Vive input data, and the FinalIK plug-in was used for the IK avatar.

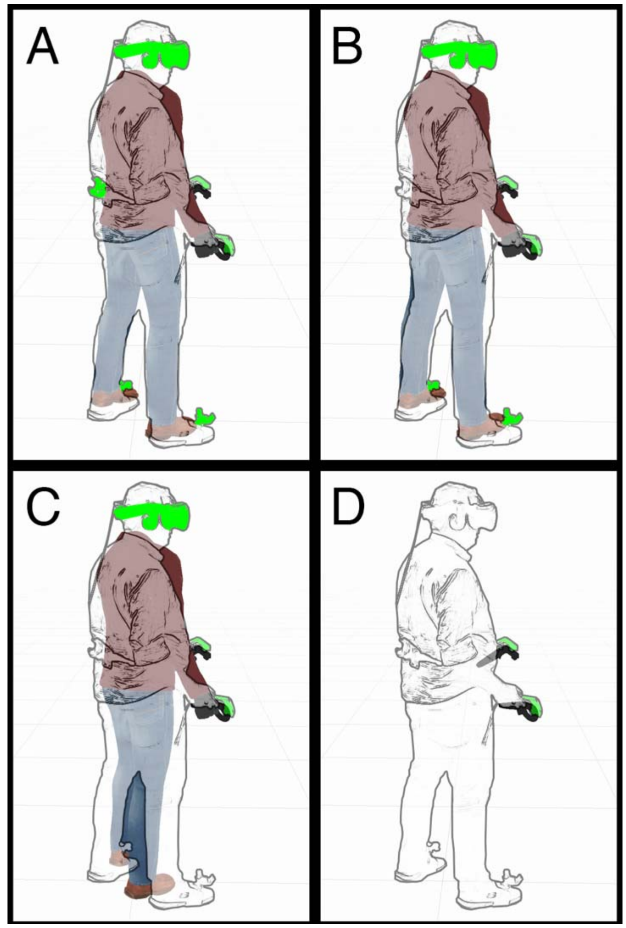

Figure 4: The four body tracking conditions investigated in our research: A) Complete, B) Head-and-Extremities, C) Head-and-Hands, and D) No-Avatar. Active IK trackers are highlighted green.

3.3 Independent Variable

For our research, our within-subject independent variable was body tracking fidelity for the IK avatar. In total, we investigated four levels of body tracking fidelity: Complete (head, hands, feet, and pelvis tracking), Head-and-Extremities (head, hands, and feet tracking), Head-and-Hands (head and hands tracking), and No-Avatar (head and hands tracking but only controllers are visible). In the **Complete** condition, the full-body avatar was controlled by all six devices, including the pelvis tracker, which better approximated the bend of the participant's knees (see Figure 4A). In the **Head-and-Extremities** condition, the pelvis tracker was disabled, but the avatar's feet were still controlled by the participant's tracked feet (see Figure 4B). In the **Head-and-Hands** condition, the feet and pelvis trackers were disabled, so the feet positions and orientations were estimated by an algorithm that auto-stepped at a distance threshold to keep the feet under the head (see Figure 4C). Finally, in the **No-Avatar** condition, the participant could only see the two virtual handheld controllers without any other avatar representation (see Figure 4D).

To avoid burdening our participants with too many conditions and a lengthy procedure, we decided to investigate our four body tracking conditions across **two studies**, using the Complete and No-Avatar conditions as high- and low-fidelity controls in both studies. The first study also investigated the Head-and-Extremities condition, while the second study also investigated the Head-and-Hands condition (see Table 3). The within-subject conditions were counterbalanced between subjects, using the full-factorial permutation, to negate any potential ordering effects.

Table 3. Overview of our tracking conditions across both studies.

