Modified Egocentric Viewpoint for Softer Seated Experience in Virtual Reality

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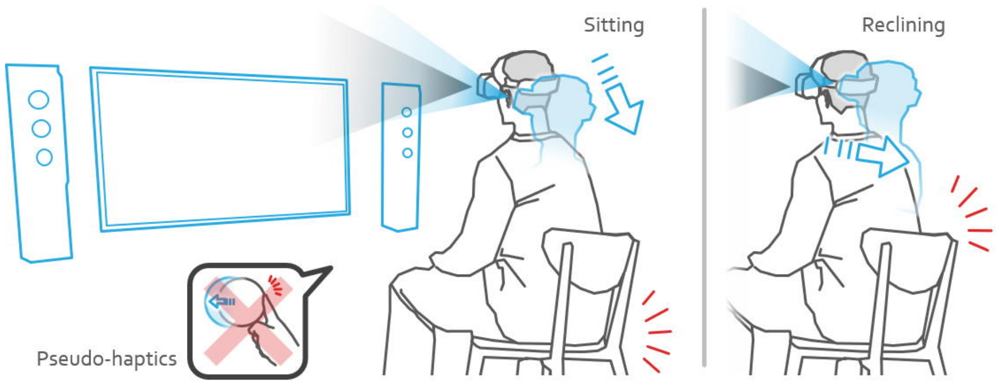

Fig. 1: Conceptual illustration of our study. We demonstrate that egocentric viewpoint modified in VR can induce softer seated experiences when sitting (left) and reclining (right) in a chair. In both cases, pseudo-haptics (inset) does not apply, given that the user cannot observe the changes in the chair's appearance. The blue objects represent objects in VR space, the red annotations indicate where the interaction occurs, and the arrows show how the virtual augmentation is performed.

Abstract—Users in a prolonged experience of virtual reality adopt a sitting position according to their task, as they do in the real world. However, inconsistencies in the haptic feedback from a chair they sit on in the real world and that which is expected in the virtual world decrease the feeling of presence. We aimed to change the perceived haptic features of a chair by shifting the position and angle of the users' viewpoints in the virtual reality environment. The targeted features in this study were seat softness and backrest flexibility. To enhance the seat softness, we shifted the virtual viewpoint using an exponential formula soon after a user's bottom contacted the seat surface. The flexibility of the backrest was manipulated by moving the viewpoint, which followed the tilt of the virtual backrest. These shifts make users feel as if their body moves along with the viewpoint; as a result, they would perceive pseudo-softness or flexibility consistently with the body movement. Based on subjective evaluations, we confirmed that the participants perceived the seat as being softer and the backrest as being more flexible than the actual ones. These results demonstrated that only shifting the viewpoint could change the participants' perceptions of the haptic features of their seats, although significant changes created strong discomfort.

Index Terms—Softness-perception, pseudo-haptics, virtual-viewpoint, chair

1 Introduction

Virtual reality (VR) has gained increasing popularity due to commoditized hardware and middleware. With the recent portable hardware, VR applications are often aimed for frequent and long-term usage. As users engage in various tasks while using VR environments, they experience different degrees of physical load. Eventually, users find the most comfortable posture depending on their task, in the same manner as done in the real world. Sitting and standing modes in VR are known to have different advantages [60]; thus, best-suited scenarios differ for each type of action [3].

VR users may wish to sit on a chair to perform some tasks, such as writing letters, reading a book, and taking a rest. However, VR users cannot sit on virtual chairs in pure VR space consisting of only visual information. To address this issue, the VR environment can be constructed based on real-world objects. For example, some methods can produce effective prop layouts in a virtual environment based on the actual room [7, 36]. These studies have demonstrated that users can sit on a chair in VR by utilizing a real counterpart. However, Brade et al. [7] did not find improvements in user experience in VR because of predefined and thus limited scenarios.

However, if application developers provide a chair that differs from the one in the real world, this inconsistency can create haptic feedback that differs from the expectation and thus decrease the user's sense of presence [19, 30]. This inconsistency can be resolved by providing features that are close to the VR chair rather than focusing on merely matching the appearance of the chair. In this study, we focus on the perceived softness of a chair co-existing in virtual and real space, particularly seat softness and backrest flexibility.

The softness of deformable objects is perceived based on cutaneous and proprioceptive information and by observing objects deform [52, 55]. Upon sitting on a chair, these two cues have a significant impact on softness perception because the user cannot observe the deformation of the chair. In this study, we primarily focus on proprioception. Proprioceptive information comes from muscles, tendons, and joints [53] and allows us to perceive body parts' positions and movements [25]. However, proprioceptive information is not the sole source of such perception. Vestibular cues play a role in the perception of head and body movements and their acceleration, and visual information affects on self-motion and body posture perception. Among these sources of perception, visual information is considered more

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significant than others when integrating multimodal information [17]. For example, visual information showing body parts whose position differs from the actual position gives an incorrect perception of elbow angle [6] and hand position [40]. Redirected walk [48] and self-motion illusion [44] utilize visual information to change participants' perceived body movements. Therefore, we hypothesized that visual information can modify body posture and movement, which change the perceived features of a chair, such as seat softness and backrest flexibility in this study (Figure 1).

Our proposal is similar to pseudo-haptic feedback in that we control visual information to modify the perceived body posture [33]. The noticeable difference is that the preceding approaches require the user to see the visual modification of target objects (Figure 1, inset), whereas we seek to find an indirect way to ensure that the user does not keep watching target objects (i.e., a chair; Figure 1). By moving the virtual scenes surrounding the user, we create a feeling of body movement conducting sitting on a softer chair.

Overall, we demonstrate that virtually manipulating a viewpoint can change the users' perception of the chair features in the following two cases.

- The downward movement of the viewpoint that gradually slowed down made the participants perceive the seat as softer than it actually was.
- The viewpoint movement following a reclined virtual backrest gave the participants the perception of a flexible backrest.

It should also be noted that in both cases, the more the viewpoint moved, the more uncomfortable the participants felt. These results were derived from a controlled experiment that excluded the effect of individual differences. We instructed the participants to sit on the chair and recline in a pre-determined manner. Evaluations under other natural seated conditions are planned for future work.

2 Related Work

In this section, we review literature that explored the influence of static and dynamic visual information on modifying softness perception. We also discuss how viewpoint manipulations in VR are used to control haptic perception.

2.1 Static Visual Information on Softness Perception

Humans can comprehend objects' properties by physically touching them and recognize softness by passive and active touches [18, 55]. Especially with hands, cutaneous sensation plays an important role in softness perception [4]. However, human perception is a result of an integration of multiple sensory modalities [14]. In particular, visual information contributes to perceived softness. For example, Ujitoko et al. stated that humans can judge the softness of materials based on visual cues alone [57]. Wu et al. also revealed that vision dominantly affects softness perception when there is a discrepancy between visual and haptic information [59].

Various studies have evaluated the impact of differences in objects' appearance, such as texture [50], thickness [27], color [37], and brightness [54], which result in differently perceived softness of objects when they are touched. Analytic studies of softness perception have mainly focused on touching objects with hands. We find only a few works focusing on the seated state. For instance, according to Erol et al., the color tones of a car seat influence the perceived softness of the seat [15]. Specifically, they suggested that gray chairs tend to be perceived as softer than black ones. To the best of our knowledge, we could not find any study that has clarified the relationship between modified sit–stand movements and the effects on softness perception. Readers may refer to [41] on the efficacy of sit–to–stand training for rehabilitation, although softness perception is out of their interest. In this research, we analyzed the perceived softness and perceptual influence of visual information during modified seated experiences.

