

Leveraging Tendon Vibration to Extend Pseudo-Haptic Sensations in VR

Yutaro Hirao, Tomohiro Amemiya, Takuji Narumi, Ferran Argelaguet, and Anatole Lécuyer

Abstract—The Pseudo-haptic technique is used to modify haptic perception by appropriately changing visual feedback to body movements. Because tendon vibration can affect our somatosensory perception, we propose a method for leveraging tendon vibration to extend pseudo-haptics. To evaluate the proposed method, we conducted three experiments that investigate the effect of tendon vibration on the range and resolution of pseudo-haptic sensation. The first experiment evaluated the effect of tendon vibration on the detection threshold (DT) of visual/physical motion discrepancy. The results show that vibrations on the inner tendons of the wrist and elbow increased the DT. This indicates that tendon vibration can increase applicable visual motion gain without being noticed by users. The second experiment investigated the effect of tendon vibration on the resolution, that is, the just noticeable difference (JND) of pseudo-weight sensation. The results indicate that both with- and without-vibration conditions had a similar JND of pseudo-weight sensation and thus, both conditions can be considered to have a similar resolution of sense of weight. The third experiment investigated the equivalence between the weight sensation induced by tendon vibration and visual motion gain, that is, the point of subjective equality (PSE). The results show that vibration increases the sense of weight, and its effect was the same as that using a gain of 0.64 without vibration. Taken together, our results suggest that using tendon vibration can enable a significantly wider (nearly double) range of pseudo-haptic sensation, without impairing its resolution.

Index Terms—Pseudo-Haptics, virtual reality, tendon vibration, cross-modal integration, maximum likelihood estimation,



1 INTRODUCTION

IN recent years, virtual reality (VR) technology has made remarkable progress, enabling users to feel as if a virtual object is actually present by providing visual and audio information. However, haptic information still has a narrower range of expression than audio-visual information, and various approaches have been proposed to present haptic information. Of these approaches, the pseudo-haptic technique is an interesting alternative for generating haptics; it is a method of modifying haptic perception by appropriately changing the visual feedback to body movement [1], [2]. Typical examples of pseudo-haptics techniques involve modifying the force of a spring [3] or perceived weight of an object [4]–[6] by changing the control-display gain to the actual motion in a virtual environment. The main advantage of the pseudo-haptics technique is that it can present haptic sensations primarily through visual stimuli and does not require bulky equipment. However, the perceived force intensity presented by conventional techniques of pseudo-haptics is severely limited because the pseudo-haptic technique separates visual and haptic information, and discrepancies that are too large induce discomfort or break the haptic perception [1], [5], [7].

Some studies have attempted to improve the range of acceptable motion alteration by increasing the contribution of visual information to sensory integration by expanding the field of view of a head-mounted display (HMD) [8] or using a more human-like avatar [9]. However, modifying

the haptic sensation by directly increasing the contribution of visual information is limited. In this study, considering that tendon vibration affects somatosensory perception, we investigate the potential of tendon vibration for expanding the range of pseudo-haptic sensations.

Vibration has several possible effects on somatosensation. When a vibration is applied to a muscle or tendon, the primary afferent of the muscle spindle is activated. This can produce illusions of position, motion, and force [10]–[12]. In addition to these illusions, the tonic vibration reflex (TVR) occurs, which causes sustained contraction of the vibrated muscle and inhibition of the activity of the antagonist muscle [13]. Based on these findings, we hypothesized that the range of pseudo-haptics could be extended by precisely controlling both tendon vibration stimuli and visual motion gain.

In this study, we evaluate the effect of tendon vibration on pseudo-haptic weight sensation and discuss design guides for combining tendon vibration and pseudo-haptics techniques. As a systematic investigation of the effect, we conducted three experiments investigating the potential effect of tendon vibration on the range and resolution of pseudo-weight sensation. Figure 1 provides a brief summary of results. The first experiment investigated the effects of tendon vibration to the agonist muscle, antagonist muscle, or both on the detection threshold (DT) of the discrepancy between physical and virtual motion with a motion gain. Because users begin to feel discomfort when they recognize the discrepancy, this DT can be considered the strictest maximum applicable motion gain for generating pseudo-weight sensation. Then, the second experiment investigated the effect of tendon vibration to the agonist muscle on the just noticeable difference (JND) in pseudo-weight sensation induced by motion gain. This JND

- Y. Hirao, T. Amemiya and T. Narumi are with the University of Tokyo, Tokyo 113-8654, Japan. E-mail: {hirao, amemiya, narumi}@cyber.t.u-tokyo.ac.jp.
- A. Lécuyer and F. Argelaguet work with Univ. Rennes, Inria, IRISA, CNRS, Rennes, France.

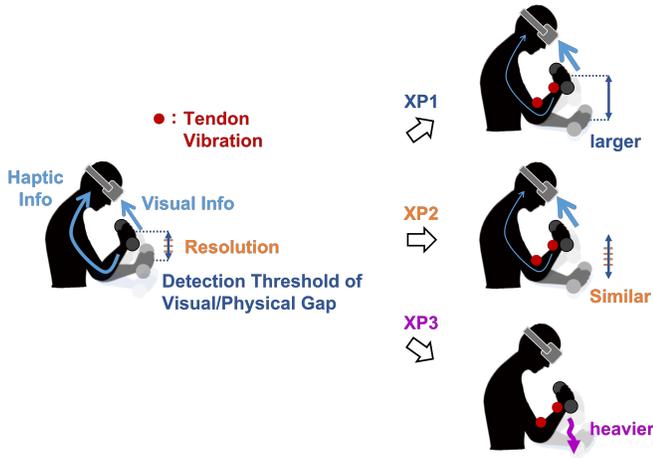


Fig. 1. Summary of results: Tendon vibration was suggested to function as noise on somatosensory information, making users rely more on visual information and leading to a potentially wider range of applicable visual motion gain (XP1). Moreover, the tendon vibration does not change the resolution of pseudo-weight sensation (XP2). Furthermore, tendon vibration increases weight sensation (XP3).

indicates the resolution of pseudo-weight sensation. We consider that the DT and JND can be used to discuss whether tendon vibration improves the range of presentable pseudo-weight sensation. Finally, the third experiment investigated the effect of tendon vibration on weight perception. This concerns the point of subjective equality (PSE) of weight perception induced by tendon vibration, compared with pseudo-weight sensation induced by motion gain. These three experiments cover the effects of combining tendon vibration and motion gain on pseudo-weight sensation in VR.

