The Critical Role of Self-Contact for Embodiment in Virtual Reality

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Abstract— With the broad range of motion capture devices available on the market, it is now commonplace to directly control the limb movement of an avatar during immersion in a virtual environment. Here, we study how the subjective experience of embodying a full-body controlled avatar is influenced by motor alteration and self-contact mismatches. Self-contact is in particular a strong source of passive haptic feedback and we assume it to bring a clear benefit in terms of embodiment. For evaluating this hypothesis, we experimentally manipulate self-contacts and the virtual hand displacement relatively to the body. We introduce these body posture transformations to experimentally reproduce the imperfect or incorrect mapping between real and virtual bodies, with the goal of quantifying the limits of acceptance for distorted mapping on the reported body ownership and agency. We first describe how we exploit egocentric coordinate representations to perform a motion capture ensuring that real and virtual hands coincide whenever the real hand is in contact with the body. Then, we present a pilot study that focuses on quantifying our sensitivity to visuo-tactile mismatches. The results are then used to design our main study with two factors, offset (for self-contact) and amplitude (for movement amplification). Our main result shows that subjects' embodiment remains important, even when an artificially amplified movement of the hand was performed, but provided that correct self-contacts are ensured.

Index Terms—Virtual Reality, Avatar, Embodiment, Agency, Body Ownership, Self-contact.

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1 Introduction

Experiencing immersive virtual reality (VR) through the real-time mapping of body postures and movements on a full-body avatar is becoming more and more commonplace. This ability to perform full-body actions enable us to leverage on our coordinated skills in order to achieve tasks in VR that remain very complex to accomplish with traditional interfaces [13]. However, the quality of this experience can be degraded by the occurrence of mismatches, such as the visual interpenetration between the virtual body and the virtual environment [10], or between parts of the virtual body itself (self-interpenetrations). The occurrence of such events is often perceived as erroneous and may potentially cause breaks in presence [34]. Self-interpenetrations, and similar cases of self-contact mismatches, were also shown to convey less efficiently the meaning of an action when transferred from a real actor onto a wide range of avatars [28]. It is therefore not surprising that most VR applications would avoid the problem by focusing on actions and movements where self-contacts are not necessary and rare. But doing so is not only limiting the range of possible applications, it is also entirely disregarding the benefits of passive haptic feedback provided by self-contact. Matching the physical contacts of the real body with the contacts of the virtual body provides the illusion of self-contact, an immensely rich and versatile source of the passive haptic feedback that has the potential for strengthening the sense of body ownership. It comes "for free" with the real-time mapping of a full-body avatar and should be used for reinforcing embodiment, in order to positively influence the sense of presence in the virtual environment.

The present study proposes to explore the hypothesis that self-contacts can be used to establish and maintain one of the core components of embodiment; the sense of body ownership (sense of self-attributing the avatar's body). We also speculate that, compared to the prime importance of correct self-contacts, other potential disruptions in the mapping of movements would be considered of lesser relevance by the participant. We propose to observe this by monitoring the sense of agency (sense of being in control of the avatar's movements [22]) when artificially amplifying the avatar's movement during a reaching task. The hypothesis is that the amplitude of distortions until which the sense of agency is negatively impacted should be higher for the self-contact condition compared to the self-contact mismatch condition.

In practice, avoiding self-interpenetrations can be considered as algorithmically solved [28]. We therefore assume this specific case of body inward self-contact mismatch to be addressed and focus instead on the dual case of body outward self-contact mismatch that we name the "floating hand" (Fig. 1A). It is characterized by a visual feedback showing that the virtual hand is not in contact with the virtual body whereas their physical counterparts are. Such a context is a clear violation of the "touchant-touché" phenomenon characterizing a self-contact, examplified by de Vignemont [12] as follows: our body appears to us both from the outside, through vision, and from the inside, through proprioception (touch). It follows that "when we touch our knee with our hand, we have a tactile experience of our knee from the outside (touché), but we have also a tactile experience of our knee from the inside (touchant), and the same is true of the hand".

In the present paper, we therefore first examine through a pilot study the participant's sensitivity to self-contact mismatches in terms of body ownership. We then study whether the quality of self-contact also impacts participants's sense of agency when the real hand is moving through the volume of space within body reach (Fig. 1B). Our interest for this class of visuo-motor mismatches is that they can get largely unnoticed. Hence such a property can be exploited to prioritize the motion capture computations for addressing the aspects the users are most sensitive too (as hypothesized here, the self-contact).

The contribution of this study is threefold: (i) Providing a mechanism for manipulating the hand movement while preventing self-interpenetrations, (ii) allowing to exploit the body as a consistent source of self-haptic feedback, and (iii) Evaluating the sensitivity to self-contact mismatch on body ownership and its influence on the sense of agency of hand movements in free space.

The paper is organized as follows. Sect. 2 recalls the state of the art on the sense of embodiment in Virtual Reality and real-time avatar control. Then Sect. 3 describes the egocentric coordinate representation and how it is extended for manipulating the posture. Sect. 4 presents the experimental framework and the results. The general discussion and the conclusion end the paper.

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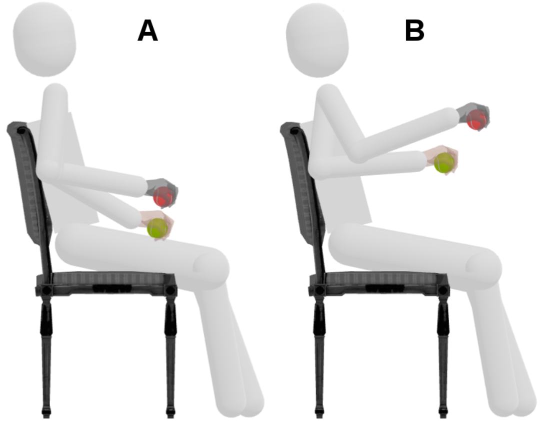

Fig. 1: Conceptual illustration of the two components of the experimental study. This simplified side view highlights only the dominant arm and hand of the subject; the dark grey hand holding a red ball is the displayed avatar hand whereas the light colored hand holding a tennis ball is the real hand location. (A) "floating hand" self-contact mismatch where the subject feels the contact of the held object on the thigh but sees a gap between the avatar hand and thigh. (B) Body-grounded amplified movement where the relative distance of the avatar hand with respect to other body parts is amplified compared to the subject posture.

2 BACKGROUND

Recent years have seen a number of contributions aiming at formalizing the concept of embodiment in the context of Virtual Reality [22]. Embodiment was initially defined in the field of cognitive neuroscience and philosophy of the mind [6]; it encompasses the relevance of sensorimotor skills and the role the body has in shaping the mind [3], as well as the subjective experience of using and 'having' a body. De Vignemont formally defined it as follows [11]: "E is embodied if some properties of E are processed in the same way as the properties of one's body". From that perspective, one may embody a tool, such as a pen or a hammer, even though that tool is not considered as being part of one's body. In that frame of mind, the present paper contributes to the lines of research exploring the necessary conditions for a full-body avatar to be embodied by a participant.