2.2 Pseudo-haptics on Softness Perception

Pseudo-haptics exploit the characteristics of human susceptibility to visual information in haptic feedback [33]. This approach induces pseudo-sensation by dynamically changing the visual representation related to softness [35], roughness [10], and weight [42]. For example, Lécuyer et al. presented a pioneering work demonstrating pseudo-haptic feedback. They adjusted the degree of deformation of a virtual spring that deformed in response to an exerted force. As a result, the participants perceived various softness according to the displayed deformation of the spring [33].

Various effective approaches have been developed to virtually change softness via pseudo-haptics. For instance, Elastic Image can alter the perceived elasticity of displayed images by manipulating the degree of deformations when images are clicked [1]. SoftAR applies spatial augmented reality to enhance objects' softness with projected object textures [46]. Ban et al. controlled softness with consistent deformation to the object and hand touching the object [2]. In addition, a mid-air action with control of the virtual object deformation impacts softness perception [26]. Moreover, various literature has shown that delayed haptic feedback creates a softer perception of the object [29, 34].

In summary, previous studies have investigated ways to change perceived experiences, especially softness, by modifying objects' appearance observed by the person touching the object. However, in this study, we attempted to change the perceived softness of a chair by shifting the egocentric view locations over time (i.e., neither by changing the chair's appearance nor by adding haptic devices). Results in previous research [47] have confirmed that exaggerated visual changes weaken perceptual impact on pseudo-haptics. Thus, we examined the degree of visual changes that can effectively induce change in perceived softness.

2.3 Viewpoint Impact on Haptic Perception

Shifting the viewpoint influences our perception. Redirected walking (RDW) is a well-known locomotion technique that imperceptibly changes the image displayed on a head-mounted display (HMD) [48] and tricks users walking in a limited real space into believing that they are walking in a vast VR space. RDW is realized with the representation of video images that apply gains to translation [23], rotation [51], and curvature [49] against the gait of the user. An analogous technique can mimic walking on a slope [39] or stairs [43].

A similar approach may work for non-walking conditions. Lécuyer et al. proposed to move the user's viewpoint up and down to represent walking [32]. Danieau et al. found that cinematographic camera motions during video viewing improve the quality of experience score [12]. Moreover, Tada et al. claimed that viewpoint displacement produces a sense of resistance when users move their hands [56]. These studies show that somatosensory-based perception is affected by the observed image. However, no study so far has investigated the effect of VR egocentric viewpoint changes on perceived softness, particularly when seated.

3 Shifting Viewpoint on Virtually Enhanced Chair

We model a virtual viewpoint animation that mimics sinking when we take a seat on a chair upholstered with soft materials (Figure 2). Based on this animation, the user's viewpoint in the virtual space lowers more than it does in real space. The shift is triggered when the user's bottom comes into contact with the chair surface (i.e., a user-dependent height is measured in advance).

We use an exponential function to model gradual changes from rapid sinking at the beginning to stable sinking at the end. This function allows us to control the depth and speed of sinking with two respective parameters: a target sinking depth, d_{sink}, and a speed control parameter, s.

$$y(t) = h_{\text{start}} - d_{\text{sink}}(1 - e^{-ts}), \tag{1}$$

where $y(t)$ represents the height at the t_{th} frame, and h_{start} denotes the height, at which the sinking animation starts (Figure 2a). Therefore, $y(t)$ eventually reaches $h_{\text{start}} - d_{\text{sink}}$. In a preliminary study with a few participants, this function best matches the expected feeling of being in a seated position among the tested functions, such as linear and sinusoidal. However, the participants commented that with a simple downward animation, they were not able to distinguish whether they

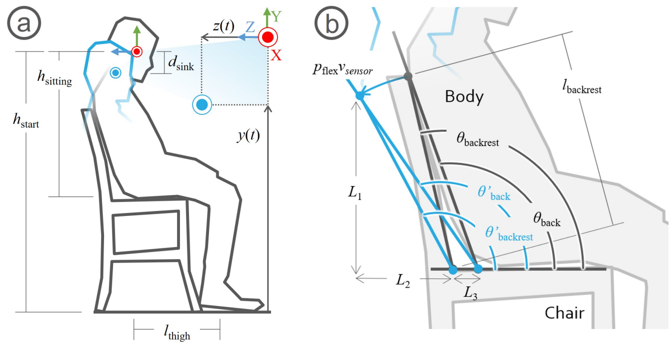

Fig. 2: Parameterizing the egocentric viewpoint shifts: (a) sitting and (b) reclining. (a) The user's viewpoint moves from the red circle at the height, h_{start}, where the sinking animation starts, to the blue circle by the target sinking depth, d_{sink}. $y(t)$ and $z(t)$ define such changing height and backward position (Eqs. (1) and (2)). The animation speed is controlled by s. $h_{sitting}$ and l_{thigh} denotes the sitting height and thigh length, respectively, and they are perpendicularly fixed. (b) The angle of a virtual backrest, $\theta'_{backrest}$, is determined by virtual chair flexibility parameter, p_{flex}, measured force, v_{sensor}, and angle between the real chair surface and backrest, $\theta_{backrest}$. $L_1 = l_{backrest}\sin\theta'_{backrest}$, $L_2 = |l_{backrest}\cos\theta'_{backrest}|$, and L_3 are the height of the contact point to the virtual backrest from the chair surface, the length of the contact point to the corner of the backrest, and the measured length from the corner to the user's bottom, respectively.

were sinking or the world was lifting. To address this issue, we add a gentle backward motion to simulate reclining when a person sits and sinks into the chair. Assuming that there is a single rigid-body person on a chair, we calculate the backward shift as follows:

$$z(t) = d_{sink}(1 - e^{-ts})h_{sitting}/l_{thigh}, \quad (2)$$

where $z(t)$ represents the backward shift at t_{th} frame, and $h_{sitting}$ and l_{thigh} denote the sitting height and thigh lengths, respectively. The participants confirmed that the additional motion cue resolved the above-mentioned confusion.

Apart from the sinking sensation when seated, we investigate how modified reclining can create a softer experience. During the contact, the reclining is pronounced. We detect the touch of the users' back to the backrest using a pressure sensor. The enhanced backrest angle, $\theta'_{backrest}$, is calculated as follows:

$$\theta'_{backrest} = p_{flex}v_{sensor} + \theta_{backrest}, \quad (3)$$

where p_{flex} is a control parameter to change the virtual chair flexibility, v_{sensor} denotes a sensor measurement force, and $\theta_{backrest}$ is a measured angle between the chair surface and backrest (Figure 2b). Given the modified backrest angle, we calculate the angle, θ'_{back}, of the virtual reclination against the backrest as follows:

$$\theta'_{back} = \pi - \arctan(L_1/(L_2 + L_3)), \quad (4)$$

where $L_1 = l_{backrest}\sin\theta'_{backrest}$, $L_2 = |l_{backrest}\cos\theta'_{backrest}|$, and L_3 is the distance measured from the corner of the backrest and the seat surface to the contact point.

In the following sections, we evaluate that two types of viewpoint shifts (i.e., shifts when seated (Eqs. 1 and 2) in Section 4 and shifts when reclining (Eq. 4) in Section 5) in two user studies. Finally, Section 6 provides an overall discussion.