Fidelity	Condition	Study 1	Study 2
Highest	Complete	X	X
High Mid	Head-and-Extremities	X	
Low Mid	Head-and-Hands		X
Lowest	No-Avatar	X	X

3.4 Dependent Variables

After completing each condition in the VR application, we administered three questionnaires via Qualtrics at a nearby computer: the Simulator Sickness Questionnaire (SSQ) [22], the Spatial Presence Experience Scale (SPES) [16], and a 10-question embodiment questionnaire (see Table 4). The SSQ was given to ensure that participants were not experiencing moderate to high levels of simulator sickness that would warrant expulsion from the study for their safety. The SPES was used to measure the participant's sense of presence during the VR experience.

Table 4. The list of embodiment questions used in our studies and the underlying structures that they address. Each question was ranked from 1 ("I do not agree at all") to 5 ("I fully agree").

No.	Embodiment Question	Structure
1	Overall, I felt as if my body was located where I saw the virtual body to be.	Self-Location
2	Overall, I felt that the virtual body was my own body.	Body Ownership
3	The movements of the virtual body were caused by my movements.	Agency
4	It seemed as if I might have more than one body.	Body Ownership
5	Overall, I felt that the virtual body belonged to someone else.	Body Ownership
6	I felt like my body was actually there in the environment.	Self-Location
7	I felt like my body appeared in the environment.	Self-Location
8	I felt like my bodily movements occurred within the environment.	Agency
9	I felt like my body affected the environment.	Agency
10	I felt like the environment affected my body.	Body Ownership

The embodiment questionnaire was administered to measure the level of embodiment that participants experienced with the IK avatar during each tracking fidelity condition. In general, researchers have used a wide array of questions to assess embodiment and many are scenario specific (e.g., [7]). Gonzalez-Franco and Peck [12] have systematically reviewed the literature for embodiment questions and have proposed a standardized questionnaire. We selected a subset of five questions from their embodiment questionnaire (#1-5 in Table 4). We also included five embodiment questions that we modeled after the SPES question structures (#6-10 in Table 4). Each question was ranked from 1 ("I do not agree at all") to 5 ("I fully agree").

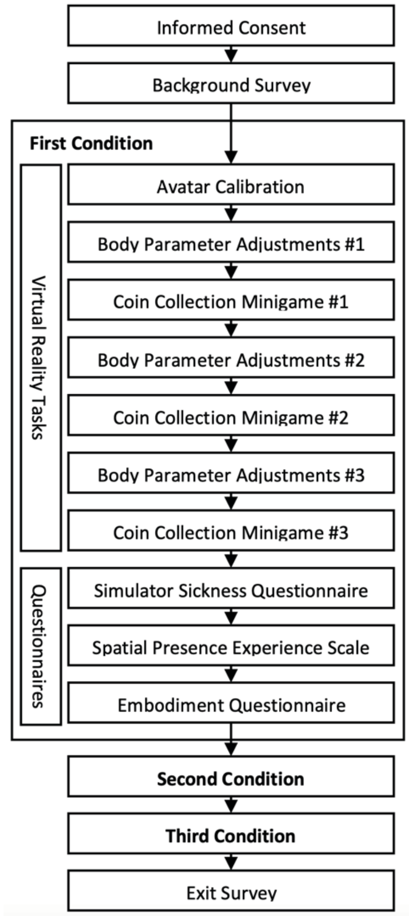

Figure 5: A flowchart of our study procedure.

3.5 Procedure

The following procedure was reviewed and approved by the University of Texas at Dallas Institutional Review Board (IRB).

The study consisted of one session lasting up to one hour for each participant. During informed consent, participants were informed that the purpose of the study was "to increase our understanding of how full-body avatars may be represented in VR applications", but they were naïve to the nature of the conditions during the experiment because they donned all of the equipment in all of the conditions.