Prior works have already demonstrated that a static avatar can be used to replicate the Rubber Hand Illusion (RHI) [8] in which the simultaneous visuo-tactile stimulation of a real hand and of a virtual hand induces the illusory ownership for the virtual hand, as observed through the measurement of a prorioceptive drift of the location of the real hand towards the location of the virtual hand [33]. This example shows that the body ownership component of the sense of embodiment [22] towards an avatar can be influenced by the action of the environment or of external operators. More recently, an experimental study exploiting a haptic version of the rubber hand has demonstrated that voluntary self-touch increases body ownership in the RHI context [16]. However, to date, very few studies include voluntary self-touch as an explicit factor for virtual embodiment. In [18] self-touch, associated to a virtual mirror, was shown to enhance self-recognition of subjects (but not ownership) towards a virtual tele-existence robot.

Beside body ownership, a critical component of embodiment is the sense of agency, i.e. the feeling that one is in control of one's actions [20, 21]. This component heavily relies on motor control mechanisms and on the proprioceptive feedback providing the current state of the body posture and speed [4]. It can be experimentally tricked to a certain extent as initially explored in neuroscience through the well-known line-drawing experiment from Nielsen [29]. Agency manipulation experiments are designed to provide an altered visual feedback of the movement that is in conflict with motor planning and proprioceptive feedback. It has been shown that the manipulation would not be noticed by participants until a strong visuo-proprioceptive or visuo-motor discrepancy is reached [14]. In Virtual Reality, similar studies have been conducted to study the sensitivity to visuo-motor and to visuo-proprioceptive discrepancies in the context of the interaction of a virtual hand with the virtual environment. For example, Burns and Brooks [9] quantified the visuo-motor sensitivity by asking subjects explicitly about the perceived speed of their virtual hand, whereas Galvan Debarba [15] asked subjects to perform a forced choice regarding the sense of agency in manipulated linear reach tasks. In another work handling an explicit context of interpenetration of the hand with a virtual planar surface it was experimentally established that subjects are more sensitive to the visual interpenetration of the virtual hand with the virtual planar surface than to the real/virtual hand location difference [10]. Here a location difference between the real and virtual hands occurs because the virtual hand remains tangent to the virtual planar surface whenever the real hand causes an interpenetration.

More recently, in the context of movements in free space, Kokkinara et al. studied subjects' adaptation to the manipulation of shoulder angular speed or offset for reaching tasks performed with one arm in a fully-extended posture [23]. They found a significant effect on the reported agency at every tested speed factors (x2 and x4), suggesting the need for investigating less dramatic distortions.

In our context, we are interested to study the VR user sensitivity to a possible alteration of their displayed avatar posture (e.g. self-contact mismatch or posture drift) and movement (e.g. differences in speed and direction mismatch). Alterations can have a variety of causes ; they can result from the imperfect modelling of the human body in the motion capture process or they can be voluntarily introduced by an application. For example, one could think of an exercising system that amplifies or reduces the user movement abilities, respectively for sustaining the user motivation or for training the movement precision. Please note that the case of the amplified movement should not be confused with the Go-Go 3D interaction technique allowing to extend the reach of an isolated 3D virtual hand far beyond the human reachable space [31]. Indeed we assume in the present study that the user is embodied in a full-body avatar and interacts within the peripersonal space —the volume of space immediately surrounding the body [17]— that allows to reach for a target without requiring to move the body globally toward that target. We also postulate that the display of a coherent full-body posture is essential for the user acceptance of the proposed experience. For these reasons, our experimental framework restricts the range of reaching distances and of scaling factors so that the avatar arm never needs to be fully extended. In that sense, the spirit of our approach is similar to the one of redirected walking [32, 37], which aims at taking advantage of the subject's perceptual tolerance for helping the design of new classes of user experiences. In our case, one idea could be to develop rehabilitation exercises for patients with reduced movement ability [19, 26, 30].

One could also link the visuo-motor discrepancies we study to the generation of pseudo-haptic feedback for VR interaction [24], where a discrepancy between the actual movement and the displayed movement is introduced. Although very much related and as interesting to study from a cognitive neuroscience perspective, the work on pseudo-haptic focuses rather on the evaluation of a felt force and of friction rather than on embodiment, and we don't develop this aspect further in the present study.

To conclude from a VR perspective, the work presented here combines the field of haptic interfaces, in the sense that we are interested in using the user body as a tangible interface, and the field of full-body motion capture and avatar control, as we are evaluating the necessary conditions to produce and maintain embodiment. We hypothetize the necessity of grounding the avatar body through a consistent display of avatar body and hand contact whenever there is an effective user self-contact. As demonstrated by Burns et al. [10], we assume that the occurrence of a visual hand interpenetration into a virtual surface, in our case the virtual body, is clearly detrimental to the sense of presence and does not need to be explored again. Instead, we exploit and extend a recent method that allows preventing self-interpenetration [28] and focus on quantifying the influence of a potential visual gap between the avatar hand and body on agency and body ownership (Fig. 1A). In a second stage, we use this result to define a two-levels factor manipulating self-contact for an experimental setup involving a new class of body-grounded posture distortions consisting in a hand movement amplification factor with respect to the other body parts (Fig. 1B). The next section describes how to establish the desired body grounding, i.e. ensuring the consistency of self-contacts, and how to introduce the movement amplification within a unified framework.

3 Distortion Model using Egocentric Coordinates

This section first presents the egocentric coordinate representation of body posture, and then exposes how we extend this formalism to manipulate body posture.

3.1 Egocentric Coordinates

The concept of relationship descriptors has been introduced in [1] to encode the spatial relations between an animated 3D character and its surrounding environment during a predefined animation with the aim of easing the automatic adjustment of the animation to variations of the environment. This concept has been revisited by Molla et. al. [28] under the name of "egocentric coordinate" to represent the 3D character body posture. Its purpose is to support the coherent real-time mapping of a source posture on a wide variety of human-like 3D characters with differing size, volume and proportions, in a context of performance animation.

This is achieved using a simplified body representation where limbs are assimilated to capsules while the head and torso are represented using a crude mesh whose vertices are sampled on both the avatar and the performer [28]. Note that in the present study, the torso and head are further simplified by respectively using a right-angled parallelepiped and a capsule, as visible on Fig. 1 and Fig. 3. Further detail about these body part approximations are provided below.

The key advantage of the egocentric coordinates representation over prior art is its ability to preserve the relative location of body parts, hence most of its semantics, without introducing self-interpenetrations in the target character.

To benefit from this essential property, we exploit the egocentric coordinate encoding for representing the location of the avatar hand with respect to the body. More precisely, the position $\mathbf{p}$ of the wrist joint is expressed as a weighted sum of n vectors (Equation 1), where n is the number of body parts—ten in our case—represented using ten simple shapes described above and further detailed here.

Each limb segment was approximated using a capsule, whose hemispheres were centered on both joints of the limb segment and whose radius was such that is matched that of the limb, measured during a calibration phase. The head was also approximated using a capsule, of predetermined shape given the absence of head contact of our experimental protocol (see end of Sect. 4.1). The last body part that needed approximation was the torso, for which we used a box, whose dimensions were matching that of the users thanks to markers placed on their chest.

Each vector is decomposed into two components, the absolute location of the closest point $\mathbf{x}_i$ on the surface, and the relative displacement vector to the body part surface $\mathbf{v}_i$ (both depicted on Fig. 2A for each body part).