4 Experiment 1: Sitting on a Chair

Design. We designed a repeated-measures within-subjects study to evaluate the perceived seat softness through viewpoint modifications. We introduced the target sinking depth, d_{sink}, and the speed control parameter, s, as independent variables. The dependent variables were the seven-point rating for seat softness and discomfort reported by the participants. We manipulated the viewpoints displayed on the HMD when the participants' bottoms reached the surface of the chair seat.

Designing Parameters. A preliminary examination with a few participants was conducted to determine the range of d_{sink} and s. In Eq. (1), we defined three parameters on $d_{sink} \in \{0.05, 0.20, 0.35\}$. The minimum value $d_{sink} = 0.05$ was chosen because with this minimum value, participants could recognize the camera's viewpoint change; $d_{sink} = 0.35$ was chosen because the average thigh length of the participants was 0.4 m (the average height of the participants was 1.7 m). In Eq. (1), we assume that users' knees are fixed at the position when they sit on the chair and their bodies rotate around the point. Therefore, the bottom does not sink deeper than the thigh length. We also added $d_{sink} = 0.20$, which is the intermediate value between the minimum and maximum target sinking depth.

For s in Eq. (1), we used $s \in \{0.018, 0.025, 0.12\}$. Given that the viewpoint changes rapidly as s increases, we selected $s = 0.12$ as the maximum value, which did not cause a sense of falling down or discomfort. The remaining parameters were determined based on the participants' feedback: We recorded the values when the participants noticed a change in the chair's perceived softness while lowering the parameter. Moreover, we added a baseline condition where the camera position was not changed. Overall, Experiment 1 used 10 visual conditions, consisting of nine conditions that combined the d_{sink} and s parameters ($3 \times 3 = 9$) and one baseline condition.

Task. We presented visual stimuli with modified viewpoints in random order in each trial. The participants sat in the chair under the determined visual conditions. Then, they were asked to rate the softness and discomfort of the seat on a seven-point scale. When rating softness, the participants were asked, "*How did you feel the chair when you sat on it?*" and provided score ranging from 1 (extremely hard) to 7 (extremely soft). When rating discomfort, the participants were asked, "*Did you feel uncomfortable when you sat on the chair?*" and ranked their sensation from 1 (not at all) to 7 (extremely unomfortable). The participants repeatedly evaluated all 10 visual conditions. The entire procedure was repeated three times.

Apparatus. We used Oculus Quest HMD[1] and Unity3D to build a VR system. The HMD and computer were connected wirelessly to for simplicity. The HMD had $2,880 \times 1,600$ pixel resolution at 72 Hz along 100° (V) and a 104° (H) field of view. Having created a room-scale virtual environment (Figure 3a), to help participants recognize the height and depth, we placed assets from the Unity assets store, such as a house cabin (*Furnished Cabin*), TV (*Bedroom - Architect*), and carpet (*Round Carpet*), at reasonable depths. We noted that no participant reported any physical discomfort related to system latency during the experiment.

We used a stable chair with an adjustable seat height (adjustable height chair no.5, Itoshin). The size of the chair was 400 mm (width) × 880 mm (height) × 460 mm (depth). The seat height could be adjusted in the range of 423–543 mm for each participant's knees height. It guaranteed that even with the largest d_{sink} the participants' bottoms did not touch the floor. Furthermore, the chair backrest was completely fixed. We added a thin cushion to the chair seat to reduce burden on the participants' bottoms due to repetitive sitting and standing postures. We confirmed that the impact of the cushion softness on the perceived softness was insignificant.

Participants. Thirteen participants ($\bar{X} = 21.8$ [SD $= 0.7$] years old, all male) volunteered in the experiment. All participants were university students and had experience using VR devices.

Procedure. The participants were first provided with an explanation of the experiment and signed consent forms. They were then introduced to a practice session of chair sitting to standardize their sitting behavior. The participants were asked to keep their backs straight to avoid leaning forward or backward when sitting down or standing up

[1]https://developer.oculus.com/resources/oculus-device-specs

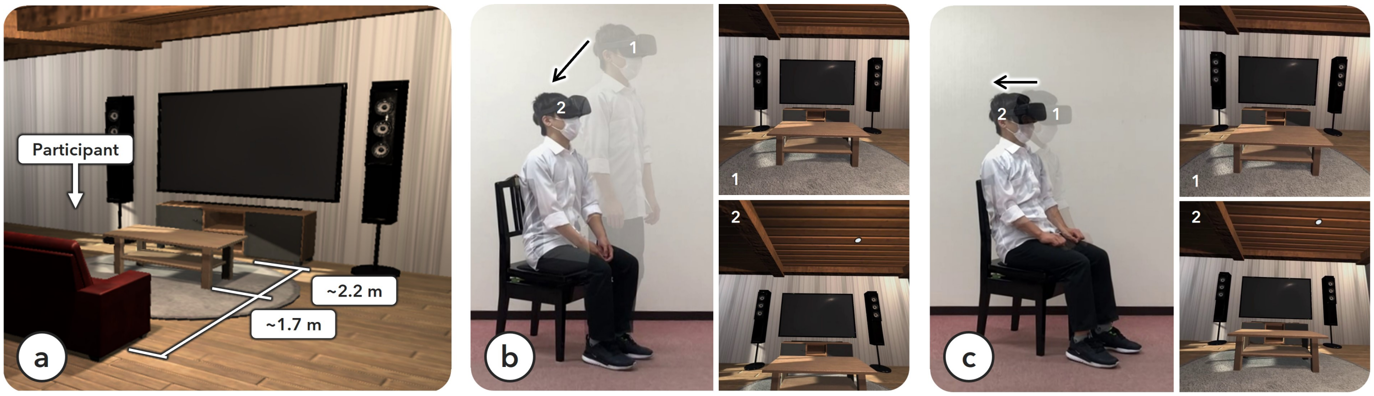

Fig. 3: Setups for the two experiments: (a) VR content and distances to the assets in front of the participant; (b) sitting in Experiment 1; (c) reclining in Experiment 2. Images 1 and 2 on the right show the user's view at the beginning and end of the action.

from the chair. They were also instructed to place their hands on their knees and not to recline in the chair. Such practice sessions continued until participants were able to sit down and stand up from the chair as instructed. The experimenter carefully observed all participants so as to sit and stand at a similar speed.

After the practice session, the main session started. The participants were allowed to take a break during the main session. They were asked to stand up and sit down from the chair under a randomly selected condition from the 10 conditions described in the "Designing Parameter" section. The camera position and orientation were initially adjusted so that the TV monitor in the virtual room was positioned in front of th and seated participant. Next, we preserved the head height and then verbally instructed the participants to sit in the chair once they assumed a standing position.

Finally, once they sat on the chair, the softness and discomfort questionnaires were displayed on the HMD against a black background. The participants answered the questionnaire verbally using a seven-point scale. The trials were repeated under all conditions, with sufficient breaks to avoid sensory adaptation. The entire procedure was repeated three times. The order of all trials was fully randomized for each participant. We collected the participants' feedback at the end of each session, and the total duration of the experiment was approximately 90 minutes per participant. In total, we collected 390 ratings (= 13 participants × 10 conditions × 3 sets).

