Malleable Embodiment: Changing Sense of Embodiment by Spatial-Temporal Deformation of Virtual Human Body

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ABSTRACT
We hypothesize that replacing the visual perception of one's body with a spatial-temporal deformed state would change sensations associated with the body. We developed a system that captures full-body movement and generates estimated past and future body movement by deformation. With a head mounted display, people could see their bodies as slightly deformed. We then investigated 1) how human movement is physically changed, and 2) how humans feel about the change in physical and emotional views of the body due to virtual body deformation. Our results show that spatial-temporal deformation of a virtual body actually changes the sense of body as well as physical movement. For instance, a body image generated at approximately 25-100 ms in the future induced a "lighter weight" sensation. On the basis of our findings, we discuss the design implication of computational control for the physical and emotional sense of body.

ACM Classification Keywords
H.5.1. Information Interfaces and Presentation: Multimedia Information Systems-Artificial, augmented, and virtual realities

Author Keywords
Virtual Reality; Perception, Embodiment, Motion, Body Ownership

INTRODUCTION
The availability of immersive reality provides an opportunity to make the perception of one's own body more malleable by manipulating the perceived properties of the body using computer graphics. We hypothesized that replacing direct visual perception of one's body with a spatially-temporally modified body representation, mediated by computer graphics, could change how the body itself, and the movement of the body, are perceived. We tested this hypothesis using an immersive virtual reality environment (IVE), where people could observe representations of their own bodies that were computationally controlled under different parameter settings.

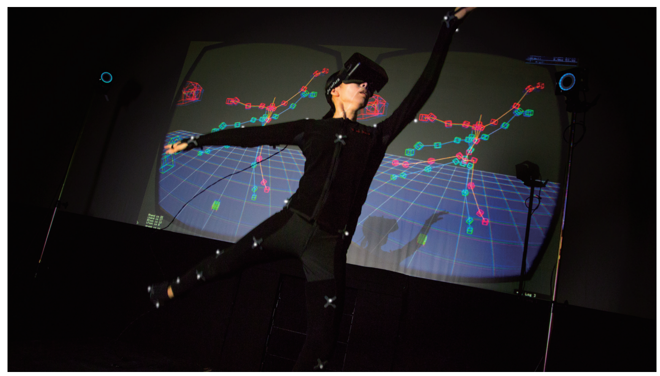

Figure 1. Setup for malleable embodiment experiments. Professional dancer is performing while seeing her virtual body through HMD. Blue skeleton represents her original movement and red skeleton represents deformed virtual body, which is temporally forwarded.

Previous research has demonstrated that perception of one's body is constructed from available information. For instance, in the body ownership illusion [6, 13] people can experience artificial body parts or fake bodies as their own. Physiological and neurocognitive studies have revealed several mechanisms to produce ownership illusion [35]. As in the ownership illusion, multi-sensory and/or sensorimotor stimulation can induce "illusions" that change the way in which the body is perceived. With the advent of immersive VR technology, the body ownership illusion can also be induced by virtual body representation [32]. Previous studies explored how human internal physical sensation and psychological emotion can be controlled by changing the properties of the virtual body representation [12, 3, 24, 18, 23].

There are many design challenges concerning how to control the physical and emotional views of the body, through dynamic movement as well as static presentation. The potentially very large design space can be constrained by requiring that the

CHI 2017, May 06-11, 2017, Denver, CO, USA.

http://dx.doi.org/10.1145/3025453.3025962

ownership of the body be maintained, along with the physical structure of the virtual body. In the research reported below, we focused on spatial deformation in terms of temporal shift, presenting views of the virtual body in motion either slightly backward (delayed) or forward (estimated) in time. This temporal deformation of a virtual body involved modulating the position of key points of the body representation. In carrying out this research we wanted to see if temporal modification of a moving body could change the sensations associated with that body.

In this study, we investigated the following two research questions;

1. "How is human movement physically changed through deformation of the virtual body?"
2. "How do humans feel, physically and emotionally, about how sensation of their body changes as their view of their virtual body is modified?"

To investigate two questions, we developed a system that captures human body movement and provides an immersive first-person view of one's deformed body in an IVE (Fig. 1). We conducted an experiment to investigate the basic properties of spatial-temporal deformation, thus addressing research questions above. The results indicated that physical movement is subtly altered by the intervention, even though most participants didn't notice the deformation of their virtual bodies. We then explored the impact of deformations to the virtual body (research question 2) by conducting a workshop study with participants who are required to be highly aware of their bodies as part of their professional practice, including professional dancers, a sports instructor, and a martial arts expert.

From the results and findings of the workshop, we discuss the design implications of computational control on the virtual body and how the body is sensed. We also discuss resulting opportunities for improving the performance of various physical activities. The potential applications of the derived design implications include full-body motion-based dance creation [16], virtual and mixed reality gaming, sports training, and physical rehabilitation.

RELATED WORK

Body ownership and Body ownership illusion

One's virtual body in an IVE has an important role in providing presence and embodiment [33], understanding space, and better cognitive processes [34]. In an IVE, it is essential for full immersion that humans identify the displayed virtual graphics as their own bodies, a phenomenon referred to as body ownership. Thus body ownership refers to the perception not only of one's physical body but also of an artificial body that is perceived to be both part of one's body and also the source of the associated bodily sensations [13]. "Body ownership illusion" (BOI) specifically refers to the illusory perception that humans assign body-ownership to non-bodily objects, and a well-known of this phenomenon is the rubber hand illusion [6].