After informed consent, each participant was assigned to one of the full-factorial condition orderings to counterbalance the potential effects of ordering. Each participant experienced three conditions: Complete, No-Avatar, and either Head-and-Extremities (Study 1) or Head-and-Hands (Study 2). The study began with a background survey on the participant's gender, age, height, weight, education, and technology experience. The participant then donned the additional trackers, straps, controllers, and HMD. The experimenter then configured the VR application to match the avatar's gender to the participant's gender and calibrated the avatar's height, using a T-pose from the participant. The experimenter then explained the two tasks described in section 3.1, and the participant completed the three repetitions for their first tracking fidelity condition, assigned based on their assigned presentation order. After successfully completing the VR tasks, the participant filled out the SSQ, SPES, and embodiment questionnaires. Each condition took approximately 20 minutes (5 minutes to adjust the sensors and calibrate the avatar, 10 minutes to complete the VR tasks, and 5 minutes to complete the questionnaires). The participant repeated this process for the remaining two tracking fidelity conditions. The study concluded with the participant completing an exit survey to obtain open-ended responses regarding the study experience. See Figure 5 for a flow chart of this procedure.

3.6 Research Questions

RQ1. Which body tracking condition will induce the most embodiment?

H1. We hypothesized that the higher the tracking fidelity, the greater the embodiment. We expected the Complete condition to result in the highest embodiment scores, followed by the Head-and-Extremities condition, and then the Head-and-Hands condition. The No-Avatar condition was expected to perform worst with the lowest embodiment scores. We hypothesized this because previous studies have shown that increased first-person perspective avatar visual fidelity leads to increased embodiment [3, 15, 21, 23, 43, 61], and we expected increased avatar tracking fidelity to result similarly.

RQ2. Which body tracking condition will afford the most presence?

H2. We hypothesized that the tracking conditions with a visible avatar (Complete, Head-and-Extremities, and Head-and-Hands) would provide a higher level of presence over the No-Avatar condition due to increased interaction fidelity [39] and because prior research has shown increases to presence from increased avatar fidelity [61].

3.7 Participants

For the first study involving the Head-and-Extremities condition, we conducted 23 males and 7 females. For the second study involving the Head-and-Hands condition, we completed 11 males and 3 females. Due to the highly disproportionate number of males to females and the potential confound introduced by the gender-matched avatar, we only consider our male participant data for our analyses. Furthermore, all of our male participants ranged in age between 18 and 25 years, except for one 51-year-old participant. Due avoid a potential confound due to age, we also excluded his data.

Our analyses of the first study, which involved Head-and-Extremities, included a total of 23 male participants. Their average age was 19.8 ± 2.1. Based on self-reported background data, 21 participants played video games on a regular basis (i.e., at least one hour per week), and 19 had prior VR experiences. Our analyses of the second study, which involved Head-and-Hands, included a total of 10 male participants. Their average age was 20.3 ± 2.1. All 10 participants played video games on a regular basis, and 8 had prior VR experiences.

3.8 Results

For our dependent variables, we conducted a Friedman test at a 95% confidence level, as the non-parametric alternative to a one-way repeated-measures ANOVA, to investigate the main effect of body tracking fidelity. Wilcoxon signed-ranked tests were used to identify significantly different conditions when a significant main effect was found.

3.8.1 Embodiment

Our embodiment questionnaire had high reliability with a Cronbach's Alpha of $\alpha = 0.813$ for all 10 questions averaged across both studies. However, recent research suggested that some of our questions (#4 and #5) were likely less reliable [45]. Hence, we maximized Cronbach's Alpha at $\alpha = 0.911$, by removing questions #4, #5, and #10. Hence, our overall embodiment scores are based on the average of the remaining seven questions.

For study 1, we found a significant main effect of body tracking fidelity on *Overall Embodiment Score*, $\chi^2(2) = 14.315$, $p = 0.001$, $W = 0.311$. The post hoc tests showed that the Complete, $Z = -3.542$, $p < 0.001$, and Head-and-Extremities, $Z = -3.258$, $p = 0.001$, conditions induced significantly more embodiment than the No-Avatar condition. However, there was not a significant difference between the two avatar conditions, $Z = -0.261$, $p = 0.794$. See Figure 6.