The remainder of this paper is structured as follows. Section 2 introduces related work. We introduce the theoretical background of pseudo-haptics and effects of tendon vibration on somatosensory sensation. Sections 3 to 5 describe the three experiments. Then, Section 6 provides a general discussion of all experimental results and comprehensive discussion of the effect of tendon vibration on the pseudo-haptic technique and design guide for application. Finally, Section 7 concludes the paper.

2 RELATED WORK

2.1 Theoretical Background of Pseudo-Haptics

The pseudo-haptic technique is used to induce haptic illusions by manipulating visual feedback to user movement [1], [2]. It can be applied for many properties of haptic sensations, such as compliance [3], [14], [15], weight [4]–[7], and friction [16]–[20]. The mechanism of pseudo-haptics has not yet been fully revealed. Still, several theories have been proposed and discussed. One of the most conventional explanation is that visual and haptic information are integrated based on the maximum likelihood estimation (MLE) [21], [22]. This theory explains that sensory information is integrated based on its reliability (likelihood) for people to estimate the properties of physical objects (Fig. 2). Ernst and Banks confirmed this in the estimation of the width of an object when the information of width is different between

vision and haptics [21]. In particular, MLE well describes spatial perception. In addition, considering the relationship between motion and force, another explanation of the mechanism of pseudo-haptics is based on the indication that the human central nervous system performs forward dynamics calculations (FDC) [7], [23], [24] and inverse dynamics calculations (IDC) [15], [25], [26]. In FDC, the motion of a target object is estimated from the force applied to it. Honda et al. adjusted the visual delay and mass of a manipulum in a system where the cursor on a monitor can be manipulated by the manipulum. They confirmed that the sensory-motor prediction error owing to the visual delay was misattributed to the mass estimation [7]. Moreover, in IDC, the force applied to a target object is inferred from its motion. Takamuku and Gomi investigated the intensity of motion resistance while varying the visual motion of a cursor on a screen to the periodic motion of a stylus pen [15]. They confirmed that the intensity of motion resistance associated with cursor delay correlates with the acceleration of the cursor in the direction of movement. This suggests that their subjects used IDC with visual motion information as input to form an internal model of the dynamics for the interaction (in this case, the spring-damper system). By further developing these theories that can well explain the primary bottom-up process of the sensory integration or relationship between motion and force estimation, the Bayesian theory was proposed; it considers top-down influences such as the intervention of predictions/prior-knowledge, and complement/replacement of sensory input by individual memory/experience [1], [22], [27]. Moreover, a more unified explanation is obtained using the free energy principle, which considers the loop between perception and behavior change [28].

2.2 Limits of Pseudo-Haptics

As discussed, the manipulation of various haptic sensations is possible by only adjusting visual feedback. However, the pseudo-haptic technique is not omnipotent. Pseudo-haptics technique separates visual and haptic information. Here, larger gaps are necessary to induce more intensive sensation; however, gaps that are too large result in discomfort or

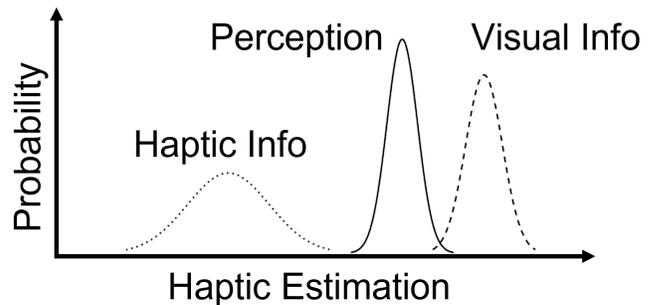


Fig. 2. Concept figure of the maximum likelyhood estimation of the sensory integration process. It shows that the haptic estimation (final perception) is made by the integration of visual and haptic information considering their reliability, i.e., the variance of the information. Note that the distribution and mean of the visual and haptic info are only for illustrative purposes.

a failure to integrate the information [1], [5], [7]. Based on Pusch and Lécuyer's model [1], larger discrepancies could result in larger complements and substitutions of sensory information from personal memories and experiences, which would increase individual differences. Moreover, if the gap is too large, the information is determined to be coming from a different source and is not integrated [22]. While, FDC and IDC theory can provide another explanation in that the illusion would not arise when the brain no longer has a model to which the large gap can be attributed [7].

Few studies have been conducted to solve the challenges of pseudo-haptic techniques. Ban and Ujitoko proposed a method for inducing pseudo-haptics more effectively by connecting the discrepancy between a user's finger and the cursor on a touchscreen with a visual string [29]. Another possible approach involves increasing the reliability of visual information in sensory integration, i.e., to decrease the variance of visual information in MLE so that the final perception is more dependent on visual information. Williams and Peck confirmed that wider fields of view in VR could extend the applicable visual gain for redirected walking techniques [8]. Furthermore, Ogawa et al. concluded that more realistic avatars could make participants notice the discrepancy between virtual and physical hand movements less than the abstract avatar (a sphere object) [9]. These studies did not mention pseudo-haptics, but their aiming technique, retargeting, creates visual/physical gaps and therefore, the results are applicable to pseudo-haptics. However, these approaches do not affect haptic information; therefore, their effectiveness is limited. Here, we investigated the method that affects haptic information with simple equipment to solve this problem using tendon vibration stimulation.

2.3 Effect of tendon vibration on somatosensory information and pseudo-haptic sensation

When vibration is applied to a tendon or muscle, the primary afferents of the muscle spindle are activated. As muscle spindles are sensors of position and motion [30], the vibration can create the illusion of movement in the direction of the muscle stretch (Fig. 3) [31]. This vibration also induces a tonic vibration reflex (TVR) that contracts muscles [13]. Here, if we resist the motion and attempt to remain static, a motion illusion is produced in the opposite direction of the TVR. In addition to the effect on position and motion, tendon vibration can also affect force and weight sensation (e.g. [32], [33]). The optimum vibration parameters for generating the somatosensory illusion vary within studies, but a vibration frequency of 70 to 100 Hz and an amplitude of approximately 5 G is deemed sufficient and widely used for VR experiments [11], [34], [35]. The required minimum duration of vibration to induce the illusion also varies, but several studies have indicated that 6 s is the minimum time required [36], [37].