The importance factor $\hat{\lambda}_i$ is built from the relative distance and orientation to each body part i (details in Sect. 3.3). The position $\mathbf{p}$ of the wrist joint can therefore be expressed as:

$$\mathbf{p} = \sum_{i=1}^{n} \hat{\lambda}_i (\mathbf{x}_i + \mathbf{v}_i) \tag{1}$$

The next section exploits the egocentric coordinate system to introduce a new type of posture alteration, i.e. preserving correct self-body contact while amplifying or decreasing the amplitude of movements relative to the body surface. This altered postural mapping can be performed on avatars of any morphology but for the sake of simplicity and ease of analysis we focus on the use case of an avatar similar to the user.

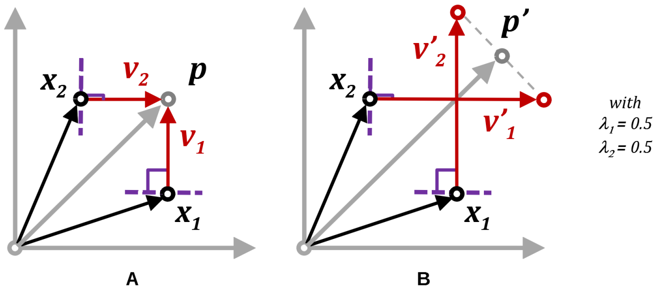

Fig. 2: Egocentric coordinates of one body joint $\mathbf{p}$ with respect to two body parts (symbolically represented with violet hashed line). (A) Each body part contributes through the absolute location of its closest point $\mathbf{x}_i$ and the relative distance vector $\mathbf{v}_i$. (B) Proposed body-grounded distortion of the body joint $\mathbf{p}$ into $\mathbf{p}'$ by scaling the relative distance vectors $\mathbf{v}_i$; please note that their contributions partially cancel each other. This happens especially when the hand is located in the close peripersonal space.

3.2 Amplitude and Offset Alteration

There are two types of distortions that are of interest for the present study, namely the gap characterizing the floating hand issue and the posture amplification. Both can be realized through a modification of the surface relative displacement vectors $\mathbf{v}_i$ in Equation 1 by using a distortion function D:

$$\mathbf{p} = \sum_{i=1}^{n} \hat{\lambda}_i \big(\mathbf{x}_i + D(\mathbf{v}_i)\big) \tag{2}$$

The distortion function could be any mapping, preferably continuous, with $D(\mathbf{v}) = \mathbf{v}$ obviously being a 1:1 mapping of the movements. For the sake of simplicity and ease of analysis, we decided to focus on a function of the following form:

$$D_{a,b}(\mathbf{v}) = a\mathbf{v} + b\hat{\mathbf{v}} \tag{3}$$

Where a denotes a scaling amplitude, b an offset and $\hat{\mathbf{v}}$ the normalized vector $\mathbf{v}$. Indeed, as pictured in Fig. 1A, when resting one's hand on a body part, if $b \neq 0$ the self-contact is altered. In contrast, when at a distance from that body part, if $a \neq 1$ then the reproduced distance is modified as visible in Fig. 1 B with a case of amplification.

This expression has both the advantage of allowing us to manipulate the two factors of interest mentioned above, and the benefit of being in a simple enough form that any result is comprehensible. As an example, if one identifies that the detection threshold for the offset component is at $b = 10\,\text{cm}$, then all can easily understand that result, as it directly characterizes the gap between the hand and the skin. The same reasoning goes for the amplitude part of Equation 3, for which complex polynomials or other formulas would not only make it more complicated to analyze but also to understand.

Fig. 2 B shows how a distorted position $\mathbf{p}'$ is obtained from the position $\mathbf{p}$ when doubling the egocentric vectors $\mathbf{v}_i$. By construction, those vectors are not co-linear. So as a consequence their distortions partially cancel each other. This is more likely to happen in the close peripersonal space and results in a smaller alteration compared to more outward hand locations.

The alteration of the relative distance vectors allows to define a continuous body-grounded distortion field spanning the whole peripersonal space, a representation of which can be seen on Fig. 9. It is important to note a clear difference with the work from [15] for which the distortion is defined only over the linear, task-oriented trajectory between two predefined 3D points.

3.3 Egocentric Importance Factor

According to [28] the importance factor $\hat{\lambda}_i$ is the product of two scalars, one characterizing the relative distance of the body joint i to the body-part, and the other their relative orientation. The distance scalar is of special interest in the present study: the value λ_p is computed as the inverse of $\|\mathbf{v}_i\|$, with a saturation to a maximum value to prevent numerical instability.

However, during the early phase of the study, we noticed that the closest body parts did not have enough relative importance compared to the furthest ones. In other words, the furthest body parts were influencing the distorted position too heavily. To reinforce the importance of the closest body parts, the importance factor λ_p has been expressed as an inverse square of the relative distance rather than a simple inverse law:

$$\lambda_i = \frac{1}{\|\mathbf{v}_i\|^2}$$

This modification does not affect the property of preventing self-interpenetration from [28].

4 EXPERIMENT

Based on the distortion model presented above we designed an experiment to evaluate how self-contact and visuo-motor feedback affect aspects of the senses of agency and body ownership of an avatar when performing hand movements in free space.

A self-contact mismatch is introduced by assigning a non-zero value to b in Equation 3 (i.e. the *offset*). The *offset* factor is expressed in cm and is explored only in the positive direction. The consequence of a positive *offset* is that the avatar hand will always float above the point of contact defined by the real hand, being unable to reach it. We discarded negative values, as interpenetrations are already known for their adverse effect on presence [10].

A visuo-motor mismatch is introduced by assigning a non-unit value to the parameter a in Equation 3 (i.e. the *scaling amplitude*). With relation to the real hand, a value below 1 slows down the avatar's hand movement, while a value above 1 speeds up the avatar's hand movement. To balance these two opposite movement manipulation directions we chose to express the amplitude with a movement *amplitude gain* factor in the experiment, i.e. in dB units [1]. For example the unit scaling factor is expressed as 0 dB, a doubling[2] scaling factor is expressed as 3 dB while a halving[3] scaling factor is expressed as −3 dB.

4.1 Implementation

Hardware and Software

An Oculus Rift CV1 served as HMD and a Phasespace Impulse X2 was used as motion capture system, with 14 cameras tracking 40 active markers being sampled at 240 Hz. The whole system's motion-to-photon latency was measured between 30 and 40 ms. Audio was delivered using a pair of Bose QuietComfort 35 wireless headphones. They feature high quality environmental noise cancellation and were additionally used to stream omnidirectional white noise, in order to fully isolate the subjects. If needed, headphones were also used as a means of communication between the subject and the experimenter, the latter making use of a microphone.

The virtual environment was created using Unity 5 and consisted of a square room of $6 \times 6 \times 3$ m, at the center of which stood a seat matching the position and dimensions of a real chair in the experimentation room. Subjects were seated on that chair and had to perform the reaching motions described hereafter.

The displayed body posture was obtained through the following steps: first, computing the dominant hand egocentric coordinates [28] from the body part locations given by the Phasespace optical marker positions; second, altering the hand location according to Sect. 3.2 and the current values of the *offset* and the *amplitude*; finally by computing the resulting arm joint angles from the altered hand location with the software FINAL-IK [2].