For study 2, we found a significant main effect of body tracking fidelity on *Overall Embodiment Score*, $\chi^2(2) = 15.846$, $p < 0.001$, $W = 0.792$. The post hoc tests showed that the Complete condition induced significantly more embodiment than the Head-and-Hands, $Z = -2.805$, $p = 0.005$, and No-Avatar, $Z = -2.803$, $p = 0.005$, conditions. There was not a significant difference between the Head-and-Hands and No-Avatar conditions, $Z = -1.365$, $p = 0.172$. See Figure 7.

To determine if there were significant differences between our two samples, we conducted Mann-Whitney U tests to compare the control conditions between the two studies. We did not find a significant difference between the studies for the Complete condition, $U = 69.5$, $p = 0.074$. We also did not find a significant difference for the No-Avatar condition, $U = 106.0$, $p = 0.724$.

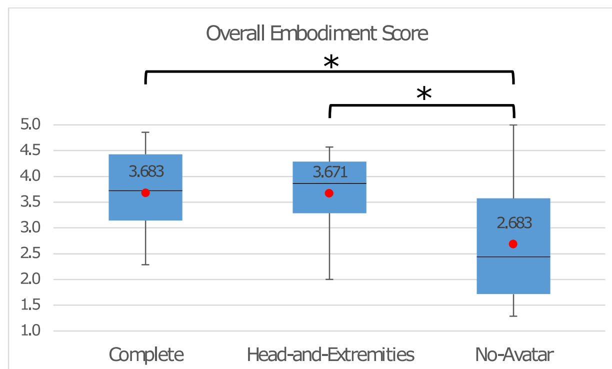

Figure 6: Boxplot of overall embodiment score for study 1. Red dots represent mean scores. Asterisks indicate significantly different body tracking conditions.

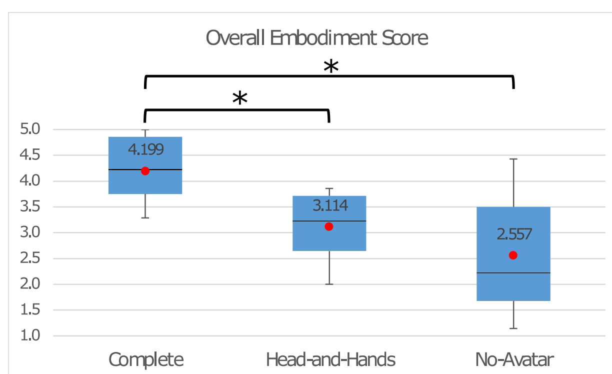

Figure 7: Boxplot of overall embodiment score for study 2. Red dots represent mean scores. Asterisks indicate significantly different body tracking conditions.

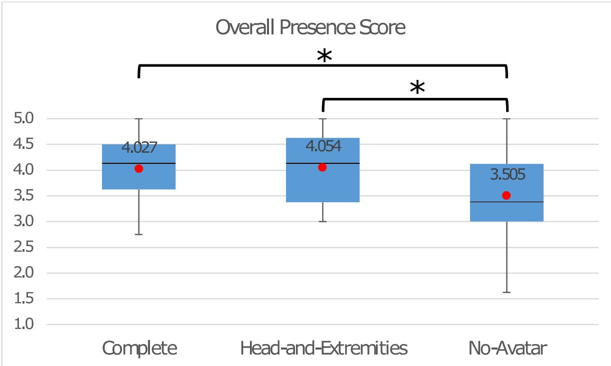

Figure 8: Boxplot of overall presence score for study 1. Red dots represent mean scores. Asterisks indicate significantly different body tracking conditions.