From studies in the neurocognitive [35] and perception fields, conditions and underlying mechanisms of BOI have been investigated based on the argument that BOI can be induced through visuo-tactile [27], visuo-motor [24], and visuo-proprioceptive information [20]. In addition, it has been found that BOI induces the illusional perception in which the size or posture of body parts has changed dramatically, even when it deviates from the configuration of the physical constraints of the human body [14, 10].

Body ownership illusion in immersive virtual environment

Body ownership illusion can also be induced with 3D computer-generated virtual representation of hands [31], [37] as well as the full body [32]. Establishing body ownership of one's virtual body provides opportunities to explore body transformation and manipulation that are not possible in the real world such as having hands with an additional finger [10] or an arm longer than the actual one [14]. Normand et al. discussed the illusion of a dramatic increase in body size with VR and synchronous visual-tactile stimulation [23].

The ability to create a sense of body ownership for computational artifacts in VR may enable the design of changes to actual sensation through computational control of a virtual body representation. Previous research demonstrated that changes in posture [3] or appearance [12] of a virtual body leads to subjective, physiological, and cognitive effects on BOI, even regarding the sensation of pain [18]. In terms of changes in physical sensation, Jauregui et al. reported that changing the motion profile of a virtual arm causes changes in the sense of the weight of a virtual object in a virtual environment [11]. Banakou et al. revealed that BOI for a child's full-body virtual avatar changed the perception of size estimation [2].

These previous studies demonstrated how interventions involving the BOI in VR can lead to substantial physical and emotional changes in how people perceive their bodies and the actions of their bodies. Potential application areas for this kind of intervention include physical rehabilitation [25], sports training, expressive activities, and therapy with VR [5].

Visuomotor adaptation

Several studies have demonstrated that BOI is induced with visuo-motor triggers when both real and fake bodies move homologous body parts at the same time [2, 12]. Those visuomotor trigger BOIs requires temporal synchronicity [30] and spatial congruence [7] between the seen and the felt movements, otherwise the body ownership fails to establish.

However, researches in neuroscience also reported that humans easily adapt to changes in the environment that involve cross-sensory discrepancies. In early exploration of this phenomenon, Helmholtz studied how our finger movement adapts to a transformed visual environment [36]. Research in motor control learning has explored how our motor control mechanisms can adapt to transformed and spatial-temporal deformed own body movement [17, 21], using changes in human arm motion as an indicator of adaptation.

Other research has focused on how visuomotor adaptation updates the internal models of the body and the world [29], and how the adaptation process recalibrates multi-sensory

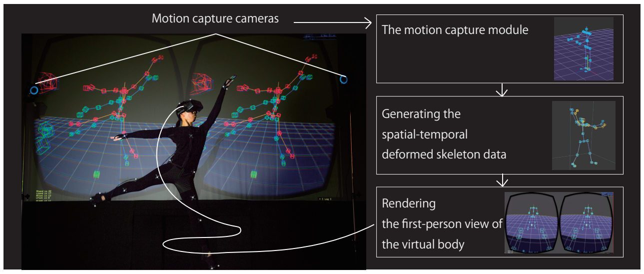

Figure 2. Proposed system captures full-body movement with motion capture and generates estimated past and future body movements through spatial-temporal deformation. With head mounted display (HMD), people can see their deformed virtual bodies from first-person perspective (as shown in back screen) with virtual mirror in immersive virtual reality environment (IVE).

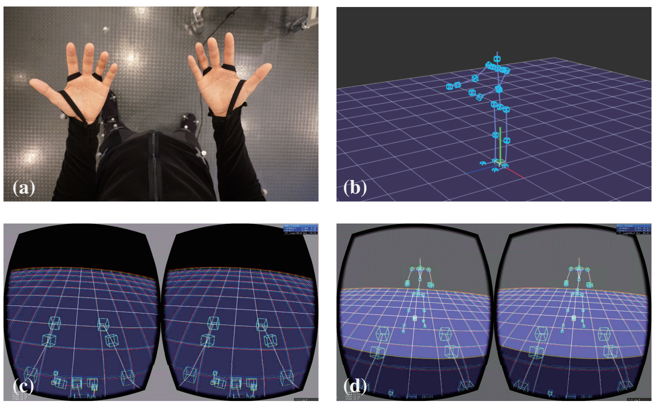

Figure 3. (a) First-person view in real world. (b) Captured human-skeleton data. (c) First-person view in virtual reality (VR). (d) Virtual mirror in VR.

relationships such as the relationship between vision and proprioception [8, 9]. It has been hypothesized that visuomotor adaptation to a transformed spatial and/or temporal motion environment affects our body perception itself. In the past, it was difficult to set up a lab environment where full body visual information could be altered using a computationally-controlled representation of a person's body. However, recent advances in virtual reality environments have now made this type of research possible [26]. Kokkinara et al. successfully employed an immersive virtual reality environment to investigate how visuomotor adaptation to the spatiotemporal and spatial distortions of arm movements affects the perception of the relationship between space and the body [15]. Thus the way is now open for research into how sensations of one's body and its movements changes as the visual representation of the body is changed.