Fig. 6 (right) illustrates the virtual environment, including an example of text message used to communicate the sequence of tasks. The tennis ball held by the avatar was added after the pilot study, in order to improve the plausibility of hand movements in the absence of finger tracking.

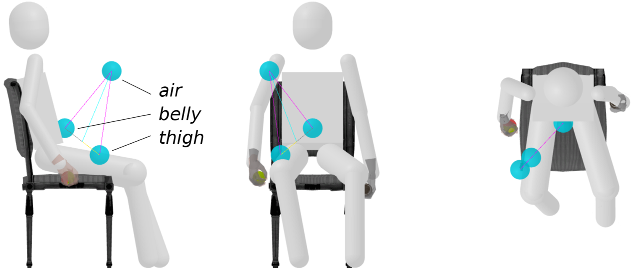

Fig. 3: Simplified orthographic views (right, front, and top, from left to right) of the three target locations: *belly*, *thigh* and *air*. The colorful lines show the geometric construction of the *air* target position, the purple lines having the desired size of 75% of the subject's arm length.

Calibration

Before beginning the experiment, the avatar's proportions were automatically adjusted to that of the subjects using the position of various markers: three of them located at the shoulder, elbow, and wrist gave a measurement for the arm's length, while four others located on the back of the motion capture suit were used to scale the spine. Legs were adjusted using a technique similar to that used for the arms. In order to avoid noticeable limb length asymmetry due to small marker placement errors, the average length of the two upper and lower limbs were computed before respectively scaling them identically.

Subjects were then asked to perform a registration of their hand's marker placement. This was done by aligning their real hands with static virtual ones in front of them, using spherical representations of the markers present on their hands. The feet were pre-calibrated since the subjects were wearing shoes holding markers whose position did not change across subjects.

Normalized Target Placement

The subject had to reach for three different targets (Fig. 3 left) respectively located on the belly (T_b), the right or left thigh matching the handedness (T_t), and in the air above the thigh (T_a). The targets were represented in the virtual environment by translucent spheres of 10 cm of diameter. The air target was automatically placed such that a subject had to travel a distance $d = 75\%$ of the arm length between any skin target (T_b or T_t) and T_a. In order to disambiguate the position of T_a, it was placed at the topmost position of the circle spanned by intersecting the two spheres of radius d centered on T_b and T_t.

Fig. 3 shows the geometric construction of such target positioning. This target placement is useful in requiring movements of equal effort, thus not changing the ability to perform the trials across subjects.

These specific target locations have been chosen for several reasons: First, given the seated position we wanted to investigate, the thigh is a reasonable contact point for instance to rest one's arms. As to the belly target, we initially placed it higher on the torso, also following the rationale that the torso is a typical point of contact when seated. But early testing showed that due to both the physical size of the HMD and its field of view, users tended not to notice a target located higher on the torso, which confused them, hence the decision to lower the target location to the belly.

4.2 Pilot Study

Given the original nature of the body-grounded distortions, we first conducted a pilot study to quantify independently the user sensitivity to the self-contact mismatches (offset factor) and to the visuo-motor distortions (amplitude gain factor).

Five subjects took part in the pilot study (aged between 22 and 26, median of 24, one female), all were right-handed. They were all staff

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[1] Value in dB $= 10 \cdot \log_{10}(a)$

[2] Actually $\times 1.995$

[3] Actually $\times 0.501$

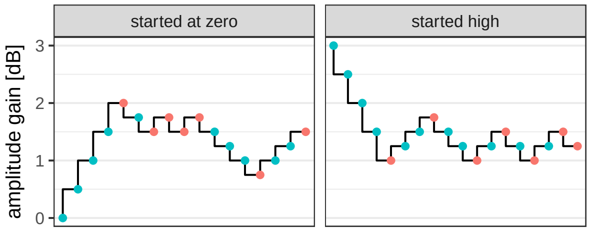

Fig. 4: Typical staircase evolution for positive *amplitude gain* values. In the case of negative values (for the *amplitude gain* only), a high starting value meant -3 dB. The highlighted dots represent the staircase turns: trials on which the evolution trend of the staircase changed.

members or students related to our research group, and were not paid for their participation.

Staircase Design

To evaluate the detection thresholds for our distortion model, we used an adaptive staircase of distortion values similar to [27]. The subjects had to perform two different kinds of movements involving two of the three targets described above: belly-air-belly, or thigh-air-thigh. After each movement, the subjects were asked to answer the following question: “Did the movement you saw exactly correspond to the movements you performed?”. The absolute strength of the distortion was then raised or lowered for a positive or negative answer respectively. The staircases were presented in a random order and, to avoid subject habituation, four staircases were progressing in parallel. This was done using a round robin order of the first four incomplete staircases. When the end of the experiment approached and only three or less staircases were left, random trials were inserted as placeholders for the missing staircases, again to avoid presenting successive trials of the same type. The process was repeated until either the strength evolution changed direction seven times (a “staircase turn”), or the subject reached twenty trials. The detection threshold for a given staircase was computed using the mean value of the last four staircase turns.

A staircase has the following parameters:

(i) *Distortion type*: *amplitude gain* or *offset*
(ii) *Starting Value*: zero or high
(iii) *Sign*: positive or negative
(iv) *Path type*: belly-air-belly or thigh-air-thigh

In the pilot study, the scaling amplitude a is evaluated in both directions : amplification ($a > 1$) and hindering ($a < 1$).

The steps of each staircase evolved as follows: a base step value of 0.5 dB or 2.5 cm (for *amplitude gain* and *offset*, respectively) was added or subtracted depending on the sign of the staircase and its current trend. Once the subjects reached a first staircase turn, the step was halved, and the trials went on using that step value. Fig. 4 shows two instances of staircase evolution for positive *amplitude gain* values.

Pilot Results

The results for this pilot study are shown on Fig. 5. Given the relatively low number of subjects who took part in this pilot study, we can only outline some trends that we use as a basis for choosing the values for our main experiment.

The positive *amplitude gain* thresholds are similar for the two types of paths whereas it is more difficult to characterize the obtained distribution for negative *amplitude gain* thresholds. It is nevertheless slightly symmetric with respect to the positive side, with a marginally lower average when comparing the absolute threshold values.

Regarding the sensitivity to the *offset* of floating hands, there seems to be a clear shift between the two path types, the *belly-air-belly* path being the source of much more tolerant offsets compared to the *thigh-air-thigh* path.