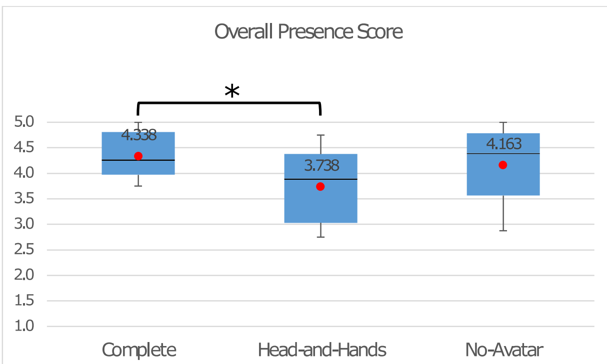

Figure 9: Boxplot of overall presence score for study 2. Red dots represent mean scores. Asterisk indicates significantly different body tracking conditions.

3.8.2 Presence

For our SPES results in study 1, we found a significant main effect of body tracking fidelity on *Overall Presence Score*, $\chi^2(2) = 8.535$, $p = 0.014$, $W = 0.186$. The post hoc tests showed that the Complete, $Z = -2.798$, $p = 0.005$, and Head-and-Extremities, $Z = -2.785$, $p = 0.005$, conditions afforded significantly more presence than the No-Avatar condition. However, there was not a significant difference between the two avatar conditions, $Z = 0.000$, $p = 1.000$. See Figure 8. We found the same significant differences for *Self-Location*, $\chi^2(2) = 8.988$, $p = 0.011$, $W = 0.195$, and for *Possible-Action*, $\chi^2(2) = 6.167$, $p = 0.046$, $W = 0.134$.

In study 2, we found a significant main effect of body tracking fidelity on *Overall Presence Score*, $\chi^2(2) = 6.788$, $p = 0.034$, $W = 0.339$. The post hoc tests showed that the Complete condition afforded significantly more presence than the Head-and-Hands condition, $Z = -2.527$, $p = 0.012$. There were not significant differences between the Complete and No-Avatar conditions, $Z = -0.422$, $p = 0.673$, or between the Head-and-Hands and No-Avatar conditions, $Z = -1.402$, $p = 0.161$. See Figure 9. We found the same significant difference that Complete was significantly better than the Head-and-Hands condition for *Self-Location*, $\chi^2(2) = 8.722$, $p = 0.013$, $W = 0.436$. We did not find any significant differences for the *Possible-Action*, $\chi^2(2) = 2.294$, $p = 0.318$, $W = 0.115$.

4 Discussion

In the next sections, we discuss how body tracking fidelity affects embodiment and presence. We also discuss the limitations of our work.

4.1 Body Tracking Fidelity Increases Embodiment

The results of our studies indicate that body tracking fidelity affects embodiment. In our first study, we found that the Complete and Head-and-Extremities tracking conditions induced significantly more embodiment than the No-Avatar condition. However, we did not find a significant difference between the Complete and Head-and-Extremities conditions in terms of the overall embodiment score. These results partially support our H1 hypothesis that the Complete condition would induce more embodiment than the Head-and-Extremities condition, which would induce more than the No-Avatar condition.

In our second study, we found that the Complete tracking condition induced significantly more embodiment than both the Head-and-Hands and No-Avatar conditions. However, we did not find a significant difference between the Head-and-Hands and No-Avatar conditions in terms of overall embodiment. These results partially support our H1 hypothesis that the Complete condition would induce more embodiment than the Head-and-Hands condition, but not our hypothesis that the Head-and-Hands condition would induce more than the No-Avatar condition.

Based on the results above, we recommend that VR developers and researchers should increase body tracking fidelity when attempting to induce embodiment. This recommendation supports the approach of using a full-body motion capture system in prior research [3, 4, 9, 29, 36, 41, 43, 58, 61]. For consumer VR systems, we recommend using additional tracking sensors when available, such as for the HTC Vive and Vive Pro systems.