SYSTEM FRAMEWORK

Implementation Environment

To explore our research questions, we developed an immersive VR system (Fig. 2). This system consists of a full-body motion-capture system [1] and VR HMD with head tracking functionality[2]. For capturing full-body movement, participants wear a suit with 37 retro-reflective markers, which are tracked with 8 infrared Optitrack cameras, providing a skeleton data stream of the human body (shown in Fig. 3-(b)) with sub-millimeter precision at 120 frames per second. The body-skeleton data consist of 23 node points $P_{n=23}$, which have 3-dimensional position and rotation information. Each node point corresponds to each body part such as "right elbow joint", "neck", and "left shoulder joint". The system generates the spatial-temporal deformed skeleton data at 60 frames per second. From the acquired body-skeleton data sequence, a deformed virtual body skeleton is generated with control parameters, as described later. With the HMD with head-tracking functionality, participants are able to see a first-person view of their virtual bodies in the virtual environment with the viewpoint depending on the acquired head position from the motion capture. The HMD provides a 100 horizontal deg and 86 vertical deg field-of-view at a 75-Hz framerate. The virtual camera position to render the first-person view is determined by position information from the motion capture and orientation information from the HMD. The system global delay from physical movement to displaying in the HMD is approximately 70 ms, as determined using a high-speed camera with 240 Fps to capture both the display graphics and the physical object tracked with the motion-capture system.

Design of virtual avatar

Based on previous research on BOIs in VR, there may be a number of ways to preserve the body ownership illusion when interacting with a virtual avatar. Previously reported experimental evidence indicates that BOIs are shape-sensitive [13]. For instance, from the first person perspective, BOIs were diminished when participants were seeing a rectangular body-sized object instead of seeing the first person view of a body shaped object [27].

Past research also suggests that texture realism is not crucial for BOI [13]. For instance, in the study by Peck et al. [24], BOI still occurred when the avatar had an unnatural purple skin color. The anatomical plausibility of the avatar appears to play a critical role in the induction of BOI [13]. Motion captured skeleton data provides sufficient human body structure with joint rotation and bone information. In addition to those insight from previous research, in our pilot studies we found that a simplified skeleton-like representation induced sufficient BOI in the IVE, while adding volumetric rendering on top of the skeleton sometimes reduced the strength of the BOI due to subtle discrepancies from the actual properties of the person's body, the clothing being worn, and the physical environment of the test room.

The perspective from which the virtual body is viewed is also critical for BOIs. Previous research has reported that showing a third-person view over a distant virtual body inhibited the BOI [19]. However, having a mirror perspective was found to convey a strong rubber hand illusion [4], which is likely related to the body ownership illusion in IVE.

[1] Optitrack system (http://optitrack.com/)

[2] Oculus-DK2

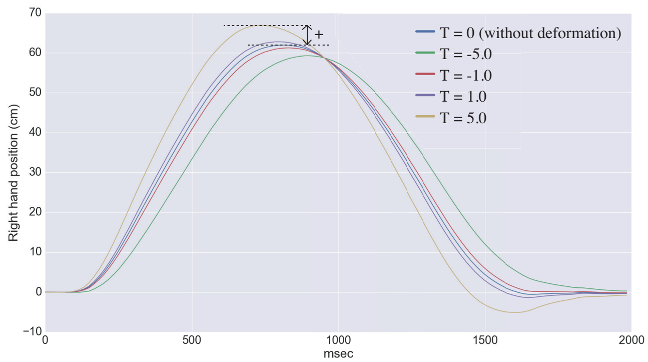

Figure 4. Example of spatial-temporal deformation in X axis. Captured the simple reaching and back action of right hand. Each line indicates the time-position profile with different deformation parameter T = -5.0,-1.0, 0.0 (original), 1.0 and 5.0. The cross mark [+] shows the overshoot effect produced with higher T parameter.

Based on this prior guidance concerning factors influencing the BOI, in our IVE system we designed the virtual bodies with boxes and lines seen from a virtual first person perspective as shown in Fig. 3-(c) and (d). In our preliminary experiments, we made sure that even those simplified graphics could induce body ownership with the virtual body. In addition to the virtual body, there was a virtual floor with line grids, several virtual boxes, and a virtual mirror, which could be controlled by the system operator .

Design of motion deformation

While there are various options for deformation, our design were to 1) provide parametric intervention and 2) preserve body ownership as much as possible. If the deformation of motion is not aligned with one's movement, the visual changes due to the deformation will be more easily interpreted as external factors that are not related to one's movement. Since our goal was to use deformations where visual changes would be interpreted as changes to one's body movement, we designed a time-based deformation model where the amount of temporal shift could be adjusted as a continuous value.

We now discuss the detailed procedure of virtual body deformation. Each node point $P_n(t)$ of the body skeleton at time t is acquired from motion capture. From this sequence, we describe the differential vector as $D_n(t) = P_n(t) - P_n(t-1)$. Then a filtered velocity $D'_n(t)$ is defined as follows, which is smoothed by weighted average with parameter k for preventing noise artifacts. In this study, we set $k = 0.1$.

$$D'_n(t) = \sum_{N=0}^{t-1} k(1-k)^N D_n(t-N)$$

With this velocity information on each node n at t, a temporally shifted position $P'_n(t+T)$ is acquired as follows:

$$P'_n(t+T) = P_n(t) + TD'_n(t)$$

After acquiring all shifted positions, the rotation of the joints was re-calculated so as to be consistent with the positions. Figure 4 shows example behavior of this motion deformation.