Analysis. We gave a score from 1 to 7 to each softness answer from "extremely hard" to "extremely soft"; therefore, a score higher than 4 means that the participants felt that the seat was soft. The discomfort score was also rated from 1 to 7 from "not at all" to "extremely uncomfortable"; therefore, when the participants felt uncomfortable, they gave a score higher than 4. First, we compared the score in each condition with the baseline score that was acquired in the condition where no viewpoint change was applied. As our data were not normally distributed ($p_s < 0.05$ based on the Shapiro-Wilk test), we used the Wilcoxon signed-rank test. A significant level was adjusted with Holm's method. If the score was significantly higher than the baseline, the viewpoint change in the condition changed the perceived softness or discomfort.

Second, we evaluated how each parameter affected the softness or discomfort perception. To analyze the interactive effects between the two parameters, we employed the aligned rank transform procedure [58] for hypothesis testing using the ARTool package[2] in the R statistical analysis software package. Thus, a 3 (d_{sink}: $0.05, 0.20, 0.35$) × 3 (s: $0.018, 0.025, 0.120$) ANOVA was conducted. If we found a significant effect ($p < 0.05$), we conducted multiple comparisons adjusting the p-value with Tukey's method.

[2]https://cran.r-project.org/web/packages/ARTool/index.html

Results. Figure 4 shows the average scores in each condition. The dashed line shows the baseline score. Figure 4a shows that the average score for the softness evaluation was higher than the baseline in the majority of the conditions. In all conditions other than the combination of $d_{\text{sink}} = 0.05$ and $s = 0.12$ ($p = 0.548$, $r = 0.167$), the participants gave a significantly higher (i.e., softer) score than in the baseline score ($p_s < 0.015$, $r_s > 0.690$). In particular, when $d_{\text{sink}} = 0.2$ or larger and $s = 0.025$ or smaller, the scores were higher than 4, which means the participants felt that the chair seat was soft rather than hard.

In addition, we analyzed the relationship between the parameters and the softness scores. Although there was no significant interaction between two parameters ($F(4,96) = 0.542$, $p = 0.705$, $\eta_p^2 = 0.011$), ANOVA revealed a significant main effect of both d_{sink} ($F(4,96) = 23.900$, $p < 0.001$, $\eta_p^2 = 0.332$) and s ($F(4,96) = 41.201$, $p < 0.001$, $\eta_p^2 = 0.462$). For d_{sink}, the smallest value of 0.05 (i.e., the shortest sinking) was scored significantly lower than the two other values ($t_s > 5.000$, $p_s < 0.001$, $d_s > 1.300$). For s-value, the largest value of 0.12 (i.e., the fastest sinking) was scored significantly lower than the two other values ($t_s > 7.350$, $p_s < 0.001$, $d_s > 1.500$). There was no significant difference in the other pairs ($t_s < 1.160$, $p_s > 0.250$, $d_s < 0.370$).

Figure 4b shows that in all conditions, the discomfort scores appeared higher than the baseline. The comparisons against the baseline score show that the scores in the experimental conditions were significantly higher than the baseline score ($p_s < 0.030$, $r_s > 0.615$). According to the ANOVA results, we found a significant main effect of both d_{sink} ($F(4,96) = 23.011$, $p < 0.001$, $\eta_p^2 = 0.324$) and s ($F(4,96) = 8.977$, $p < 0.001$, $\eta_p^2 = 0.158$). As the d_{sink} value increased, the discomfort score also significantly increased ($t_s > 2.550$, $p_s < 0.035$, $d_s > 0.840$). Regarding parameter s, the largest value of 0.120 significantly decreased the discomfort score (vs. 0.018 $t = 4.077$, $p < 0.001$, $d = 0.985$; vs. 0.025 $t = 3.038$, $p = 0.009$, $d = 0.776$). As shown in Figure 4b, this statistical significance can be due to the lower score in the condition of the largest s value (0.12) with the smallest d_{sink} value (0.05). The interaction between the two parameters can be marginally significant because of this lower score ($F(4,96) = 2.424$, $p = 0.053$, $\eta_p^2 = 0.048$).

5 Experiment 2: Reclining Toward a Backrest

Design. We designed a repeated-measures within-subjects study to evaluate the perceived backrest flexibility of the chair by viewpoint modifications and introduced p_{flex}, the flexibility of the chair's backrest, as an independent variable. The dependent variables were the seven-point rating for backrest flexibility and discomfort rating reported by the participants. We manipulated the viewpoints displayed on the HMD according to the strength with which the participants reclined in the chair.

Designing Parameters. p_{flex} in Eq. (3), which indicates the virtual chair flexibility, was set to five levels: 0.5°, 1.0°, 1.5°, 2.0°,

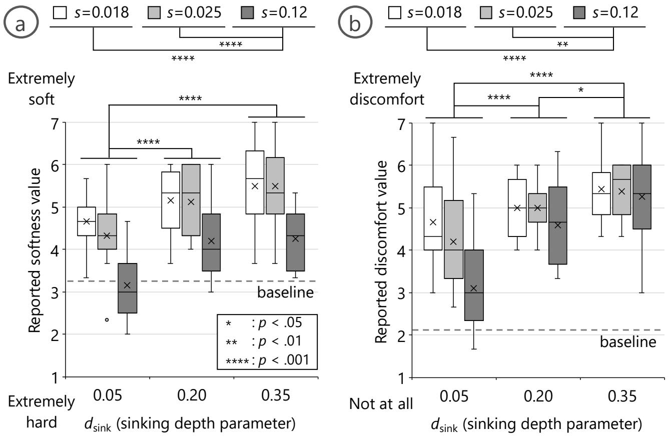

Fig. 4: Box plot of scores in each parameter setting. (a) Perceived softness. (b) Perceived discomfort. The X-mark shows the median score and horizontal line in each bar shows the average score.

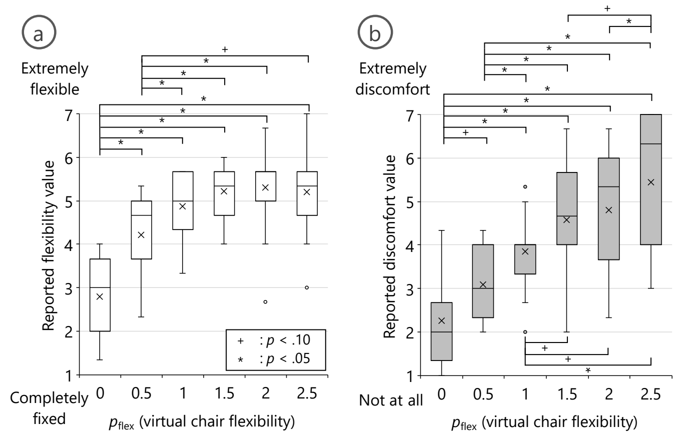

Fig. 5: Box plot of scores in each parameter setting: a) perceived flexibility and b) perceived discomfort. The X-mark shows the median score and horizontal line in each bar shows the average score.

and 2.5° per 100 g pressure (see Apparatus). Moreover, we added a baseline condition where the camera position was not manipulated. Overall, six visual conditions were used.

Task. We presented visual stimuli to represent a flexible backrest by manipulating the viewpoints. The participants were then asked to rate the seat flexibility and discomfort using a seven-point scale. Regarding flexibility, the participants were asked "*How did you feel when you leaned on the backrest?*" and rated their feelings from 1 (absolutely rigid) to 7 (extremely flexible). As for comfort, the participants were asked "*Did you feel uncomfortable when you reclined?*" and ranked their sensation from 1 (not at all) to 7 (extremely uncomfortable). The participants repeatedly evaluated all visual conditions, and the entire procedure was repeated in three times.