Although many tendon vibration studies have been conducted for static situations, several studies have confirmed that the tendon vibration illusion can be induced during active motion [38], [39]. Sitting et al. observed that during elbow flexion-extension movements, applying a vibration to the biceps likely affected position perception in slow

movements (approximately 6 deg/s) and velocity perception in fast movements (60 - 130 deg/s at maximum) [38]. Furthermore, Inglis and Frank determined that vibration on the biceps (agonist muscle) does not affect positional accuracy during arm flexion-extension movements of 40-60 deg/s, whereas vibration on the triceps (antagonist muscle) does, suggesting that muscle spindle afferents from the extending antagonist muscle contribute to limb positional accuracy during voluntary movements [39]. Although many studies have investigated and confirmed the effect of muscle vibration on somatosensory sensation, the reproducibility of the effect is difficult and inconsistent across studies. One reason is that vibrating one muscle may induce some activity in neighboring or antagonistic muscles, which may result in a change in the direction of the illusion or even its disappearance [40]. In addition, individual differences in anatomy increase the difficulty in selectively vibrating the intended muscle in a practical set-up outside of the experiment. Another reason is that the tendon vibration illusion is strongly influenced by visual information (e.g. [34], [41], [42]). It is also affected by cognitive factors such as learning, attention, and even imagination [11]. Neuroimaging studies have shown that the same brain regions are activated in both motor imagery [43] and illusory arm movements [36]. Therefore, motor imagery could influence motion illusions. Thyriou and Roll confirmed that motor imagery weaken/strengthen the illusory motion induced by the vibration of biceps, and even modulate its perceived direction [44]. In this manner, the motion illusion of tendon vibration may not be always robust.

In addition to effect on position and motion, some studies have investigated the effect on force and weight estimation. Most studies have suggested that vibration on the contracting muscle increases the sense of force or weight (e.g. [33], [45], [46]). The mechanism of sense of force and weight is not yet fully understood, but somatosensory information is known to be a combined mechanism of central and peripheral signals. These signals are the afferent signal, which is generated by external stimuli, and efferent copy, which is generated in corollary discharge with the command to perform physical movements. The efferent

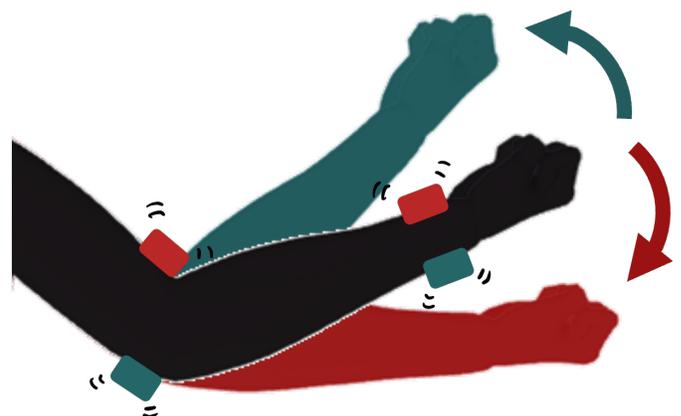


Fig. 3. Relationship between the position of tendon vibration feedback and direction of motion illusion.

copy is sometimes described as the sense of effort, and this sense of effort, as well as peripheral signals, is known to influence force and weight perception [10], [12]. The reason for overestimating the exerted force by tendon vibration can be explained in terms of two aspects: afferent and efferent signals. Concerning afferent signals, vibrations to the tendon and TVR cause neurons in the Golgi tendon organ, which is a sensor for the degree of muscle contraction, to activate and this additional afferent signals increase force and weight perception [45]. This is also supported by the vibration effect being reduced during muscle fatigue [47] and that the desensitization of the Golgi tendon organ caused by relatively long-term vibration [40], [48] reduces weight perception [46]. Concerning efferent signals, vibration to the driving muscle leads to the inhibition of the antagonist muscle, increasing the effort required to overcome this inhibition and exert the target force, resulting in increased force or weight perception. [12], [33]. However, these effects are not always consistent as noted by several studies reporting conflicting results. McCloskey et al. observed that muscle exertion perceived in vibrated muscles is underestimated [32]. They mentioned that participants do not consider the force from TVR induced by the tendon vibration as additional force input; thus, TVR resulted in reducing the sense of effort. Moreover, the effects vary depending on the context, such as with tasks or questionnaires [49], [50]. Furthermore, as motion and force sensation are closely related, the difficulty involved in using tendon vibration to induce motion illusion implies that to induce force perception.

By considering studies on the effect of tendon vibration on somatosensory sensation, we hypothesized two possibilities to solve the problem regarding the gap between visual and physical information by leveraging tendon vibration. One possible usage is to precisely control the somatosensory sensation. This holds if the effect of tendon vibration on somatosensory sensation is local, robust, and easy to control. However, if the first hypothesis does not work, the other possible usage is to degrade the reliability of somatosensory information using tendon vibration as noise on the sensation, which makes the final perception rely more on visual information. This hypothesis is inspired by the work of Ernst and Banks [21] that confirmed that noise on visual information increases variance and makes the width estimation rely more on haptic information. In addition, this hypothesis is supported by the simultaneous vibratory stimulation of the agonist and antagonist muscles producing high firing rates of spindle endings in both sets of muscles, masking (degrading) the spindle input that occurs during actual movement, and reducing somatosensory accuracy [51], [52]. This second hypothesis could be practical if the effect of tendon vibration is broad and complex.

3 XP1: INFLUENCE OF TENDON VIBRATION ON THE RANGE OF THE MAXIMUM APPLICABLE VISUAL/PHYSICAL GAP

This experiment investigates the influence of tendon vibration on the applicable range of pseudo-weight sensation. In this experiment, the DT of the discrepancy between actual and VR motion with a motion gain was investigated with the inner, outer, and both sides of vibration on the

wrist and elbow tendons, as well as a with no vibration condition. As discussed, the effects of tendon vibration on somatosensory perception are complex. In particular, the experiments in previous studies were conducted in a strict experimental environment with the subject's body part fixed, as the purpose was to purely confirm the effects of tendon vibration on somatosensory perception. In contrast, this experiment aims to clarify the effects in a more practical situation, such as considering engineering applications. The research question guiding this experiment was whether and how tendon vibration affects the DT of the visual/physical motion discrepancy in our setup.