4.2 Foot Tracking Induces More Embodiment

Despite having fewer participants in our second study than our first study, we found that the Complete tracking condition afforded significantly more embodiment than the Head-and-Hands condition in the second study while we found no significant difference between the Complete and Head-and-Extremities conditions in terms of overall embodiment, for the first study. This indicates that tracking the feet, the only difference between the Head-and-Extremities and Head-and-Hands conditions, induces significantly more embodiment over a full-body IK avatar, like the one used in our studies.

This result is not surprising considering the nature of the FinalIK VRIK full-body solver. When foot tracking is not available, the solver auto-steps at a distance threshold to keep the feet under the head. As a result, when the participant steps forward with their right foot, the VRIK algorithm may respond by auto-stepping their virtual avatar's left foot forward. Clearly, these types of incongruencies can negatively impact embodiment.

Considering the results between our studies, we recommend that VR developers and researchers at minimum should include foot tracking when using a full-body IK avatar and attempting to induce embodiment.

4.3 Body Tracking Fidelity Affects Presence

The results of our studies indicate that body tracking fidelity also affects the sense of presence. In our first study, we found that the Complete and Head-and-Extremities tracking conditions afforded significantly more presence than the No-Avatar condition, in terms of both self-location and possible action. This result supports our H2 hypothesis that a visible avatar would provide a higher level of presence over the No-Avatar condition. In our second study, we found that the Complete condition afforded significantly more presence than the Head-and-Hands condition. In that study, we did not find a significant difference between the Complete and No-Avatar conditions or between the Head-and-Hands and No-Avatar conditions. This lack of differences was most likely due to our small sample size (10 participants) and does not support our H2 hypothesis that the Complete and Head-and-Hands conditions would provide greater presence than the No-Avatar condition.

More research needs to be conducted to better understand the effects of body tracking fidelity on the sense of presence. The results of our first study indicate that increasing fidelity increases presence, similar to prior results indicating that increasing interaction or display fidelity improves presence [39]. However, the results of our second study do not clearly support that concept.

4.4 Limitations of Our Work

As currently presented, there are two limitations of our work: 1) our results are based on a non-representative sample, and 2) our small sample likely did not capture some significant differences among our evaluated tracking fidelity conditions.

We were forced to end our studies prematurely due to the COVID-19 pandemic, and as a result, we only have 30 completed participants for the first study and 14 completed for the second study. Due to a disproportionate number of males to females in both studies (23 to 7 in the first, and 11 to 3 in the second), we decided to only consider our male participant data for the current work. This decision was to avoid potential confounds due to differences in the male and female avatars used in our studies. We also excluded one male participant's data due to his age being a significant outlier. Hence, our results are only representative of young, male users. Therefore, our results should be further confirmed with a more-representative sample of the general population, especially since Peck et al. [44] have recently shown that changes in simulator sickness are systematically associated with the proportion of female participants to male participants.

In addition to our non-representative sample, our sample was small (23 participants in the first study, and 10 in the second). Hence, it is likely that our results did not capture some significant differences among the four tracking fidelity conditions. For example, with more participants, we may find that the Head-and-Hands condition affords significantly more embodiment than the No-Avatar condition. However, despite our small sample sizes, we did find significant differences among our tracking fidelity conditions in terms of embodiment and the sense of presence. Hence, we believe this work will serve as a foundation for future researchers to expound upon and better understand the effects of body tracking fidelity on embodiment of a full-body IK avatar.

5 Conclusion

Full-body virtual avatars are commonly used to aid in visuomotor stimulation of embodiment. We found that there is robust investigation into embodiment stimulation techniques, avatar appearance, and synchronicity and congruency of avatars, but we found a gap in the evaluation of embodiment with regard to the degree of body tracking fidelity. We have presented one of the first works to investigate the effects of body tracking fidelity on embodiment of a full-body IK avatar. The results of our studies indicate that increased body tracking fidelity induces more embodiment and likely affords more presence. Furthermore, comparison of our conditions shows that foot tracking increases embodiment by avoiding poor approximations of steps that may conflict with the user's physical steps. However, it is important to note that our results are based on a small, non-representative sample of young, male participants.

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