Apparatus. We used the same VR system as in Experiment 1. However, there was no cushion on the seat to prevent the participant from slipping when reclining. In addition, a square-shaped pressure sensor (FSR406, Interlink Electronics) was affixed to the upper back of the chair to measure the force applied to the backrest. The signal data from the pressure sensor were sent to the computer via Arduino (Arduino Uno R3) at a frequency of 60 Hz. The viewpoint on the HMD was changed based on this data.

Participants. Fifteen participants (13 male, two female. $\bar{X} = 22.9$ [SD $= 1.3$] years old) volunteered in the experiment. As in Experiment 1, all participants were university students and had experience using VR devices. Three of the participants also joined Experiment 1.

Procedure. After filling out consent forms, the participants began a preparation session. This session adjusted the seat position of the chair to regulate the contact point of the pressure sensor. We measured each user's distance from the seventh cervical vertebra to the tailbone and defined the contact point as one-third of its length from the seventh cervical vertebra. This control means that the pressure sensor was pressed at a position slightly below the line connecting the left and right shoulder blades. We also asked the participants to sit in the chair at an angle of $\theta_{\text{back}} = 110°$. The height of the chair's seat was adjusted, and the seating position was marked so that the participants could follow the above conditions.

The preparation session was followed by a practice session, during which the participants were given time to practice reclining in the chair as instructed. The initial posture begins with sitting in the chair with the back straight. The participants then gradually reclined in the chair. When the applied pressure reached an equivalent of 2 kg of weight, a pre-set beep alarm sound went off. After the beep sounded, the participant gradually returned to the initial posture. The participants were asked to keep their hands on their knees during the experiment. These practice sessions continued until the participants were able to recline in the chair as instructed.

The practice session was succeeded by the main session. The participants were allowed to take a break during the main session. The participants reclined gradually from their initial posture holding their back straight until a beep sounded under a randomly selected condition from the six conditions described in the "Designing Parameter" section. The camera position and orientation were initially adjusted so that the TV monitor in the VR environment was positioned in front of the seated participant. They returned to the initial posture following the beep sound. This back-and-forth action was repeated five times at the participant's pace.

Thereafter, the flexibility and discomfort questionnaires were displayed on the HMD against a black background, as in Experiment 1. The participants answered the questionnaire verbally on a seven-point scale. The trials repeated under all conditions taking sufficient breaks to avoid sensory adaptation. This procedure was repeated three times. The order of all trials was also fully randomized for each participant. We collected comments from the participants at the end of each session. The total duration of the experiment was approximately 90 minutes per participant. In total, we collected 270 ratings ($=$ 15 participants $\times$ 6 conditions $\times$ 3 sets).

Analysis. We assigned a score from 1 to 7 to each flexibility answer from "absolutely rigid" to "extremely flexible" and to each discomfort score from "not at all" to "extremely uncomfortable." A score higher than 4 meant that the participants felt that the backrest was flexible or uncomfortable. The baseline score in this experiment is the $p_{\text{flex}} = 0$ condition, where we did not add any viewpoint movement. Because there was only one parameter that we changed its value in this experiment, we conducted a Friedman test and used a Wilcoxon signed-rank test with Holm's method for a multiple comparison. If the scores in the experimental conditions were significantly higher than the baseline score, the participants felt that the backrest was more flexible or uncomfortable than the actual one.

Results. Figure 5 shows the flexibility and discomfort score for each p_{flex} value. First, the flexibility scores are presented in Figure 5a. The score increased as the p_{flex} value increased and became flat after 1.0. The analysis revealed the significant effect of the p_{flex} value ($\chi^2(5) = 46.418$, $p < 0.001$, $\eta_p^2 = 0.619$). The baseline score was significantly lower than all other conditions ($p_s < 0.020$, $r_s > 0.800$). In addition, when the p_{flex} was 0.5, the flexibility score was significantly lower than in other conditions ($p_s < 0.045$, $r_s > 0.700$). Although a comparison to the 2.5 condition was marginally significant ($p = 0.091$, $r = 0.633$), there was no significant difference from the 1.0 to 2.5 conditions ($p_s < 0.240$, $r_s > 0.550$).

Second, the discomfort score (Figure 5b) monotonically increased. The effect of the p_{flex} value was significant ($\chi^2(5) = 44.686$, $p < 0.001$, $\eta_p^2 = 0.596$). The discomfort score in all conditions was marginally ($p_{\text{flex}} = 0.5$: $p = 0.091$, $r = 0.495$) or significantly higher than the baseline score ($p_s < 0.025$, $r_s > 0.750$). In addition, other than the following pairs, the scores between all pairs of the p_{flex} values were significantly different ($p_s < 0.050$, $r_s > 0.690$): the difference was marginally significant between the 1.0 and 1.5 conditions ($p = 0.057$, $r = 0.634$), the 1.0 and 2.0 conditions ($p = 0.050$, $r = 0.673$), and the 1.5 and 2.5 conditions ($p = 0.060$, $r = 0.600$) and was not significant between the scores of the 1.5 and 2.0 conditions ($p = 0.350$, $r = 0.240$).

6 Overall Discussion

In this study, we virtually changed the users' viewpoints to modify the perceived features of a chair (i.e., seat softness and backrest flexibility). In Experiment 1, we attempted to change the perceived softness of the chair seat by virtually moving the users' viewpoints along with the exponential function right after they sat on a real chair. In Experiment 2, to modify the perceived flexibility of the backrest, we virtually moved the users' viewpoints backward and downward. The results showed that, except for the fastest–shallowest movement condition in Experiment 1, the participants perceived the seat softer or the backrest more flexible than the actual chair. However, they reported some discomfort as well.

6.1 Seat Softness

We compared the perceived seat softness induced by downward viewpoint movements changing the speed and sinking depth. Both parameters affected the perceived softness independently. The deeper or slower the viewpoint moved, the softer the seat was perceived to be (Figure 4a). In the fastest–shallowest movement condition, the perceived softness did not differ from the baseline. For all the other conditions, the participants evaluated the seat as softer than the baseline.

Two Factors for Softness Perception. We consider that this softer perception was due to by the following sequential factors. First, the participants illusorily perceived their body movement from the modified movement modeled in Section 3. Some participants commented that they felt their body move as if they sat on a soft seat. Humans can discern such detailed speed perception. For example, Brandt et al. [8] shows participants could perceive the speed of illusory self-motion based on visual information. Second, this illusory body movement brought the participants the feeling of softness. Humans can perceive the shape and softness of an object based on either or all visual information, hand movement, or postures, even without touching it [16, 38]. As in the case of hands' movements, the whole-body movement can be a source of softness perception as humans can maintain body balance on a soft surface based on only the perceived body posture and movement [17]. Therefore, these mechanisms and our results explain the softer seated experience in Experiment 1.

Each parameter affected the acceleration and depth of the perceived movement. In the real world, the acceleration and depth of the sitting body are different depending on the seat's softness. In our experiment, the perceived softness would have been the softness of the real seat that produced a body movement similar to the illusory movement. In everyday life, when people sit on a soft seat, their body sinks deeper into the seat. The viewpoint change of a larger d_{sink} led to the perception of such a body movement; therefore, the participants perceived a softer seat. Similarly, the body sinks with some resilience when sitting on the soft seat. Therefore, the participants would have perceived the seat as soft with a smaller s that produced the slow movement.