3.1 Methods

3.1.1 Apparatus

Figure 4a shows the experimental apparatus. The experiment was conducted with participants in a sitting position. Participants wore wristbands with two vibrators (VIBRO transducer VP210, Acouve Lab. Inc.), on the wrist and elbow of the right arm. The vibrators were positioned to stimulate the inner and outer tendons of the wrist and elbow, respectively. The participants wore a VR headset (Oculus Quest 2) and noise canceling headphones and held a VR controller in each hand. The frequency of the vibration was 80 Hz and the amplitude was 5 G except when vibrating both the inner and outer tendons, for which it was 2.5 G. Subsection 3.1.3. provides a detailed explanation.

3.1.2 Task

Calibration and measurement of motion illusion induced by tendon vibration: The experiment involved two parts. The objective of the first part is to calibrate the vibrators' position and measure the motion illusion induced by tendon vibration. First, participants were informed that the vibration may induce a motion illusion, but its direction was not indicated to avoid bias. Subsequently, participants were asked to sit wearing equipment and with their right arm extended straight down. They were then instructed to look straight ahead with their eyes closed. Next, an experimenter activated the vibration stimuli to the inner sides of the

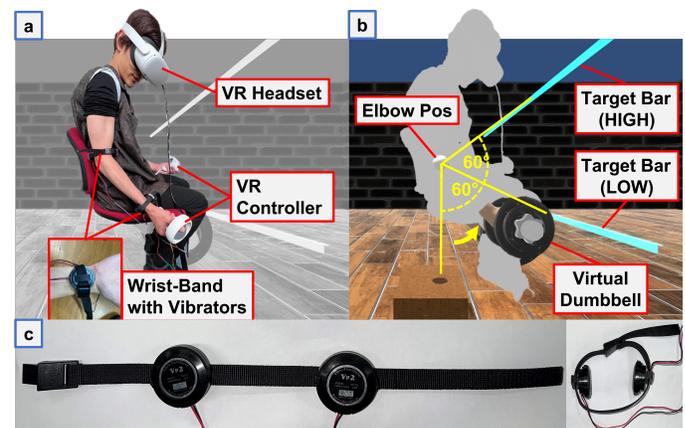


Fig. 4. Apparatus (a), virtual environment (b), and wrist band with vibrators (c). Participants wore noise-cancelling headphones during the experiment. In addition, the two target bars were not presented simultaneously but one-by-one in each condition.

participant's right wrist and elbow. The vibration lasted for 6 s. Subsequently, the experimenter asked the participants if they felt a motion illusion during the vibration. Six seconds can be considered the minimum duration required to induce motion illusion from previous studies [36], [37] and our informal pilot test. If the motion illusion was not induced, the experimenter slightly changed the position of the vibrators. These steps were repeated five times or until the participants experienced the motion illusion. Furthermore, when they did not experience the motion illusion after repetitions two and four, the experimenter activated a series of vibrations in the order of the inner, outer, and inner tendon to increase the probability that the participants would experience the illusion [53]. The same calibration process was performed for the vibration of the outer tendon.

After calibrating all vibrators positions, the participants were asked to measure the vector of motion illusion they experienced. First, the experimenter provided inner vibration stimuli to the participants for 6 s. Then, the participants were asked to replicate the motion they experienced using the right controller for this. In particular, participants pulled the index trigger at the initial position. They replicated the motion illusion by holding the trigger until the end of the motion illusion. A "beep" sound was provided when the trigger was pulled or released. This replication task was performed three times for each inner and outer tendon vibration. Note the participants remained with their eyes closed.

Investigation of DT of visual/physical discrepancy: The second part is the main part of this experiment. The DT is measured using the staircase method. In brief, participants were asked to lift the virtual dumbbell with a motion gain and answer if they noticed the difference between actual and visual motions. A detailed explanation follows.

The participants performed the lifting task following the staircase method. A visual gain was applied to the motion in VR. There were two groups of gain: HIGH, in which the visual gain was greater than 1.0, indicating that the virtual motion was larger than the actual motion; and LOW, in which the visual gain was less than 1.0, indicating that the virtual motion was smaller. In the staircase method, the initial motion gain was 1.0 or 2.0 for HIGH and 0.5 or 1.0 for LOW. The gain was increased or decreased by one step from ten levels in the range of each group. Whether the visual gain was increased or decreased depended on the participants' response to the questionnaire asking whether they experienced the motions of virtual and physical hands were the same or different. When participants answered "the same," the visual gain moved one step closer to 1.0, and when they answered "different," it moved one step farther from 1.0. The experiments ended after five turning points in the direction change of visual gain. Furthermore, the visual gain did not exceed the initial visual gain. If the answer would make the visual gain exceed the initial gain, the visual gain remained at the value, and the count of turning points was increased.

A detailed explanation of the lifting task follows. Figure 4b shows the virtual environment. In the VR environment, a virtual dumbbell was placed at the participant's right hand where their right arm naturally reached when extended straight down in a seated position. In addition, participants

could see a virtual right hand at the position of their right hand through the VR headset, and they could grab or release by pulling or releasing the index trigger of the VR controller, respectively. During the task, participants heard white noise. First, participants grabbed a dumbbell and waited 6 s before lifting it. Here, if the participants were being presented with the vibration stimulus, the vibration presentation started, and a 6 s countdown display and metronome sound at 120 bpm were simultaneously presented. This step induces the motion illusion. After the 6 s, the participants lifted the virtual dumbbell until it touched the blue bar in front of them in 2 s. The two seconds was determined to be a sufficient duration to have some effect and let the participants move with moderate speed by our pilot test, where we compared 1, 2, and 3 s in the same setup as this experiment. Participants were instructed to bend their elbow when they lifted the dumbbell. A gain was applied to the rotation of the elbow. The blue bar was placed at 60 degrees for LOW and 120 degrees for HIGH from the initial posture of the right arm. The position of the blue bar was determined so that the participants physically performed the same range of motion for the HIGH and LOW conditions. Note that only one blue bar was presented during the task, not simultaneously as shown in the Fig. 4b. When the virtual dumbbell reached the blue bar, all virtual objects and stimuli disappeared. Then, a virtual panel with the written question "I felt that the motions of my virtual and physical hand were:" "the same" or "different," appeared in front of the participants. The participants were asked to choose one of the two options using the left controller.