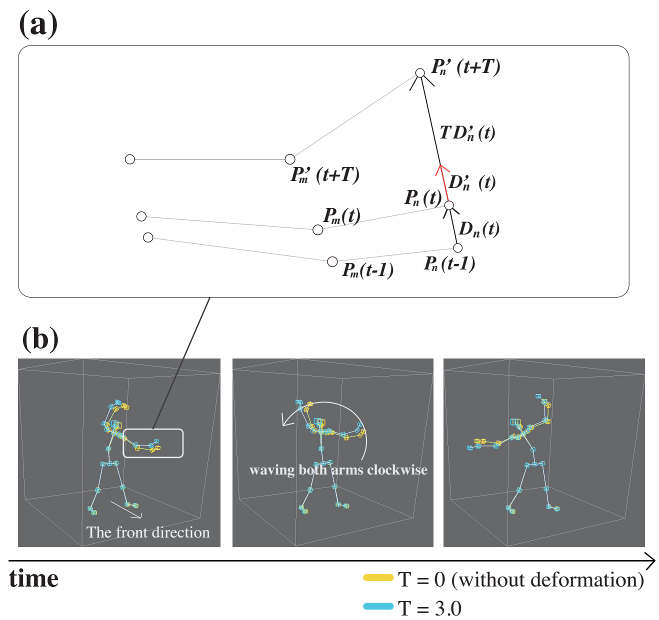

Figure 5. Example of spatial-temporal deformation of virtual body representation. (a) illustrates the generation of deformed skeleton data ($P'_n(t+T)$). (b) Yellow skeleton shows current body representation (T= 0.0) and blue skeleton shows deformed body representation estimated as 50 msec ahead ($T = 3.0$). In this sequence, the person is waving both arms clockwise.

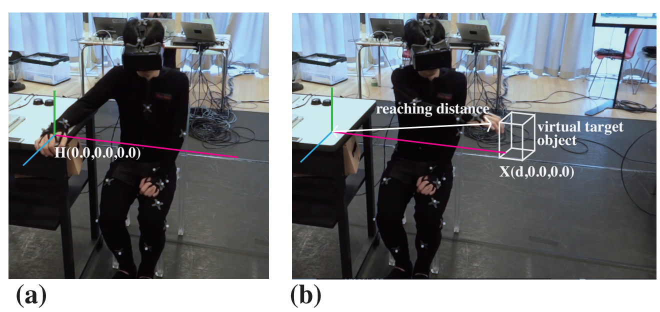

Figure 6. Experimental environment. (a) Participants sat on straight-backed chair in motion-capture area while wearing HMD. (b) Participants were asked to reach for the target with their right hand.

Here, T can be roughly defined as how much the position is shifted temporally. For instance, when the framerate of the procedure is 60 per second, $T = 3.0$ means $1000/60 \times 3.0 = 50ms$ ahead of the system baseline. In the same way, $T = -3.0$ means a 50 ms delay from the system baseline.

As we can see in this figure, a positive and higher deformation parameter (e.g. $T > 5$) produces a noticeable overshoot effect (Fig. 4-(+)). Likewise, a negative and lower deformation parameter (e.g. $T < -5.0$) produces a noticeable smoothed damper effect. Although these effects are computational artifacts, the corresponding questions; whether and how humans distinguish these effects and how humans perceive these effects, are also significant for this research.

PRELIMINARY EXPERIMENT: DOSE DEFORMATION CHANGE ACTUAL MOVEMENT?

We investigated research question 1) "How does human physical movement unconsciously change due to deformation?". In this experiment, participants were asked to repeatedly carry out a simple reaching task with our system. During this simple reaching task, the parameter of the virtual body deformation was changed without announcement. The aim of this experiment was to investigate how a participant's physical movement is unconsciously modulated due to deformation of the virtual body. To assess how physical movement was modulated, we measured the change in the reaching distance and observed how participants felt about their movement.

Procedure

Seventeen participants (8 male, 9 female, aged 25-40, Mdn = 32) took part in this study. As in experiment 1, participants were first asked to move their hands and look at their bodies from the first-person view for at least 5 minutes without any deformation of the virtual bodies. Participants were seated on a chair in the motion-capture area while wearing the HMD. Through the HMD, participants could see the virtual body representation, floor, and graphical indication for the home position $H(0.0, 0.0, 0.0)$ (Fig. 6-(a)). Before the experiment session, the target position $(X(d, 0.0, 0.0) d = 40 - 70cm)$ for reaching motion was manually adjusted in advance so that each participant could reach with his/her arm. In each reaching trial, the reaching task was carried out as follows:

1. The participant was asked to put his/her right arm on the table as the home position H (Fig. 6-(a)).
2. The virtual target box appeared at the front-left position.
3. The participant was asked to reach toward the virtual target box with his/her right hand (Fig. 6-(b)).
4. When the participant's right hand reached the target, the virtual object changed color and disappeared.
5. The participant was requested to return to home position H.

The task-execution interval was randomly determined to be between 4.0 and 5.0 sec. The reaching movement was limited to once per trial; therefore, if the participant could not reach the target, they were not allowed to reach for it again.

Design of parameter sequence

From our preliminary experiments, we confirmed the relationship between the range of the parameter value "T" of deformation and the preservation of body ownership, i.e. how strongly the participants perceive the virtual avatar as representing their own body. The range of the parameter T that preserves body ownership depended on the assumed task. After initial pilot test we determined the parameter range [-3.0 to 3.0] where participants did not notice the deformation, and designed the experimental parameter sequence within that parameter range to ensure that participants would not be consciously aware of the temporal deformations to the visual representation of their bodies during the experiment. The parameter control sequence used was [0.0, 1.5, -1.5, 3.0, -3.0, 0.0, -3.0, 3.0, -1.5 1.5]. Participants were asked to perform the reaching task in blocks of 10 trials for each step in the sequence of 10 T parameter values. Thus each participant performed 150 trials of the reaching task in total.