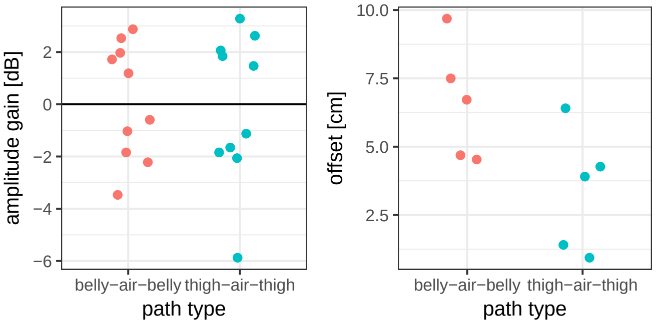

Fig. 5: Results for the pilot experiment. Each dot represents the mean of two staircases from the same subject with two different starting values. These elements allow us to determine reasonable upper bounds for the *amplitude gain* and *offset* factors. The *path type* seems to have little influence regarding the *amplitude gain* threshold results whereas the distribution of the *offset* threshold results show a clear shift that could be linked to the path location and/or orientation within the field of view

Fig. 6: Setup for the experiment. Left: A member of the research group outfitted as a subject ready to take part to the experiment (due to the addition of the attention sustaining task in the experiment, only these subjects were holding an Oculus Touch controller). Right: the virtual environment used (a carpet was added to match the floor of our tracking space). The avatar was viewed in a first person perspective and had no visible head in order to avoid any visual artifacts.

Beyond serving as calibration tool for the full experiment to determine a clear upper bound for the *amplitude gain* and to the *offset*, this pilot study suggests that the *amplitude gain* tolerance is rather large when the distortion is body-grounded. However, one has to remember that, as noted in Sect. 3.2, the scaled egocentric vectors may partially and mutually cancel each other’s influence. So, assuming that the body model has more than a single body part, a positive *amplitude gain* always results in a smaller virtual amplified hand displacement in the body-grounded context compared to the linear task-oriented case [15]. For this reason the tolerance values should not be compared in a strict sense between the two contexts.

4.3 Methods

Experimental design

The experiment combines the two factors of self-contact (*offset*) and visuo-motor (*amplitude gain*) distortions in a factorial design. It also includes an orthogonal task, described below, to sustain the attention of the subjects. During the entire experiment, subjects were asked to hold a tennis ball in their dominant hand (tracked). This way, all finger postures are set to a constant pose and do not need tracking.

We used three positive values of *amplitude gain* as follows: 0 dB, 1.6 dB, and 2.9 dB[4]. The latter two roughly correspond to the first and

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[4] Corresponding respectively to the a values of 1.0 , 1.45 and 1.95

third quartile of the thresholds that we assessed in the pilot experiment. Likewise, for the *offset* we decided to take one value at 0 cm, and one above the identified detection threshold, at 7.5 cm, so as to identify any effect this offset might have on the senses of agency and body ownership. A complete overview of the manipulated factors during our experiment can be found in Table 1.

Table 1: Variables in the experiment.

Variable	Levels
Amplitude gain	0 dB 1.6 dB 2.9 dB
Offset	0 cm 7.5 cm
Path type	belly-air-belly thigh-air-thigh
Color change (control variable)	true false

All subjects performed five repetitions of each combination of the factors above, for a total of $3 \times 2 \times 2 \times 2 \times 5 = 120$. Trials presentation order was randomly defined for each subject.

Once the calibration phase was complete, but before the start of the valid trials, the subject went through a set of ten training trials. The first five were performed using a high offset (i.e. 7.5 cm), and the next five using a high *amplitude gain* (i.e. 2.9 dB). This implies that our results were obtained with subjects who were trained to spot the distortions we introduced.

Attention Monitoring Task

The differences observed for the *offset* distributions of the two path types in Fig. 5 are suggesting that the subjects were not observing the movement entirely, and thus were not really paying attention to contact mismatches on the belly because this target lies more on the fringe of the field of view. In order to mitigate this effect we introduce an orthogonal task for the full experiment that is aimed at forcing the subjects to look at the whole movement. The *color change* task consisted in detecting the color changes of the ball. Once the first target of the trial was hit, a random timer between 0 and 4 s was started, at the end of which the ball changed from regular tennis-green to purple (two color-blind safe colors) for a random duration between 0.5 and 1 s. In case the last target was hit before the end of the timer, the color change was triggered then, and the maximum value of the timer was reduced by 0.2 s to adapt to the faster pace in future trials. Subjects were instructed to press a button of an Oculus Touch controller (held in the non-dominant hand) as soon as they detected such color change. Their answers, or the lack thereof, was recorded for each trial. The error rate in this task was used as a control to determine whether subjects were focused on the experiment as requested.

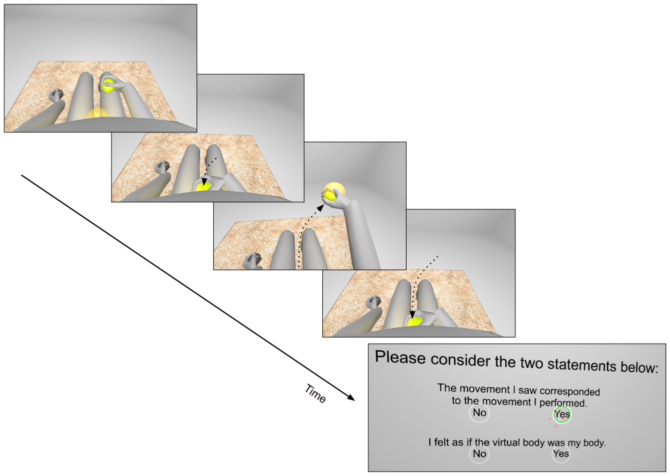
Trial Overview

Each trial (Fig. 7) consisted of bringing the dominant hand to the first target, then to the second one in the air, and back to the original one, after which subjects were asked to rate two statements by selecting Yes or No using their gaze (central cross in field of view). The statements assessing their senses of agency and body ownership were the following:

Agency — "The movement I saw corresponded to the movement I performed."

Body ownership — "I felt as if the virtual body was my body."

Subjects were then instructed to keep their hand out of their field of view when answering, but also not on their thigh nor on their belly, so as to avoid involuntary activation of the first target for the next trial. Once the last statement was assessed, the engine changed the distortion parameters and a new trial could begin.



Please consider the two statements below:

The movement I saw corresponded to the movement I performed.
No Yes

I felt as if the virtual body was my body.
No Yes

Fig. 7: First person views during a typical trial on the belly-air-belly path.

The agency and ownership responses for each combination of factor per subject were computed as the arithmetic average of the "yes"—set to 1—and "no"—set to 0—responses. Therefore, response variables are values ranging from 0 to 1, where high values represent strong agreement with the agency or body ownership affirmations.

Subjects

Subjects were recruited on campus and were requested to be fluent in English, to have normal or corrected to normal vision, and to have normal physical and psychological condition.

A total of 21 subjects took part in the experiment. Two of whom were excluded in the analyses reported below due to faulty recordings. The remaining subjects were aged from 19 to 31 (median age: 25), four of which were female and three were left handed. They all reported having either never participated in a VR experiment before or only a few times. One of them reported using an HMD every day, and most said they played video games a few times.

The subjects received both in written form and orally the instructions describing the experiment and their task. They had to read and sign a written informed consent form to participate and were informed that they could stop and leave the experiment at any time, without having to give any justification. The subjects were paid CHF 20.- per hour for their participation.

Analysis

Statistical analysis was carried using repeated measures analysis of variance (ANOVA), with *offset*, *amplitude gain* and *path type* as factors. Differences were deemed statistically significant for p-values below the threshold $\alpha = .05$. We tested the assumption of normality of residuals with the Shapiro-Wilk test. If residuals are deemed not normal we transform the response with a Box-Cox transformation y^{λ}, which does not alter the order of the response values. We conducted post-hoc analysis with pairwise t-tests and Holm-Bonferroni correction for multiple comparisons. The analysis was conducted using the R software.