3.1.3 Conditions

The experiment used a within-subjects design. The tested condition related to the placement of the vibrations and included three levels: the inner, outer, and all tendons vibrating, including the control condition without vibration. The amplitude of the vibration was 5 G for the inner and outer tendons, and 2.5 G for the all tendons condition. Motion illusion is known to weaken when the amplitude of tendon vibration is reduced [54]. However, we considered that it was more important to maintain the total intensity of vibration stimuli the same. This is because if the vibration affects a motion illusion, the effect of inner and outer tendon vibration should cancel each other.

3.1.4 Collected data

The vector of the motion illusion induced by the vibrations were measured in the first part. In addition, the values of motion gain at the turning point of the staircase method were measured in the second part. These values were averaged to calculate the DT. In the end of the experiment, participants were asked to fill in a free structure interview.

3.1.5 Procedure

Twenty participants (twelve males and eight females in their twenties) participated in the experiment. First, the objectives, methods, and procedures were explained to them. Next, the participants completed a consent form. Then, the participants were asked to wear the equipment and headphones (Fig.4a). After the first part, the position of

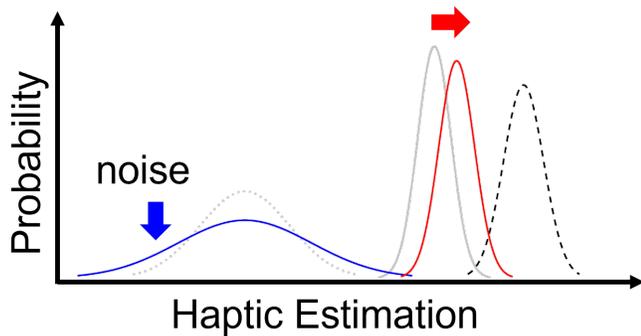


Fig. 5. Concept figure of MLE with noise added on haptic information ([H1-2]). Noise on haptic information increases its variance and shifts the perception to the value estimated by visual information.

the elbow was measured to co-localize the user with the virtual content. The participants were instructed not to move their elbow during the experiment. Before the second part, participants conducted a training phase to understand the staircase procedure without vibrations or gain. There were eight blocks consisting of four vibration conditions with the HIGH and LOW visual gain groups. Each block had two series of visual gain: one began with the visual gain of 1.0 and the other began with the visual gain farthest from 1.0 within the range, i.e., 2.0 for HIGH and 0.5 for LOW. Each series of the staircase method was presented in turn and ended after five turning points of changing the direction of the visual gain. The order of the vibration conditions was counterbalanced between participants, and the other orders on HIGH/LOW and the two series of visual gain were randomly chosen. During the trials, participants could take a break whenever and as often as they wanted. After finishing all trials, the participants removed all their equipment and completed the free-structured interview. The participants were remunerated with an Amazon gift card of 20 euro for their participation.

3.1.6 Hypotheses

We had two hypotheses regarding the impact of tendon vibration on the DT. These are as follows:

- [H1-1] Muscle spindle input induces motion illusion.
- [H1-2] Tendon vibration functions as noise on somatosensory sensation.

As the activation of muscle spindle induces the sensation of the extension of muscle, [H1-1] implies that the DT of the visual gain becomes higher/lower with the inner/outer tendon vibration than that without vibration and both sides' vibration. Whereas, the tendon vibration was confirmed to degrade proprioceptive responsiveness [51], [52]. Here, noise on sensory information can increase its variances it and thus increases the contribution ratio of the other sensory information in the sensory integration process [21]. In this case, if the tendon vibration functions as noise on somatosensory sensation, the visual information should be more dominant for position sensation, and users will notice the discrepancy between visual and somatosensory information less (Fig. 5). Therefore, [H1-2] means that the visual gain of the DT becomes higher/lower with vibration

conditions than that without vibration condition for the HIGH/LOW visual gain group.

3.2 Results

3.2.1 Direction and amount of motion illusion at rest

All participants successfully confirmed to experience motion illusion in the first part of the experiment. The data of one participant was removed because of recording issues and therefore the data of nineteen participants was used to analyze the results of the first part. Motion illusion was measured as a vector from the initial position to the end position of the illusion. Then, we first assigned 1 or -1 for all data of the motion illusion to observe the relationship between the inner/outer tendon vibration and direction of the motion illusion. In particular, 1 was assigned for the results of motion illusion if the arm moved in a folding direction (forward), and -1 was assigned for the opposite. Here, the ratio of 1s to -1s were 13:6 for inner vibration and 16:3 for outer vibration. Then, the Spearman rank correlation test was conducted for the direction results of the motion illusion between inner and outer tendon vibration. Consequently, we could not determine a significant correlation.

In addition, we analyzed the effect of tendon vibration on the amount of motion illusion. Here, we used the absolute value of the results of the motion illusion. The average of the absolute distance was 0.19 ± 0.23 (m) and 0.16 ± 0.25 (m) in the inner and outer tendon vibration, respectively. We conducted the Pearson correlation test for the results of the absolute distance of the motion illusion between inner and outer tendon vibration. Here, we determined a significant positive correlation between the absolute distances of motion illusion of the inner and outer tendon vibration ($r = 0.74, p < 0.001$).

3.2.2 DT of the visual gain

Figure 6 shows the results of the DT. To obtain the DT within a block of the staircase method, ten turning points from both series of staircase methods were averaged. In the statistical analysis, we used the inverse values of the LOW group to enable a comparison of the effect of vibrations on the DT between the HIGH and LOW groups. Two-way analysis of variance (ANOVA) was conducted on the vibration conditions vs. HIGH/LOW group, and when the sphericity assumption was violated (Mauchly's sphericity test), the degrees of freedom were adjusted using the Greenhouse-Geisser correction. A significant main effect was observed in the HIGH/LOW group factor ($F(1, 19) = 4.56, p = 0.0460, \eta^2 = 0.0324$), and a trend of interaction effect was also determined ($F(2.54, 48.17) = 2.84, p = 0.0562, \eta^2 = 0.0288$). Then, Shaffer's modified sequentially rejective Bonferroni post-hoc tests were conducted for multiple comparisons. Consequently, a significant difference between control ($mean = 1.41, \sigma = 0.17$) and inner ($mean = 1.53, \sigma = 0.21$) vibration condition ($p = 0.0498, r = 0.56$) in High visual gain were found. Moreover, as a result of other post-hoc test on the simple effect for the interaction, we determined a significant difference between the HIGH and inverse LOW group for the inner vibration condition ($p = 0.0165, \eta^2 = 0.142$).