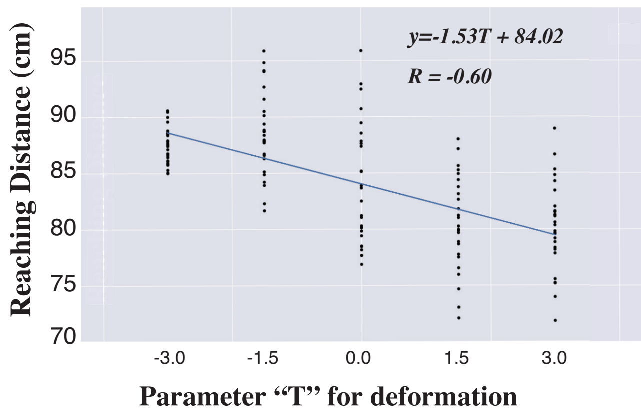

Figure 7. Example plots between T and reaching distance from home position (H), and its linear regression for participant 9 (P9).

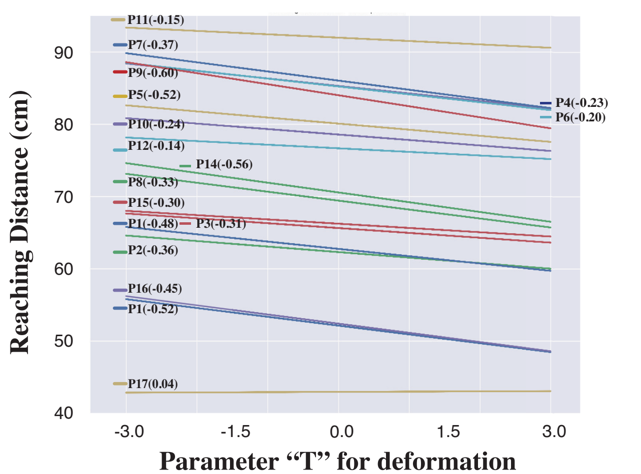

Figure 8. Plots of linear regression between deformation parameter T and reaching distance from home position H for each participant (PN). T was varied: -3.0, -1.5, 0, 1.5, and 3.0. Correlation coefficient (r) for each participant is shown as $PN(r)$.

Results

Figure 7 shows an example plot (for one participant) between the parameter T and the reaching distance (in centimeters) from the home position H. We carried out a linear regression to estimate the linear trend. Figure 8 shows the results of the analyses between T and reaching distance for all participants. The reaching distance tended to change depending on the value of the parameter. For instance, comparing the reaching distance between T=-3.0 and 3.0, with changes of more than 10 centimeters between the smallest and largest parameter values being observed in some participants.

From the collected post-interviews, participants generally did not notice the temporal deformation or changes in the distance of their movement and reaching time. However participants

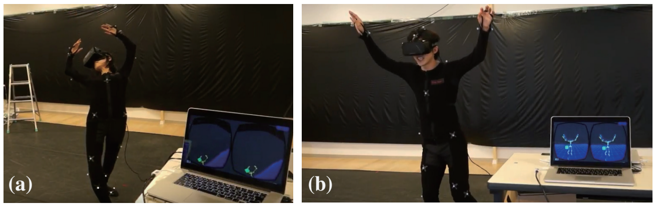

Figure 9. Workshop with specially recruited participants. (a) Professional ballet dancer dancing "Adagio". (b) Professional contemporary dancer inspired by virtual body representations.

became aware that something had changed when they did not reach the target. They usually interpreted this change as due to their own behaviour. For instance, a couple of participants mentioned that "I thought that I was too tired since I could not reach the target".

These results demonstrate that deformation of a virtual body representation can change physical movement using the body in situations where people are not consciously aware of the change caused by the deformation. After demonstrating this effect, we then designed a workshop to investigate subjective feelings associated with moving while viewing a temporally modified representation of a virtual body.

WORKSHOP STUDY

To investigate research question 2) "How do humans physically and emotionally feel the change in physical and emotional views of the body through virtual body deformation?", we conducted a workshop study with a range of participants including those who professionally use their bodies. We then analyzed the observations from our workshop, user behavior, and recorded data to derive findings and design implications.

Design of Workshop

Rather than use a controlled experiment, the workshop environment allowed us to explore more naturalistic activities. We first recruited 12 (6 male, 6 female, aged 20-40, Mdn = 33) participants who had experience, mastery, and heightened awareness of their own body, including a professional ballet dancer, contemporary dancer, dance instructor, jazz dancer, Kung-fu master, and triathlete. They were asked to verbally describe what they felt when they participated in the workshop activity.

The workshop consistsed of two sessions. In the first session, participants described their changes in sensation corresponding to various deformation conditions, but without knowing what the system was actually doing. In the second, interactive session, the goal was to derive insights and identify possible applications of the intervention based on the feedback provided by participants reflecting on their activities.

The activities and discussions in both sessions of the workshop were video recorded. Our analysis included analyzing the transcriptions of verbal reactions and discussions and analyzing participants' behaviors in each session with video material and recorded motion-captured data.