Viewpoint Movement for Softness Perception. There can be two reasons why the largest s of 0.12 failed to make the participants feel the seat softness. First, in the $d_{\text{sink}} = 0.05$ and $s = 0.12$ condition, the participants could have failed to perceive the illusory body movement because of the too short and fast viewpoint change. As explained above, no illusory body movement induced no softness perception. Second, as some participants stated, the illusory body movement with the extreme condition produced the effect of falling off rather than sitting. When s was set to 0.12, the viewpoint moved 50% of the d_{sink} depth in only the first 0.1 second, and the slowing down movement in the later part was unnoticeable. Furthermore, an upward optical flow brings a self-motion perception of falling off [24].

The control of illusory body movements is one of the keys to presenting the exact virtual softness of the seat. However, the participants felt less extent of the movements than those programmed in VR. In other words, enhanced movements must have been programmed to present confident softness. As we discuss in the following sections, conflicts between different modality information decrease self-motion perception. Therefore, enhanced movements should be presented, especially because our approach solely relies on visual information. In fact, the participants' bottom almost reached the floor when their viewpoint moved by 35 cm, which was the largest value in d_{sink}. The sinking duration with the smallest s was three seconds, which is not usually the case for an actual soft cushion.

6.2 Backrest Flexibility

In Experiment 2, we measured the perceived backrest flexibility under various viewpoint movements that depended on measured forces. The virtual viewpoint moved more backward than the actual viewpoint did. The results showed that the larger the viewpoint change was, the more flexible the backrest was the perceived to be (Figure 5a). However, the average score of the perceived flexibility no longer significantly increased after the change rates reached 1.0° per 100 g force and showed a tendency to slightly decrease under the largest change rate.

Viewpoint Movement for Flexibility Perception. We considered that the two similar sequential factors in Experiment 1 caused the flexibility perception. In other words, as demonstrated with the sway motion in a previous study [17, 21], our participants could perceive flexible backrest from the illusory reclination caused by the viewpoint movement based on real-world experiences. However, as mentioned above, the effect was not statistically significant among the conditions where p_{flex} was 1.0° or larger per 100 g. Four participants stated that they were in favor of the smaller movements and gave the highest score to the conditions other than the largest p_{flex} condition (Figure 5a). One of them also explained that the viewpoint moved too much. In addition, many participants, including the above four, pointed out that the inconsistency between the real and in-VR face directions gave them a strange feeling, which can lead to weakened perception of the illusory body movement.

Individual Differences in Flexibility Evaluation. Based on the obtained feedback and flexibility scores, we divided the participants into roughly equal groups, one of which liked the larger movements and the other liked the smaller movements. Such a difference in preferences can be explained by personal reliance on the senses [22, 45]. The participants who relied on proprioceptive and/or vestibular information more than on the visual information can prefer the small movements, and vice versa. In Experiment 2, the proprioceptive and vestibular information suggested a rigid straight backrest. If the visual information did not deviate from this physical state, the participants perceived an illusory body movement and, thus, felt that the backrest was flexible. However, when the gap between multimodal information became prominent, the proprioceptive and vestibular information interfered with the perception of illusory body movement. As a result, the participants felt that the backrest was less flexible. On the other hand, the participants who tended to rely more on visual information could perceive larger illusory body movements and, therefore, more flexible backrests.

6.3 Sources of Discomfort

In both experiments, the uncomfortable feeling increased by the viewpoint change. In Experiment 1, the viewpoint movement that created a perception of softness mostly evoked a strong uncomfortable feeling (Figure 4b). In addition, when the viewpoint change was rapid, the participants felt uncomfortable with medium deep sinking movements in spite of the low softness score. In Experiment 2, although the flexibility scores were flat, with more than a certain p_{flex} value, the uncomfortable feeling increased monotonically (Figure 5b). The following two crossmodal conflicts could be the main source of uncomfortable feeling.

Conflict in Body Posture Perception. The first conflict is the body posture perception. Multimodal information, such as visual, proprioceptive, and vestibular systems, contributes to the body posture perception [21]. As we changed the viewpoint virtually, the body posture based on the visual information differed from the information gathered by other senses. This conflict, especially between the visual and vestibular systems, can have more impact on the uncomfortable feeling experienced in relation to a flexible backrest than to seat softness.

A larger inconsistency existed in the perceived head direction induced by the visual information and the vestibular information in relation to the backrest. The virtual view was directed upward when the participants applied sufficient force to the backrest with larger p_{flex} values. As a result, the participants could see the ceiling in the virtual room, although their head remained straight in the real space. The vestibular system conveys information of motion, head position, and spatial orientation to the brain [11]. Given that the system is sensitive to head movement, it detected the participants' head directions. Three participants pointed out strange feelings in their head direction as they were facing front, although what they saw was the ceiling. In addition, six participants spontaneously reported that they felt sick with the large viewpoint movement (i.e., VR sickness) when we asked for their feedback after the experiment. This conflict between information from the vestibular system and the visual system is one of the main sources of motion sickness [20, 31]. The conflict becomes larger as the viewpoint change increases. Therefore, the uncomfortable feeling would have increased monotonically.

As for seat softness perception, there was certainly an inconsistency between information from the visual and the vestibular systems. However, unlike the backrest case, both participants' face and virtual viewpoint were consistently directed straight ahead. The acceleration of the downward body movement was the biggest conflict between the visual and vestibular systems: The viewpoint went downward, but the actual body did not. The inconsistency in acceleration decreased as the sinking speed decreased. If the conflict in the body posture perception was the main source of uncomfortable feeling related to seat softness perception, the discomfort score should have been higher with the larger s value. However, the results did not show this pattern. Therefore, the conflict in the body posture perception can partially explain varying uncomfortable feeling, but there must have been another source of discomfort in Experiment 1.

Conflict in Softness Perception. Another considerable source of discomfort was a conflict in the softness perception based on the body posture and the buttock skin. The spatial distribution of pressure on skin contributes to softness perception [5]. The participants perceived the seat as hard, based on the information collected from their buttock skin, whereas they perceived it as soft due to the viewpoint change (i.e., the change of their perceived body posture). As a result, in the conditions to which they attributed a high softness score, this contradicted perception would have led the participants to feel uncomfortable. A comment from a participant, "My body felt as if sinking into a soft seat, but the chair was hard," represents the conflict between the body posture and the skin sensation.

This conflict existed in the flexible backrest case, too. The reaction force from the real backrest was too high for the flexibility perceived from the illusory body movement based on the visual information. This certainly affected the discomfort evaluation; two participants also brought up this inconsistency. Although this inconsistency did not cause motion sickness, many participants reported feeling sick with the large viewpoint movement. Therefore, the conflict between the body posture and skin sensation has a relatively smaller effect than the vestibular information.