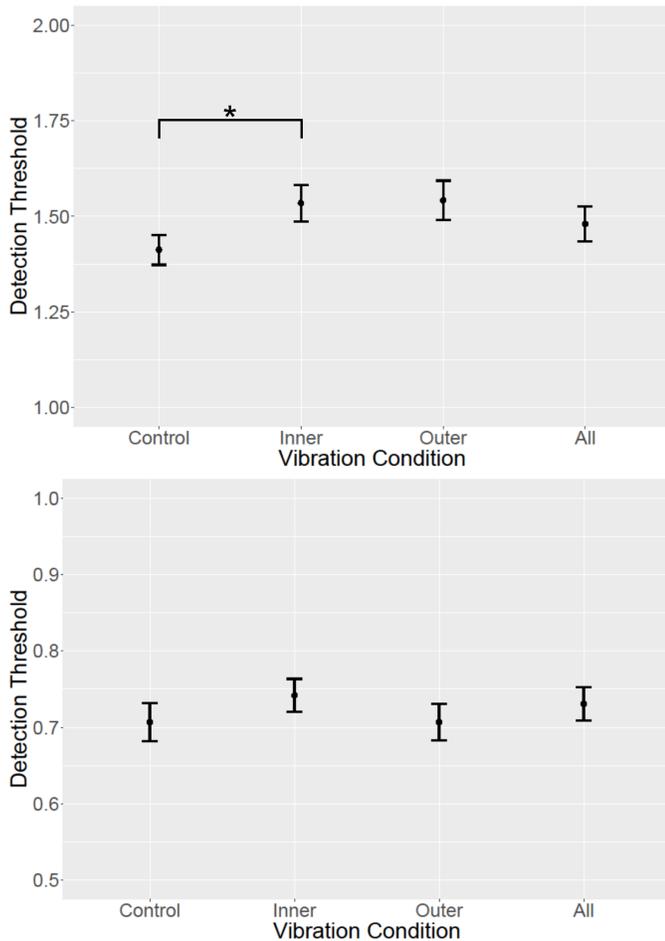


Fig. 6. XP1 results: Average of the DT of the discrepancy between physical and virtual motion with a visual gain. The top figure shows the results of the HIGH group, and the bottom figure shows the LOW group. The error bars indicate the standard error. "*" indicates the statistical difference with $p < 0.05$.

3.2.3 Relationship between motion illusion and DT

First, we analyzed the relationship between the DT results and direction of motion illusion measured in the first part of the experiment. Because we focused on the direction and its effect on the DT, we assigned 1 or -1 for all data of the motion illusion and DT. In particular, 1 was assigned to the DT results if it increased compared with the DT without vibration, and -1 for the opposite results. Then, the Spearman rank correlation test was conducted for the pairs of the results of motion illusion and DT within the same tendon vibration condition. Consequently, we found a significant negative correlation between the results of motion illusion and the DT of the LOW group, with inner tendon vibration ($r = -0.46, p = 0.047$).

In addition, we analysed the relationship between the DT results and distance of motion illusion. To obtain the effect the vibration had on the DT, we standardized the DT data by the DT values without vibration. Then, the Pearson correlation test was conducted for the pairs of the absolute distance of motion illusion and DT results. Consequently, we determined no significant correlation.

3.3 Discussion

3.3.1 Effect of tendon vibration on motion illusion at rest

Unlike the previous report (e.g. [38], [39]), the results of the direction of motion illusion in the first part of the experiment were inconsistent between the participants, and the inner and outer tendon vibration did not always have the opposite effect. We considered that this difference was because our experiment setup had no restriction on user movement, unlike in most existing studies. Because of the freedom of the movement, some participants experienced motion illusion in the direction of lengthening the muscle, whereas others experienced TVR inducing the motion in the direction of straining the muscle. Furthermore, the tendon vibration illusion can be said to be strongly biased because of top-down effects such as knowledge and expectations [11], [44]; therefore, the motion illusion varies in a practical setup where users can freely move their body. Nonetheless, a correlation was found between the amount of motion illusion caused by inner and outer tendon vibration, suggesting that at least consistent individual differences exist in the illusion of motion to tendon vibration.

3.3.2 How does tendon vibration affect the DT?

The results suggest that tendon vibration has an effect on the DT of the discrepancy between actual and visual motion, particularly with a high visual gain for which visual motion was larger than actual motion. Participants had a higher DT with tendon vibrations for the HIGH group of visual gain. This indicates that tendon vibration could extend the range of applicable visual gain without being perceived by users. Regarding the effect of tendon vibration on the DT, we had three different hypotheses. Of these hypotheses, [H1-2] explained our results the best: tendon vibration functions as noise on somatosensory sensation, and participants noticed the discrepancy between visual and somatosensory information less. If [H1-1] was true, the DT should decrease for inner tendon vibration compared with the control condition in the HIGH gain group. However, the results indicated that the DT increased in both inner and outer tendon vibration. Moreover, the results showed that no positive correlation exists between the direction of motion illusion induced by tendon vibration during rest and whether DT increases compared with the control condition. Therefore, [H1-2] seems to fit these results the most.

The fact that the effect of all tendon vibration on DT was weaker than that of inner and outer tendon vibration suggests either that the effects of inner and outer tendon vibrations cancel each other, or that what is important for the effect on the DT is not the total amount of vibration intensity, but the amplitude of each vibration. Although it is unclear which of the two explanations is correct based on the present experiment alone, the latter explanation is more likely to be correct, given that there was no correlation between whether the vibration is inner or outer and the direction of motion illusion.

The effect of tendon vibration was larger with the HIGH condition than LOW condition, and our results were consistent with previous results reporting that people were more sensitive to the visual/kinesthetic discrepancy in the LOW visual gain than HIGH visual gain [55]. Another possible

reason might be that, in our experiment, the amount of visual motion was less with LOW visual gain (60 degrees) than with HIGH visual gain (120 degrees). Therefore, although the physical motion range was the same in the LOW and HIGH condition (60 to 120 degrees), the visual information in the LOW condition may affect the motion perception less. Consequently, although the motion perception relied more on the visual information owing to the noise effect of the tendon vibration, its effect on the DT was small in LOW visual gain.