Figure 10. Workshop with paired participants. Two participants were in IVE together with same or different virtual body deformation.

Procedure

The workshop session was carried out with single or paired participants. The basic technical setup was explained to the participants and they were notified of the risk of cybersickness. Participants were informed that they could stop the session at any time if they thought they were becoming sick. Participants wore the HMD and were asked to confirm perceived ownership of their body representation for a long enough period of time that they felt adapted to the initial condition, i.e., T=0. Throughout the first session, the virtual mirror and virtual objects were available for use by the participants.

In the first workshop session participants described how much they assigned ownership to the virtual body with various controlled parameters. They were also asked to describe the rationale for their answer as well as how they felt. Participants could try various body movements such as ballet or kung-fu depending on their preference.

We then proceeded to the interactive session. We explained how we intervened through deformation and its effect. Once participants confirmed their understanding of the deformation, we jointly explored with them the resulting change in sensation and we discussed how they felt in response to the deformation. During this first session, we interactively changed the parameter conditions and virtual settings to help participants explore the change in their sensation.

We also investigated a buddy mode in which two participants were in the IVE together and could see each other's virtual bodies as well as their own virtual body. This condition enabled the investigation of interpersonal sensation beyond individual body movement. In the two conditions used in the buddy mode, the two participants either had 1) the same deformation or 2) different deformations.

RESULTS OF WORKSHOP STUDY AND IMPLICATIONS

We analyzed the observations from our workshop, statements, and recorded data to yield findings and design implications. Several patterns emerged that were found in most of the participants. Many of the collected statements were associated with physical phenomena such as weight, smoothness, stiff-

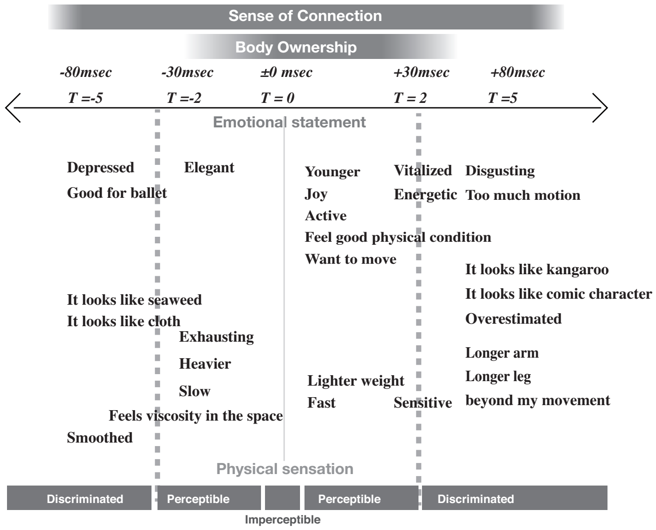

Figure 11. Structured map from collected statements regarding sensation with deformed virtual body

ness, and proportion, and related emotional expressions. As a general tendency, the deformation toward the future (i.e. T >0) induced lighter, nimble, and vitalized sensations. In contrast, the deformation toward the past (i.e. T <0) induced heavier, dull, and diminished sensations in motion. This symmetric profile was noticeable in a smaller degree of deformation (i.e. -2<T < 2). It is interesting to note this change in the spatial-temporal information of body image being translated as other physical properties with bidirectionality depending on the positivity or negativity of the parameter. It would be interesting for future research to investigate whether similar bidirectionality in physical properties is observed when using other deformative parameters.

Derived structured insight

Figure 11 shows the compiled structured map from the collected derived insights from our analysis. We found that there were three states in the parameter space in terms of how participants perceived the change in physical and emotional sensation. The following states exist, depending on the noticeability of the intervention: (a) "imperceptible", in which participants did not notice the change in sense of body, so they preserved ownership of the virtual body, (b) "perceptible change with ownership", in which participants actually perceive the change in sense of body but still preserve ownership, and (c) "Discriminated", in which participants distinguish the discrepancy between their body and the virtual body, i.e., ownership has been disconnected. However, they still have a sense of connection with the virtual body as an external or interactive object. According to our findings, these three states are aligned roughly symmetrically in the parameter space. Note that the range of these states varies depending on the personality and sensitivity of individuals.

When in state (b) as described in he preceding paragraph, the participants described the change in sensation as an internal change related to their body state, e.g., *“***I** *got a lighter body"*, *“I feel* **my body** *is a bit heavy"* and *“Now* **my body** *is nimble as I wanted it to be"*. Associated with those physical sensations, we obtained emotional statements such as *“hmm, I think I am bit exhausted? I feel tired"* or *“ hey, did you hack something? I am now more vitalized"*.

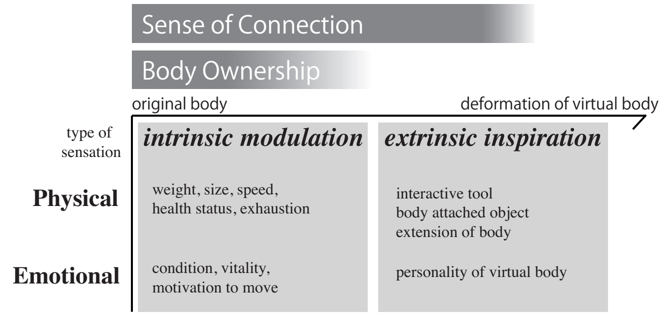

Figure 12. Design space with virtual body deformation. It roughly consisted of two spaces: "intrinsic modulation" and "extrinsic inspiration".