6.4 Limitation

We designed a controlled study to test whether the modified egocentric viewpoint could provide the participants a different softness perception. To this end, we controlled all the other factors, except for the focused factor (i.e., viewpoint manipulations). Therefore, we trained the participants to sit or recline in the chair in a pre-defined manner. In Experiment 1, the participants had to keep their upper body straight, although the viewpoint moved backward. Similarly, they were not allowed to move their neck in Experiment 2. The factors that must have affected a chair deformation, such as the speed of sitting on a chair, sitting posture, and sitting position, were carefully controlled as confound factors. Some of the participants stated after the experiments that they wanted to move their body or neck more naturally when they sat on the chair or reclined. As discussed in "Two Factors for Softness Perception" in Section 6, we expect that our method would give a modified softness perception even with more natural conditions, as long as it induces an illusory body movement on a soft chair.

To relax the constraint, we could extend the dimensions of the available body and head movements. However, as discussed, increased motion freedom would result in more sources of discomfort. This discomfort is a type of VR motion sickness, and many researchers have been attempting to tackle this issue [9, 28]. Unfortunately, no practical solution has been found, although some scholars succeeded to reduce motion sickness using vibration and airflow [13, 28]. Information on other modalities can provide a cue to improve our system.

Although the proposed simple viewpoint modification in Section 3 successfully gave the participants different softness perceptions, there are rooms to address more close-to-real movements based on real chairs. Furthermore, the participants were recruited from a demographically similar group.

7 Conclusion

We proposed and evaluated a method to modify the perceived haptic features of a chair using visual information in VR. We hypothesized that by virtually moving the viewpoint, the participants could perceive an illusory body movement. As a result, they perceived the softness corresponding to the body movement.

In the first experiment, we evaluated whether seat softness could be modified by a viewpoint movement. The viewpoint virtually continued going downward after the participants sat on the chair. The participants perceived the seat as softer than the actual one, especially with a slow and large movement. In the second experiment, the perceived flexibility of the backrest was modified by the viewpoint change. Based on the force applied to the backrest, the virtual backrest moved backward, and the viewpoint followed the movement. The perceived flexibility was scored significantly higher than the actual one. The score increased as the recline angle of the virtual backrest per force increased and remained constant after a certain point ($1.5°/100$ g).

In both experiments, the participants reported stronger uncomfortable feeling as the viewpoint movement became larger. It can be explained by the conflict in multimodal information, mainly visual, proprioceptive, vestibular, and cutaneous. For instance, this issue related to VR application use can be solved using other modality information to improve the information consistency between the manipulated vision and other modules. In addition, to control the confounding factors, the participants in our experiments sat on or recline in the chair in a predefined manner. The participants found that such constraints enforced them to move unnaturally and thus feel uncomfortable. The evaluation in a more natural setting can strengthen our approach and clarify the relationship between softness perception and uncomfortable feelings.

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References

[1] F. Argelaguet, D. A. G. Jáuregui, M. Marchal, and A. Lécuyer. Elastic images: Perceiving local elasticity of images through a novel pseudo-haptic deformation effect. *ACM Transactions on Applied Perception (TAP)*, 10(3):1–14, 2013. 2

[2] Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose. Controlling perceived stiffness of pinched objects using visual feedback of hand deformation. In *IEEE Haptics Symposium (HAPTICS)*, pp. 557–562, 2014. 2

[3] M. Bellgardt, S. Pick, D. Zielasko, T. Vierjahn, B. Weyers, and T. W. Kuhlen. Utilizing immersive virtual reality in everydaywork. In *IEEE 3rd Workshop on Everyday Virtual Reality (WEVR)*, pp. 1–4, 2017. 1

[4] W. M. Bergmann Tiest and A. M. Kappers. Kinaesthetic and cutaneous contributions to the perception of compressibility. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, pp. 255–264. Springer, 2008. 2

[5] A. Bicchi, E. P. Scilingo, and D. De Rossi. Haptic discrimination of softness in teleoperation: the role of the contact area spread rate. *IEEE Transactions on Robotics and Automation*, 16(5):496–504, 2000. 7

[6] P. Bourdin, M. Martini, and M. V. Sanchez-Vives. Altered visual feedback from an embodied avatar unconsciously influences movement amplitude and muscle activity. *Scientific Reports*, 9(1):1–9, 2019. 2

[7] J. Brade, D. Rüffert, A. Kögel, M. Bernhagen, F. Klimant, and A. C. Bullinger. Take a seat-the influence of sitting down in a virtual environment on workload, user experience and presence. In *Proc. Mensch und Compute*, pp. 270–274. 2021. 1

[8] T. Brandt, J. Dichgans, and E. Koenig. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research*, 16(5):476–491, 1973. 6

[9] E. Chang, H. T. Kim, and B. Yoo. Virtual reality sickness: a review of causes and measurements. *International Journal of Human–Computer Interaction*, 36(17):1658–1682, 2020. 7

[10] A. Costes, F. Argelaguet, F. Danieau, P. Guillotel, and A. Lécuyer. Touchy: A visual approach for simulating haptic effects on touchscreens. *Frontiers in Information and Communication Technology*, 6:1, 2019. 2

[11] K. E. Cullen and J. E. Roy. Signal processing in the vestibular system during active versus passive head movements. *Journal of Neurophysiology*, 91(5):1919–1933, 2004. 7

[12] F. Danieau, J. Fleureau, P. Guillotel, N. Mollet, M. Christie, and A. Lécuyer. Toward haptic cinematography: enhancing movie experiences with camera-based haptic effects. *IEEE MultiMedia*, 21(2):11–21, 2014. 2

[13] S. D'Amour, J. E. Bos, and B. Keshavarz. The efficacy of airflow and seat vibration on reducing visually induced motion sickness. *Experimental Brain Research*, 235(9):2811–2820, 2017. 7

[14] M. O. Ernst and M. S. Banks. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870):429–433, 2002. 2

[15] T. Erol, C. Diels, J. Shippen, D. Richards, and C. Johnson. How does car seat appearance influence perceived comfort. In *Proc. International Conference on Design and Emotion*, pp. 172–180, 2016. 2

[16] C. Fang, Y. Zhang, M. Dworman, and C. Harrison. Wireality: Enabling complex tangible geometries in virtual reality with worn multi-string haptics. In *Proc. ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1–10, 2020. 6

[17] R. Fitzpatrick and D. McCloskey. Proprioceptive, visual and vestibular thresholds for the perception of sway during standing in humans. *The Journal of Physiology*, 478(1):173–186, 1994. 2, 6

[18] R. M. Friedman, K. D. Hester, B. G. Green, and R. H. LaMotte. Magnitude estimation of softness. *Experimental brain research*, 191(2):133–142, 2008. 2

[19] D. Gall and M. E. Latoschik. The effect of haptic prediction accuracy on presence. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 73–80. IEEE, 2018. 1

[20] J. F. Golding. Motion sickness susceptibility. *Autonomic Neuroscience*, 129(1-2):67–76, 2006. 7

[21] E. E. Hansson, A. Beckman, and A. Håkansson. Effect of vision, proprioception, and the position of the vestibular organ on postural sway. *Acta Oto-Laryngologica*, 130(12):1358–1363, 2010. 6, 7

[22] M. A. Heller. Haptic dominance in form perception: vision versus proprioception. *Perception*, 21(5):655–660, 1992. 6

[23] V. Interrante, B. Ries, and L. Anderson. Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *IEEE Symposium on 3D User Interfaces*, 2007. 2

[24] G. Johansson. Studies on visual perception of locomotion. *Perception*, 6(4):365–376, 1977. 6

[25] L. A. Jones. Peripheral mechanisms of touch and proprioception. *Canadian Journal of Physiology and Pharmacology*, 72(5):484–487, 1994. 1