4 XP2: INFLUENCE OF TENDON VIBRATION ON RESOLUTION OF PSEUDO-WEIGHT SENSATION

In this experiment, the JND of pseudo-weight sensation induced by motion gain with and without inner tendon vibration was investigated. The first experiment indicated that the tendon vibration could extend the range of applicable visual gain. However, considering the possibility that tendon vibration functions as noise on somatosensory information, tendon vibration may degrade the sensitivity of pseudo-weight sensation. Therefore, the research question of this experiment was whether the tendon vibration affected the sensitivity of pseudo-haptic weight sensation. Note that if the tendon vibration improves or does not change the JND compared with the no-vibration condition, we can conclude that tendon vibration can effectively increase the range of pseudo-haptic weight sensation.

4.1 Methods

The equipment and virtual environment was the same as the first experiment.

4.1.1 Task

The experiment was conducted using the constant stimuli method. The task involved comparing the weights of two different virtual dumbbells: the reference and comparison dumbbells. First, participants lifted the first virtual dumbbell. The lifting task was the same as that in the first experiment for the HIGH gain group. When the virtual dumbbell reached the blue bar, the dumbbell disappeared and the other dumbbell appeared at the initial position. Then, participants lifted the second dumbbell to the blue bar. Subsequently, a question panel was presented in front of them, and they had to answer the question "Which dumbbell did you feel heavier?" with "the former" or "the latter." They used the left VR controller to answer. Subsection 4.1.2. and 4.1.4 provides the detailed condition and flow, respectively.

4.1.2 Conditions

There were two conditions regarding the vibrations: with and without inner tendon vibration. The vibration conditions of the reference and comparison were the same. This means that if the reference is without vibration, the comparison is without vibration, and if the reference is with vibration, the comparison is with vibration. In addition, the reference dumbbell had a motion gain of 1.5, and the comparison dumbbell had motion gains of -30%, -15%, -8%, +8%, +15%, or +30% of the reference gain (that is, motion

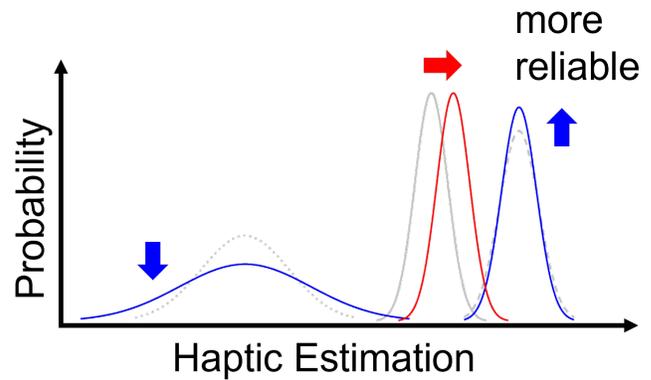


Fig. 7. Concept figure of MLE with noise on haptic information and increment of the reliability of visual information. The increment of the reliability of visual information decreases its variances and makes the final perception have less variances ([H2-1]) and shift to the value estimated by the visual information.

gains of 1.05, 1.28, 1.38, 1.62, 1.73, 1.95, respectively). These values were determined through the pilot test. Note that several motion gains exceeded the DT. Our pilot test confirmed that participants could experience a pseudo-weight sensation for these gains while they noticed the motion modification. We considered only the inner tendon vibration because it was expected to have the biggest effect on the results, considering the results of the first experiment.

4.1.3 Collected data

Each participant answer was measured to calculate the the JND of pseudo-weight sensation. Furthermore, questionnaires regarding tiredness, confidence of the answer, strategy to answer, and impression of vibration were asked.

4.1.4 Procedure

Ten participants (7 males and 3 females in their 20s) participated. The flow was almost the same with the first experiment until the first part of the experiment. The difference was that the calibration and measurement were conducted only for the inner tendon vibration. Subsequently, participants continued to the main part of the constant stimuli method. There were 5 blocks in total. Within a block, all combinations of the two vibration conditions and six motion gains of the comparison condition were presented considering the presenting order of the reference and comparison dumbbells. Therefore, each block included 24 trials, and each comparison condition was compared to the reference condition ten times. At the end of the experiment, participants removed all of their equipment and filled in a questionnaire. Subsequently, they were remunerated with an Amazon gift card of 20 euro for their participation.

4.1.5 Hypotheses

The hypothesis of this experiment is as follows:

- [H2-1] The JND does not increase because users rely more on the visual information.

As depicted in Fig.5, the variance of the somatosensory sensation increase if the tendon vibration functions

as noise, increasing the variance of the final perception: pseudo-weight sensation. In this case, the JND increases. However, we hypothesized that participants would rely more on visual cues because of the noise on somatosensory information and would then decrease the variance of the visual sensation (Fig. 7). If this occurs, the JND would not be necessarily increased.

4.2 Results: JND of pseudo-weight sensation

All participants successfully confirmed to experience motion illusion in the first part of the experiment. The Probit analysis [56] was conducted for the results of each participant, which calculated the parameters of the best-fitting cumulative normal function. Then, we computed the JND for each vibration condition as a half of the distance between the points of 25% and 75% on the psychometric curve for each participant. These values were 0.20 ± 0.02 for the condition without vibration (control) and 0.19 ± 0.01 for the condition with the inner tendon vibration (vibration). The JND of the vibration condition was approximately 5% smaller than that of the control condition, but a t-test confirmed that this difference is insignificant. Figure 8 shows the psychometric curves calculated with the averaged values of all participants' results.

4.3 Discussion

The results of the JND suggests that the sensitivity of pseudo-weight discrimination was the same or even better with the inner tendon vibration than that without vibration. These results support [H2-1]. Tendon vibration is known to degrade proprioceptive responsiveness [51], [52] and this should induce an increment of the variance of somatosensory information and thus induce that of final perception, that is, pseudo-weight sensation. However, considering the results obtained, the variance of visual information should decrease. Regarding this, as mentioned above, we hypothesize that this is because participants relied more on visual

information, and this decreases the variance of the information [57].