In state (c), however, participant reports indicated that they perceived the virtual representation as other than their body, i.e., *“* **it's** *like seaweed, now my arm looks like seaweed"*, *“it's obviously* **not my arm**, *but interesting playing with it."* , *“***it** *looks like a spring attached to my arm"*. Although they disconnected the sense of ownership, they still actually changed their physical behavior. For instance, one of the professional dancers mentioned, *“I'm actually happy to use this virtual spring attached to my body. By playing with it, I got inspiration for body movement"*. This is because the extrinsic factor also influenced and inspired them to change their physical movements. in addition, even outside the condition of body ownership, the notable change in their virtual body induced interesting emotional effects, i.e., *“I see my avatar is acting like a comic character, I feel she (the virtual avatar) is really cheerful, so I am happy to feel that I could be her"* or *“I feel comfortable and feel elegant to see the smoothed version of my body. It's really elegant, which is what I want to do in my ballet expression Adagio "* (Fig. 9 - (a)).

Design space: intrinsic and extrinsic

From the observations in the preliminary experiment, we found that there are several types of change in sensation. A significant finding is that these physically related changes in sensation were only mentioned when the deformation parameter was in the range in which participants could preserve body ownership to the displayed virtual body, as stated above. This indicates that there was more than one mechanism on how participants interpreted the sensory conflict produced by the deformation.

When body ownership had been established and preserved, participants unconsciously interpreted the sensory conflict as a change in their sensations associated with their body. This suggests that visual intervention induces a change in human internal physical properties and conditions. In other words, it induces **intrinsic modulation** in the sense of body.

In contrast, as the sense of being connected with the virtual body and/or sense of body ownership decreased, participants recognized the virtual body as an external object rather than their body. This suggests that visual changes are grounded in one's sensory conflict, but is interpreted as an interactive virtual object related to his/her body. In other words, it induces **extrinsic inspiration** for the sense of body.

From these insights, we derived two design spaces regarding the deformation of the body image, **"intrinsic modulation"** and **"extrinsic inspiration"**, depending on how humans perceive the induced sensory conflict due to virtual body deformation (Fig. 12). We now describe the design implications and possible application scenarios in these design spaces.

Intrinsic modulation

The largest advantage of this design space is that modulating the physical and emotional sense of the body can be induced unconsciously. Although the amplitude of the effect cannot be large if ownership is to be preserved, it actually affects physical factors such as weight, size, and sense of health status. In general, a temporal shift forward induces a sense of a lighter body, longer and larger proportion, faster movement, and better sensation of physical condition. In contrast, a temporal shift backward induces a sense of a heavier body, slower movement, and exhaustion. These unconscious modulations of physical sensation will also affect the associated physiological and mental states.

Computational interventions can be programmed and scheduled to provide gradual and subtle modulation so that participants will not notice. A possible application is physical condition control for athletes and dancers. This will also be able to extend to physical and mental rehabilitation. Another application will be to use these effects in VR games, which will actually change the sense of body, such as when a player is hit by an enemy, the player will actually feel exhausted, and when virtual medicine has been administered, the player will feel re-vitalized.

Extrinsic inspiration

In this design space, a person can be inspired and influenced by their virtual body. The significant advantage of this design space is the freedom of expression of the virtual avatar including spatial-temporal deformation, as we demonstrated, but not limited to this. This could be a kind of hyper mirror-type application such as video games with a camera capturing one's body image or virtual cloth fitting system with a large screen. In this design space, the virtual mirror takes an important role in giving the context that the user is looking at the reflection of his/her body, which allows him/her to watch the his/her body be transformed.

Although there are a large variety of design spaces, one significant implication is designing the movement of virtual objects to provide a sense of connection with one's own body, in other words, sense of agency. By preserving this sensation, humans will interpret virtual objects as connected to their body or as an extension of their bodies. These sensations will induce a change in human physical behavior and inspiration to create motion. This feature is valuable for dance choreography because it can provide dynamic context through computational control. The metaphor of external objects with certain virtual physicality will also contribute to sports training and rehabilitation in which a person can imagine a virtual object as a guide toward the target body movement. In addition to the effect on human physical motion, emotional influence is also important in this design space. As we can observe statements about feelings toward the virtual body, the spatial and temporal deformation of virtual body will also be valuable for therapy and entertainment applications.

Experimental paired session

In the empirical paired session, 3 pairs (6 participants) tested two parameter conditions, in which two participants see the same or different parameter-deformed virtual bodies; their own and their buddy's (Fig. 10). An obvious limitation in this session was that physical contact at certain speed induced visuo-haptic conflict, which refers to the sensory conflict between visual context and haptic and tactile sensation or simply the sense of touch.

We also observed changes in the impression of the buddy's body movement. Consistent with our findings from the preliminary experiment, when two participants were performing a dance motion with shaking hands in the forward temporal deformation state, both participants felt that the buddy's movement was lighter, or more lively, as well as their own.

In addition, two participants moved with different deformation parameters (e.g. P1 was watching P1 and P2 virtual bodies forward-shifted deformed, and P2 was also watching P1 and P2 virtual bodies but those were backward-shifted deformed). In this situation, as long as they were keeping their hands connected, they believed that they were in the same deformation condition. This implies that applying difference parameter for multiple individuals would induce a kind of parallel reality in terms of their body sensing. This type of phenomena creates interesting possibilities for designing multi-person physical experience in an IVE

DISCUSSION

Limitations of illusion

For designing experiences for the "intrinsic modulation" space, we also need to know the limitation of preserving ownership to induce illusional change in sensations associated with the body. Throughout our research, we carefully interviewed participants on how and when ownership could not be preserved.