[26] T. Kawabe. Mid-air action contributes to pseudo-haptic stiffness effects. *IEEE Transactions on Haptics*, 13(1):18–24, 2019. 2

[27] T. Kayawari, Z. Jue, and N. Sugamura. Hardness evaluation for silicone rubber button on the basis of tactile and visual information. In *Proc. International Conference on Kansei Engineering and Emotion Research (KEER)*, number 100, pp. 245–254, 2014. 2

[28] B. Keshavarz. Exploring behavioral methods to reduce visually induced motion sickness in virtual environments. In *Conference on Virtual, Augmented and Mixed Reality (VAMR)*, pp. 147–155. Springer, 2016. 7

[29] B. Knorlein, M. Di Luca, and M. Harders. Influence of visual and haptic delays on stiffness perception in augmented reality. In *Proc. International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 49–52, 2009. 2

[30] M. Kuschel, F. Freyberger, M. Buss, and B. Färber. A presence measure for virtual reality and telepresence based on multimodal conflicts. In *Proceedings of PRESENCE 2007: The 10th Annual International Workshop on Presence*, 2007. 1

[31] J. J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32(1):47–56, 2000. 7

[32] A. Lécuyer, J.-M. Burkhardt, J.-M. Henaff, and S. Donikian. Camera motions improve the sensation of walking in virtual environments. In *Proc. IEEE Virtual Reality (VR)*, pp. 11–18, 2006. 2

[33] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet. Pseudo-haptic feedback: Can isometric input devices simulate force feedback? In *Proc. IEEE Virtual Reality (VR)*, pp. 83–90, 2000. 2

[34] R. Leib, I. Rubin, and I. Nisky. Force feedback delay affects perception of stiffness but not action, and the effect depends on the hand used but not on the handedness. *Journal of Neurophysiology*, 120(2):781–794, 2018. 2

[35] M. Li, M. B. Ridzuan, S. Sareh, L. D. Seneviratne, P. Dasgupta, and K. Althoefer. Pseudo-haptics for rigid tool/soft surface interaction feedback in virtual environments. *Mechatronics*, 24(8):1092–1100, 2014. 2

[36] C.-e. Lin, T. Y. Cheng, and X. Ma. Architect: Building interactive virtual experiences from physical affordances by bringing human-in-the-loop. In *Proc. ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1–13, 2020. 1

[37] V. U. Ludwig and J. Simner. What colour does that feel? Tactile–visual mapping and the development of cross-modality. *Cortex*, 49(4):1089–1099, 2013. 2

[38] T. H. Massie and J. K. Salisbury. The phantom haptic interface: A device for probing virtual objects. In *Proc. ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, vol. 55, pp. 295–300, 1994. 6

[39] K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose. Walking uphill and downhill: Redirected walking in the vertical direction. In *Proc. Conference on Computer Graphics and Interactive Techniques (SIGGRAPH)*, pp. 1–2. 2017. 2

[40] M. Matsumuro, H. Kobayashi, F. Shibata, and A. Kimura. Change of body representation in symmetric body parts. In *Proc. Annual Meeting of the Cognitive Science Society (CogSci)*, vol. 43, 2021. 2

[41] H. Miyasaka, K. Yoshioka, K. Kawakami, Y. Tonogai, Y. Hioki, M. Ogawa, E. Kurotani, G. Tanino, S. Okamoto, and S. Sonoda. Influence of rehabilitation combined with art devices on the number of sit-to-stand movements and resulting psychological effects. *Japanese Journal of Comprehensive Rehabilitation Science*, 10:65–70, 2019. 2

[42] S. Mori, Y. Kataoka, and S. Hashiguchi. Exploring pseudo-weight in augmented reality extended displays. In *Proc. IEEE Virtual Reality (VR)*, pp. 703–710, 2022. 2

[43] R. Nagao, K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose. Ascending and descending in virtual reality: Simple and safe system using passive haptics. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 24(4):1584–1593, 2018. 2

[44] S. Palmisano, R. S. Allison, M. M. Schira, and R. J. Barry. Future challenges for vection research: Definitions, functional significance, measures, and neural bases. *Frontiers in Psychology*, 6:193, 2015. 2

[45] S. Palmisano, D. Apthorp, T. Seno, and P. J. Stapley. Spontaneous postural sway predicts the strength of smooth vection. *Experimental Brain Research*, 232(4):1185–1191, 2014. 6

[46] P. Punpongsanon, D. Iwai, and K. Sato. Softar: Visually manipulating haptic softness perception in spatial augmented reality. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 21(11):1279–1288, 2015. 2

[47] A. Pusch and A. Lécuyer. Pseudo-haptics: From the theoretical foundations to practical system design guidelines. In *Proc. International Conference on Multimodal Interfaces (ICMI)*, pp. 57–64, 2011. 2

[48] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected walking. In

Proc. Conference of the European Association for Computer Graphics (Eurograpgics), 2001. 2

[49] M. Rietzler, J. Gugenheimer, T. Hirzle, M. Deubzer, E. Langbehn, and E. Rukzio. Rethinking redirected walking: On the use of curvature gains beyond perceptual limitations and revisiting bending gains. In *Proc. International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 115–122, 2018. 2

[50] J. RPC, Y. Tokuyama, C. Sonehara, and T. Hattori. The influence of texture on perceiving haptic stiffness. *Kansei Engineering International Journal*, 11(4):199–206, 2012. 2

[51] P. Schmitz, J. Hildebrandt, A. C. Valdez, L. Kobbelt, and M. Ziefle. You spin my head right round: Threshold of limited immersion for rotation gains in redirected walking. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 24(4):1623–1632, 2018. 2

[52] E. P. Scilingo, M. Bianchi, G. Grioli, and A. Bicchi. Rendering softness: Integration of kinesthetic and cutaneous information in a haptic device. *IEEE Transactions on Haptics*, 3(2):109–118, 2010. 1

[53] C. S. Sherrington. *The integrative action of the nervous system*. Reprint, Arno Press Inc., New York, NY, 2nd. ed., [1947] 1906. 1

[54] N. Slobodenyuk, Y. Jraissati, A. Kanso, L. Ghanem, and I. Elhajj. Cross-modal associations between color and haptics. *Attention, Perception, & Psychophysics*, 77(4):1379–1395, 2015. 2

[55] M. A. Srinivasan and R. H. LaMotte. Tactual discrimination of softness. *Journal of Neurophysiology*, 73(1):88–101, 1995. 1, 2

[56] S. Tada and T. Ogawa. Evoking pseudo-haptics of resistance force by viewpoint displacement. In *IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 674–675, 2020. 2

[57] Y. Ujitoko and T. Kawabe. Perceptual judgments for the softness of materials under indentation. *Scientific Reports*, 12(1):1–11, 2022. 2

[58] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proc. SIGCHI Conference on Human Factors in Computing Systems (CHI)*, pp. 143–146, 2011. 4

[59] W.-C. Wu, C. Basdogan, and M. A. Srinivasan. Visual, haptic, and bimodal perception of size and stiffness in virtual environments. In *ASME International Mechanical Engineering Congress and Exposition*, vol. 16349, pp. 19–26. American Society of Mechanical Engineers, 1999. 2

[60] D. Zielasko and B. E. Riecke. To sit or not to sit in VR: Analyzing influences and (dis)advantages of posture and embodied interaction. *Computers*, 10(6):73, 2021. 1