We hypothesize that the increase in offset and amplitude gain will result in lower agency (H1) and body ownership (H2) responses as a result of the altered responsiveness and correspondence of seen and felt sensory stimulation. We further hypothesize that, for the range of studied manipulations, incongruent self-contact will have a greater negative impact to body ownership than the movement amplification factor (H3). That is because the latter does not affect the continuity of the body whereas the former does.

4.4 Results

First, the maximum error rate recorded for the orthogonal *ball color change* task was 0.183. This measure indicates that all subjects paid

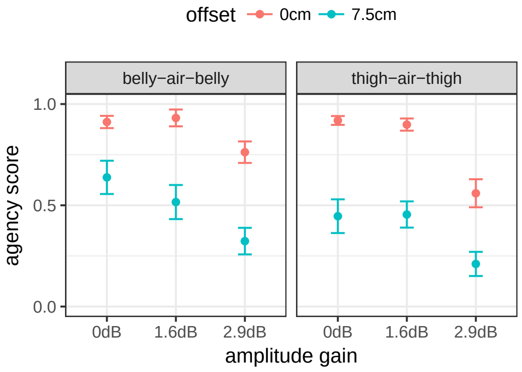


Fig. 8: Results for the sense of agency response. Error bars represent the standard error of the mean.

attention to the movement, and therefore, no subject was excluded based on this metric. We have also verified that this factor had no evident impact on the response variables using a repeated measures ANOVA test with the four factors listed in Table 1. Therefore, we disregard the *color change* factor in further analysis.

Moreover, we removed outlying trials based on the completion time for each combination of *amplitude gain*, *offset*, *path type* and subject. We defined inliers as $Q_1 - IQR * 1.5 \leq inliers \leq Q_3 + IQR * 1.5$, where Q_1 and Q_3 are the first and third quartiles, and $IQR = Q_3 - Q_1$. In total, 180 trials have been discarded, leaving a total of 2100. This left a minimum of 6 remaining trials per combination of factor per subject, out of the 10 initially available. We ran separate analysis for agency and ownership response variables.

Agency

With respect to agency, we found a significant three way interaction between *offset*, *amplitude gain* and *path type* ($F_{(2,36)} = 6.43$, $\eta_p^2 = .26$, $p < .005$). We believe that this interaction reflects the fact that the mechanics of the distortion caused by non-zero *amplitude gain* and *offset* are affected by the different path types. More specifically, as depicted in Fig. 9, thigh-air-thigh requires a backward compensation when reaching the air target (i.e. rotated movement direction), while the belly-air-belly distortion is mostly applied toward the direction of the air target, effectively making the movement shorter when a positive *amplitude gain* is used. The fact that subjects had a stronger negative response to changes of *amplitude gain* can be observed in Fig. 8. This observation led to the decision of performing separate analysis for the belly-air-belly and thigh-air-thigh *path type* variable levels.

Agency response to the belly-air-belly path yields a significant effect of both *amplitude gain* ($F_{(2,36)} = 21.6$, $\eta_p^2 = .56$, $p < .001$) and *offset* (7.5 cm $<$ 0 cm, $F_{(1,18)} = 39.4$, $\eta_p^2 = .69$, $p < .001$) main effects, as well as their interaction ($F_{(2,36)} = 3.88$, $\eta_p^2 = .18$, $p < .05$). This interaction can be observed in Fig. 8, where agency response for 0 dB and 1.6 dB *amplitude gain* in the congruent (0 cm) *offset* condition are similar, while for the incongruent (7.5 cm) *offset* condition a linear reduction in the agency response is apparent as the *amplitude gain* of the movement increases. Moreover, the fact that the response scale is nearly saturated when there is no offset may have an influence. Therefore, we avoided the post-hoc of the interaction, and analyzed the main effect of *amplitude gain* in the belly-air-belly path. Post-hoc analysis of the *amplitude gain* levels shows that the sense of agency was significantly lower for 2.9 dB condition than for 0 dB ($t_{(18)} = 5.7$, $p < .001$) and 1.6 dB ($t_{(18)} = 4.3$, $p < .001$) conditions. The test failed to reject equivalence between 0 dB and 1.6 dB conditions ($t_{(18)=1.9}$, $p > .05$).

Agency response to the thigh-air-thigh path presented a significant effect of both *amplitude gain* ($F_{(2,36)} = 45.3$, $\eta_p^2 = .72$, $p < .001$) and *offset* (7.5 cm $<$ 0 cm, $F_{(1,18)} = 81.2$, $\eta_p^2 = .82$, $p < .001$) main effects. Post-hoc analysis of the *amplitude gain* levels shows that the sense of agency was significantly lower for 2.9 dB condition than for 0 dB ($t_{(18)} = 7.1$, $p < .001$) and 1.6 dB ($t_{(18)} = 7.5$, $p < .001$) conditions. The test failed to reject equivalence between 0 dB and 1.6 dB conditions ($t_{(18)} = .64$, $p > .5$).

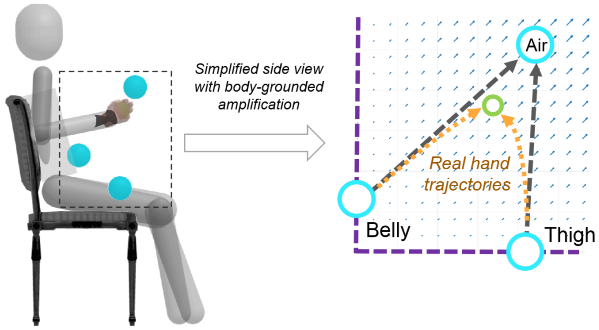


Fig. 9: Simplified close-up side view to highlight the real hand trajectory differences when submitted to an amplified body-grounded distortion. The *belly* starting location has almost equal egocentric coordinates from the torso and the legs all along the reach trajectory resulting in a felt 1D point-to-point distortion similar to [15]. Conversely, the reach trajectory starting at the *thigh* location sees an important relative decrease of the legs influence and increase of the torso influence in terms of egocentric coordinates, resulting in a more curved real hand trajectory to reach the target. Subjects seems to be more sensitive to this type of 3D vector field distortion compared to the 1D point-to-point distortion.

The agency score declines at a higher rate for the thigh-air-thigh movement compared to the belly-air-belly movement. We believe that this can be explained by the higher complexity of completing a distorted movement leaving from the thigh, as illustrated in Fig. 9. Moreover, the increase in both *offset* and *amplitude gain* factors resulted in lower sense of agency responses, rejecting the hypothesis of equivalence of the response across the manipulated levels and confirming H1. Mind that the intermediate level of the amplitude gain (1.6 dB) yielded an agency response that could not be differentiated from the neutral condition, which suggests that the manipulation of this factor is acceptable up to a threshold from the perspective agency.