Visio-motor discrepancy with small motion

When participants moved their hands in small movements such as waving, they were more likely to recognize the discrepancy at an early phase of the motion. With forward-shifted deformation, the participants mentioned, *"this (the virtual body) looks like it is reading my mind and goes there before I go", " I feel the existence of another who is trying to be faster than me".*

Visio-motor discrepancy with sudden motion

Another observation in distinguishing visio-motor conflict was the sudden stop in the motion. This was noticeable in larger parameter values in forward-shifted deformation. In the current procedure to generate a temporal shift, overshooting artifacts of the motion occurred in forward-shifted deformation, as shown in Fig. 4. This sense of conflict was also mentioned by participants, e.g., *"I found that my virtual hand had overestimated, and when I stopped the hand, it came back to my* *hand* (T = 5) or *"I feel it (virtual body) is bouncy"*. This limitation in visio-motor conflict suggests that a more accurate procedure of estimating the future state of body movement will expand the possibility of the spatial-temporal deformation of a virtual body with our system.

Assessment of mastery

From the results and interviews in experiment 1 and the workshop, we found that participants who had their own body motion dictionary (i.e. have experience or a mastery in specific motions or body forms) easily distinguished visio-motor conflicts, even when there was a small difference. They used their mastery in such motion for answering questions. The participant who was experienced in kung-fu mentioned that, *"I know when and how my hand and arm are located as a "form" of kung-fu. So, I was very sensitive to visual errors"*. An experienced swimmer mentioned , *"For experiment 1, I used a swimming movement with my arms that I was most used to. But without it, I would not be able to distinguish the changes"*. Therefore, when we design the intrinsic modulation with deformation of a virtual body, we will need to carefully assess how much the participant has mastery of the physical movement.

Visio-haptic discrepancy in physical interaction

One more significant observation regarding the disconnect in body ownership is visio-haptic conflict. For instance, by clapping hands or hitting a part of one's body, participants easily found discrepancies. This is also critical when participants physically interacted, e.g., touched, the physical environment and other people such as in the martial arts.

These issues are related to well known problems of how to create the sense of touch for virtual objects in VR. There are several possible solutions including "active haptics" [22] with the aid of robotics, tactile devices, and tactile suits. In addition, leveraging the perceptual illusion, as we did, "haptic re-targeting" [1] in terms of objects and the human body, and "re-directional walking" [28] in terms of the body and physical environment may be potentially useful in overcoming these limitations.

Reason for sense of changing weight

As we observed in the workshop, we found that several statements about change in the physical sense of the body are related to the sense of weight, e.g., the forward-shifted deformation make us feel lighter, and backward-shifted deformation makes us feel heavier. However, the underlying mechanism still remains to be proven.

Current limitations of study

Throughout our investigation, we found that there are limitations in terms of technical issues between the reality of the study and task reliability, and generalization of our results. We investigated the temporal shift of motion. As we discussed above, to validate the phenomena we found, a system with low latency and a more accurate procedure to estimate the future motion state is necessary.

Another current limitation is the requirement to use an IVE which separates the person from the actual world. This restriction might be removed by used a mixed reality version of the current system with an optical see-through HMD. Such implementation will enable the deformation of the virtual body to be grounded in the actual real body and change in sense will be interpreted as what happened with the actual body.

Another issue is related to the methodology of this study. To investigate the phenomena that our intervention induced, it might be deemed preferable to control the movements made more precisely. For instance, the use of a robotic manipulandum to move the participant's arm in a precise way. However, too much design and restriction of human behavior will decrease the reality of the study and result in detachment between the investigated procedure and actual behavior for prospective practical applications.

Each participant saw the same sequence of (10) blocks in the preliminary experiment reported above. As noted by the reviewers it would have been better to fully counterbalance or randomize the orderings between participants. However, separate analyses of the regressions between T and reaching distance for the first five vs. second five experimental blocks showed similar results, demonstrating that order effects did not have an effect on the negative relationship between T and reaching distance that was observed for all but one of the participants.

CONCLUSION

We investigated the hypothesis that: altering one's body image through spatial-temporal deformation changes the sense of his/her sensations associated with the body. We developed a VR system that captures full-body movement and generates estimated past and future body movement through spatial-temporal deformation. With an HMD, people can see their virtual bodies from the first-person perspective. We first conducted a preliminary experiment to study the research question: 1) "How is human movement physically changed through deformation of the virtual body?". The results revealed actual physical effects due to spatial-temporal deformation. We then conducted a workshop study with specially recruited participants to investigate research question 2) "How do humans feel, physically and emotionally, about how sensation of their body changes as their view of their virtual body is modified?". Our results show that spatial-temporal deformation of a virtual body actually changes the perception of the body as well as physical movement. Based on the results obtained from the experiment and from the workshop study, we derived two design spaces of virtual body deformation and discussed the implications of these design spaces. The present results and discussion concerning the impact of spatial-temporal deformation of the virtual body may provide the way for exciting new possibilities and potential applications involving computational control of how a person's body is perceived and controlled, along with associated impacts on feelings and emotions.

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