Body ownership

With respect to the ownership response, we found a significant effect of *offset* (7.5 cm $<$ 0 cm, $F_{(1,18)} = 118.5$, $\eta_p^2 = .87$, $p < .001$) and *amplitude gain* ($F_{(2,36)} = 13.65$, $\eta_p^2 = .43$, $p < .001$). Post-hoc analysis of the amplitude gain levels shows that the sense of body ownership was significantly lower for 2.9 dB condition than for 0 dB ($t_{(18)} = 4.37$, $p < .02$) and 1.6 dB ($t_{(18)} = 4.22$, $p < .02$) conditions. The test failed to reject equivalence between 0 dB and 1.6 dB conditions ($t_{(18)} = .87$, $p > .38$). Body ownership results are presented in Fig. 10.

The increase in both *offset* and *amplitude gain* factors resulted in lower sense of body ownership responses, rejecting the hypothesis of equivalence of the response across the manipulated levels and confirming H2. Mind that, once more, the intermediate level of the amplitude gain yielded a body ownership response that could not be differentiated from the neutral condition, which suggests that the manipulation of this factor is acceptable up to a threshold from the perspective of body ownership. Finally, we note that, in support to H3, the *offset* factor presented greater effect size ($\eta_p^2 = .87$) than the *amplitude gain* factor ($\eta_p^2 = .43$).

5 DISCUSSION

Significant effects have been observed for both factors on the agency and ownership responses. More specifically, the high amplitude distortion and the self-contact mismatch factors yielded significantly different

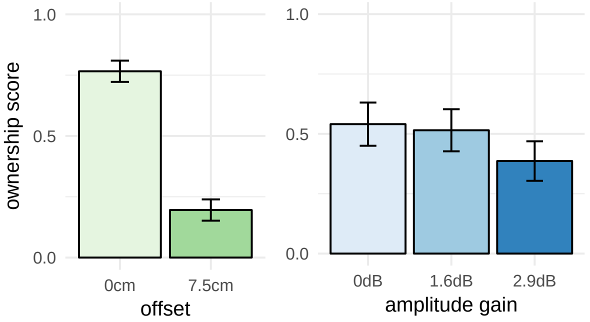


Fig. 10: Results for the ownership response. Error bars represent the standard error of the mean.

results. These allow us to conclude that both the "floating hand" effect and the body-grounded distortion have an impact on the senses of agency and body ownership. The results of the self-contact effect suggest that this issue is not to be taken lightly when designing a Virtual Reality application: when carefully treated, the body may act as a free source of high fidelity haptic feedback; if neglected however, it will cause inconsistencies that will lessen the impact of any full-body tracked application.

Overall, the agency responses reflect the criteria used in the choice of the amplitude and offset levels during the pilot experiment. That is, zero and low levels of amplitude distortion are closer in terms of distortion perception than the low and high levels of amplitude distortion for which significant differences have been found. A second observation supported by the difference in agency scores for high distortions is their dependency to the starting point on the body. We believe this is due to the complex nature of the 3D vector field induced by the body-grounded distortion that leads to more noticeable hand trajectory variations in case of important transfer of influence among body parts, i.e. when moving from one body part to get closer to another one (Fig. 9). Further usability studies are necessary to assess the application potential of this type of posture and movement transformation.

The significant effect of the self-contact mismatch on body ownership allows us to state that the floating hand issue is also a clear source of disruption in terms of body ownership (similarly to self-interpenetration). Different aspects of the discontinuity caused by our manipulation may explain the decrease in the senses of agency and body ownership, and in particular the importance of congruent self-contact to the sense of body ownership. Notably, it is argued that the experience of embodiment emerges from the coherent multisensory integration taking place in the brain [5, 7, 25]. However, self-contact discontinuities (e.g. the floating hand) result in visuo-tactile and visuo-proprioceptive mismatches, and thus present multisensory integration with inconsistent sensorial signals that may affect the ecological validity of the experience of a virtual body. We believe that the lack of contact between the virtual hand and the virtual body when the offset was active might elicit the sensation that the virtual body is different in shape than that of the subject, impeding self identification with the avatar [5]. Therefore, we strongly recommend to ensure a consistent visual feedback when users experience a tactile stimulation resulting from self-contact, especially for body parts that are in the first person viewpoint field of view such as belly and thighs. It remains to confirm whether this effect also happens for other body parts when subjects are seeing their avatar from a third person viewpoint.

Although the manipulation of movement amplitude also exerted a significant effect on the body ownership response, the effect progression was less important. Presumably, the fact that movement distortions do not affect the continuity of the body might be related to the less damaging effect to the body ownership response. That is, even if a high amplitude distortion could be easily spotted in terms of agency, it did not cause strong multi-modal incongruency, and did not confront the subject with a physically impossible situation. In a related topic, Tieri et al. [38] have shown that the mere observation of a virtual body discontinuity affects the feeling of ownership of a virtual body. In their experiment, the avatar was missing a segment of the arm and the hand appeared to be detached from the body. Here we show that a less extreme discontinuity—but very common in VR experiences including full body motion capture—is sufficient to strongly impact the sense of ownership of a virtual body. By extension, this mismatch could also affect the place and plausibility illusions [35], as they have strong relation with virtual body action and motion [36].

6 CONCLUSION

This research explores the hypothesis that, during immersion with an HMD in first-person view, body self-contacts can be used to establish and maintain a strong sense of embodying the avatar's virtual body. We also hypothesized that, compared to the prime importance of correct self-contacts, other potential disruptions in the mapping of movements would be considered of lesser relevance by participants.

For testing these hypothesis, we introduced a body posture transformation methodology to reproduce the imperfect or voluntarily manipulated mapping between the real and the virtual body. Our approach uses an egocentric coordinate representation (see [28]) to implement self-contact conditions where real and virtual hands do actually coincide whenever the real hand is in contact with the body (visuo-tactile congruency).

An experiment was conducted to evaluate subjective ratings of body ownership and agency under two conditions of self-contact (congruent or incongruent visuo-tactile consistency), and three levels of movement amplitude gain. Results show that the sense of body ownership remains important even when manipulated through an artificially amplified movement of the hand, provided that self-contact is ensured. Furthermore, after confirming that our distortion of movement was effective (it reduces the sense of agency for high distortion condition), we could observe that the sense of agency is strongly influenced by the self-contact factor. In particular, and as hypothetized, participants report a maximum value of agency for moderate movement distortion only in the condition when self-contact is guaranteed.

Taken together, our results confirm that correct self-contact is of primary importance for supporting a strong sense of embodying an avatar during immersion in VR. Considering the central role of embodiment for the sense of presence, every factor supporting subjective feelings of body ownership and agency should be developed. Self-contact, which strengthens the illusion that the virtual body is real (and therefore that the virtual world is real), is easily implemented with the real-time mapping of a full-body avatar and will hopefully become a standard for VR thanks to the growing availability of motion capture devices on the market.

Among foreseen applications, we believe that the ideas presented here could motivate the development of motion capture and avatar calibration methods that focus on ensuring self-contact. As we demonstrate, users are sensitive to inconsistent multisensory signals about the experienced virtual body, and to some extend, ensuring self-contact is a more pressing problem than the precise representation of movements in free space through absolute tracking. Moreover, our observations on the tolerance of amplified movements could help to develop rehabilitation exercises for patients with reduced movement ability [19, 26, 30].

As a future work, we even anticipate that a similarly strong embodiment could be built towards more arbitrary 3D characters provided that the real-time semantic mapping from [28] is exploited in order to guarantees the transfer of the user self-contacts on the chosen avatar body.

SUPPORTING MATERIAL

An accompanying video has been uploaded together with the submission.

ACKNOWLEDGMENTS

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REFERENCES

[1] R. A. Al-Asqhar, T. Komura, and M. G. Choi. Relationship descriptors for interactive motion adaptation. In *Proceedings of SCA '13*, pp. 45–53, 2013.

[2] A. Aristidou and J. Lasenby. FABRIK: A fast, iterative solver for the inverse kinematics problem. *Graph. Models*, 73(5):243–260, Sept. 2011. doi: 10.1016/j.gmod.2011.05.003

[3] G. Arnold and M. Auvray. The graphesthesia paradigm: drawing letters on the body to investigate the embodied nature of spatial perspective taking. *I-Perception*, 8:1–5, 2017.

[4] A. Berthoz. *The brain's sense of movement*, vol. 10. Harvard University Press, 2000.

[5] O. Blanke. Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews Neuroscience*, 13(8):556–571, 2012.

[6] O. Blanke and T. Metzinger. Full-body illusions and minimal phenomenal selfhood. *Trends in cognitive sciences*, 13(1):7–13, 2009.

[7] O. Blanke, M. Slater, and A. Serino. Behavioral, neural, and computational principles of bodily self-consciousness. *Neuron*, 88(1):145–166, 2015.

[8] M. Botvinick and J. Cohen. Rubber hands 'feel' touch that eyes see. *Nature*, 391(6669), 1998. doi: 10.1038/35784

[9] E. Burns and F. P. Brooks. Perceptual sensitivity to visual/kinesthetic discrepancy in hand speed, and why we might care. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, VRST '06, pp. 3–8. ACM, New York, NY, USA, 2006. doi: 10.1145/1180495.1180499

[10] E. Burns, S. Razzaque, A. T. Panter, M. C. Whitton, M. R. McCallus, and F. P. Brooks Jr. The hand is more easily fooled than the eye: Users are more sensitive to visual interpenetration than to visual-proprioceptive discrepancy. *Presence: Teleoperators and Virtual Environments*, 15(1):1–15, 2006.

[11] F. De Vignemont. Embodiment, ownership and disownership. *Consciousness and cognition*, 20(1):82–93, 2011.

[12] F. de Vignemont. Bodily awareness. In E. N. Zalta, ed., *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, summer 2016 ed., 2016.

[13] P. Dourish. *Where the action is: the foundations of embodied interaction*. MIT press, 2001.

[14] P. Fourneret and M. Jeannerod. Limited conscious monitoring of motor performance in normal subjects. *Neuropsychologia*, 36(11):1133–1140, 1998.

[15] H. Galvan Debarba. *Embodiment Sensitivity to Movement Distortion and Perspective Taking in Virtual Reality*. PhD thesis, EPFL, 2017. doi: 10.5075/epfl-thesis-7180

[16] M. Hara, P. Pozeg, G. Rognini, T. Higuchi, K. Fukuhara, A. Yamamoto, T. Higuchi, O. Blanke, and R. Salomon. Voluntary self-touch increases body ownership. *Frontiers in psychology*, 6, 2015.

[17] N. Holmes and C. Spence. The body schema and the multisensory representation(s) of peripersonal space. *Cognitive processing*, 5(2):94–105, 2004.

[18] Y. Inoue, F. Kato, M. Y. Saraiji, C. L. Fernando, and S. Tachi. Observation of mirror reflection and voluntary self-touch enhance self-recognition for a telexistence robot. In *Virtual Reality (VR), 2017 IEEE*, pp. 345–346. IEEE, 2017.

[19] S. Israely and E. Carmeli. Error augmentation as a possible technique for improving upper extremity motor performance after a stroke–a systematic review. *Topics in stroke rehabilitation*, 23(2):116–125, 2016.

[20] M. Jeannerod. *The cognitive neuroscience of action*, vol. 1997. Blackwell Oxford, 1997.

[21] M. Jeannerod. The mechanism of self-recognition in humans. *Behavioural brain research*, 142(1):1–15, 2003.

[22] K. Kilteni, R. Groten, and M. Slater. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012.

[23] E. Kokkinara, M. Slater, and J. López-Moliner. The effects of visuomotor calibration to the perceived space and body, through embodiment in immersive virtual reality. *ACM Trans. Appl. Percept.*, 13(1):3:1–3:22, Oct. 2015. doi: 10.1145/2818998

[24] A. Lécuyer, J.-M. Burkhardt, and C.-H. Tan. A study of the modification of the speed and size of the cursor for simulating pseudo-haptic bumps and holes. *ACM Trans. Appl. Percept.*, 5(3):14:1–14:21, Sept. 2008. doi: 10.1145/1402236.1402238

[25] D. Legrand. The bodily self: The sensori-motor roots of pre-reflective self-consciousness. *Phenomenology and the Cognitive Sciences*, 5(1):89–118, 2006.

[26] M. F. Levin, P. L. Weiss, and E. A. Keshner. Emergence of virtual reality as a tool for upper limb rehabilitation: incorporation of motor control and motor learning principles. *Physical therapy*, 95(3):415–425, 2015.

[27] T. Meese. Using the standard staircase to measure the point of subjective equality: A guide based on computer simulations. *Perception & Psychophysics*, 57(3):267–281, 1995.

[28] E. Molla, H. G. Debarba, and R. Boulic. Egocentric mapping of body surface constraints. *IEEE Transactions on Visualization and Computer Graphics*, 2017.

[29] T. I. Nielsen. Volition: A new experimental approach. *Scandinavian journal of psychology*, 4(1):225–230, 1963.

[30] D. Perez-Marcos, O. Chevalley, T. Schmidlin, G. Garipelli, A. Serino, P. Vuadens, T. Tadi, O. Blanke, and J. d. R. Millán. Increasing upper limb training intensity in chronic stroke using embodied virtual reality: a pilot study. *Journal of NeuroEngineering and Rehabilitation*, 14(1):119, Nov 2017. doi: 10.1186/s12984-017-0328-9

[31] I. Poupyrev, M. Billinghurst, S. Weghorst, and T. Ichikawa. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In *Proceedings of the 9th annual ACM symposium on User interface software and technology*, pp. 79–80. ACM, 1996.

[32] S. Razzaque. *Redirected walking*. University of North Carolina at Chapel Hill, 2005.

[33] M. V. Sanchez-Vives, B. Spanlang, A. Frisoli, M. Bergamasco, and M. Slater. Virtual hand illusion induced by visuomotor correlations. *PloS one*, 5(4):e10381, 2010.

[34] M. Slater. A note on presence terminology. *Presence connect*, 3(3):1–5, 2003.

[35] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1535):3549–3557, 2009.

[36] M. Slater, B. Spanlang, and D. Corominas. Simulating virtual environments within virtual environments as the basis for a psychophysics of presence. *ACM Transactions on Graphics (TOG)*, 29(4):92, 2010.

[37] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, 2010.

[38] G. Tieri, E. Tidoni, E. Pavone, and S. Aglioti. Mere observation of body discontinuity affects perceived ownership and vicarious agency over a virtual hand. *Experimental brain research*, 233(4):1247–1259, 2015.