5 XP3: INFLUENCE OF TENDON VIBRATION ON WEIGHT SENSATION MEASURED BY PSEUDO-WEIGHT INDUCED BY VISUAL MOTION GAIN

This experiment investigated the PSE between the pseudo-weight sensation induced by the inner tendon vibration and that by motion gain. Through the first and second experiment and our informal test, we observed that tendon vibration increased a sense of weight while lifting a virtual object in VR. As mentioned in Section 2, the effect of tendon vibration on force and weight sensation has been investigated in previous studies. However, first, as the results regarding the motion illusion in the first experiment were different from those obtained in previous studies, we considered that investigating the effect on weight was also important using our practical setup. In addition, to the best of our knowledge, this study is the first to measure the effect of tendon vibration on the sense of weight by comparing the pseudo-weight sensation induced by motion gain. The objective of this study was to investigate the PSE between the sense of weight induced by tendon vibration and that by motion gain. The knowledge of the PSE leads the design guide of the use of tendon vibration with pseudo-haptics technique concerning the sense of weight.

5.1 Methods

The equipment and virtual environment was the same as the first and second experiments.

5.1.1 Task

The experiment was conducted following a staircase design. The objective was to determine the PSE between the sense of weight induced by the inner tendon vibration and that by a motion gain. The inner tendon vibration was used considering the results of the first experiment that indicated that the inner tendon vibration was most effective to the motion sensation for our lifting task. As a task of the staircase method, participants lifted a reference and comparison dumbbell independently, and then answered the two-alternative forced choice (2AFC) question "Which is heavier?" with "the former," or "the latter." The lifting task was the same as that of the first and second experiments.

5.1.2 Conditions

There were primarily 2 groups of staircase methods: vib-ref and con-ref. In the vib-ref group, the reference condition was a motion gain of 1.0 with inner tendon vibration. Here, the comparison condition was without vibration and with a motion gain that was one of ten steps from 0.4 to 1.0. In the con-ref group, the reference condition was without vibration and with a motion gain of 1.0. Then, the comparison condition was with inner tendon vibration and a motion gain that was one of ten steps from 1.0 to 2.5. Our pilot test determined these values. In the vib-ref group, the PSE indicates a motion gain that induces the same weight sensation as the inner tendon vibration. In the con-ref group, the PSE indicates the motion gain required to cancel the sense of weight induced by the inner tendon vibration.

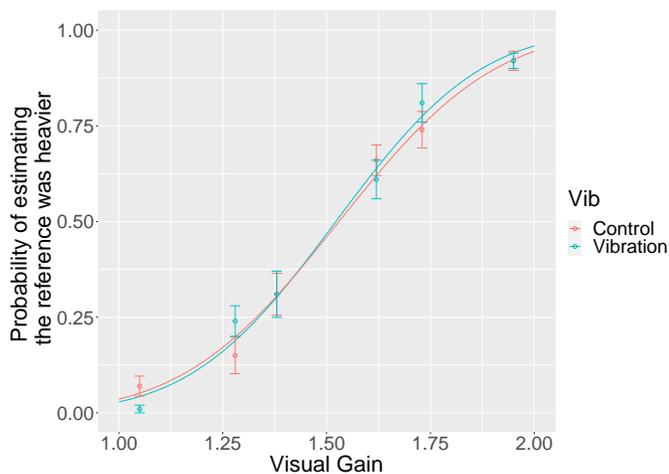


Fig. 8. XP2 results: Psychometric curves of the averaged results. It plots the average percentage of answers in which participants considered the reference dumbbell to be heavier than the comparison dumbbell. The error bar indicates the standard error (SE). Note that Control indicates the condition without vibration.

5.1.3 Collected data

Each motion gain at a turning point was measured to calculate the PSEs by averaging them.

5.1.4 Procedure

Twenty participants (12 males and 8 females in their 20s) participated in the experiment. The procedure before the main task was the same as that in the first and second experiments, including the calibration of the vibrator positions and measurement of motion illusion. The main part was conducted with the staircase method, and the vib-ref and con-ref groups were the two blocks. Both groups had two series where one began with a minimum motion gain of 0.4 for vib-ref and 1.0 for con-ref, and the other with a maximum gain of 1.0 for vib-ref and 2.5 for con-ref. The gain of the comparison dumbbell was increased or decreased in an interval of 0.06 for vib-ref group or 0.15 for con-ref group following the participants' answers. When participants answered that the comparison dumbbell was heavier, the motion gain increased by one step. When participants answered that the reference dumbbell was heavier, the motion gain decreased by one step. A block of stair case methods ended when both series reached the 5th change of the direction on increasing or decreasing the gain. In addition, the motion gain did not exceed the minimum or maximum gain. If the motion gain was to exceed the limit, it remained at the same gain, and the count of turning points increased. The presenting order of reference and comparison conditions were randomized. In addition, the order of blocks was counterbalanced.

5.2 Results: PSE of pseudo-weight sensation between tendon vibration and motion gain

All participants successfully confirmed experiencing motion illusion in the first part of the experiment. The 10 motion gains at the turning points in a block were averaged for each participant to compute the PSE. Table 1 indicates the PSE results. The PSE was 0.64 ± 0.22 in the vib-ref group and 1.62 ± 0.76 in the con-ref group (each PSE was *average* $\pm 2\sigma$). Here, the results of the PSE had large variances beyond the JNDs obtained in XP2. Then, we analyzed the correlation between the two PSE results to determine if they were consistent within each participant. Figure 9 shows the plots of PSE results of each participant in the vib-ref and con-ref groups. The Pearson correlation test was conducted for the relationship between the results of the PSE in the vib-ref and con-ref groups. Consequently, we determined a significant negative correlation ($r = -0.61, p = 0.0042$). In addition, the same correlation test was conducted for the relationship between the absolute value of the intensity of motion illusion at rest and each PSE result. Then, a significant positive correlation was found between motion illusion and the PSE of the con-ref group ($r = 0.68, p = 0.00093$).

5.3 Discussion

The PSE from the two groups were in a symmetrical relationship. This suggests that the inner tendon vibration increases the sense of weight and its effect is the same as that using a motion gain of 0.64. That is, a motion gain

TABLE 1
PSE of pseudo-weight sensation between inner tendon vibration and motion gain.

Condition	PSE (<i>average</i> $\pm 2\sigma$)
vib-ref	0.64 ± 0.22
con-ref	1.62 ± 0.76

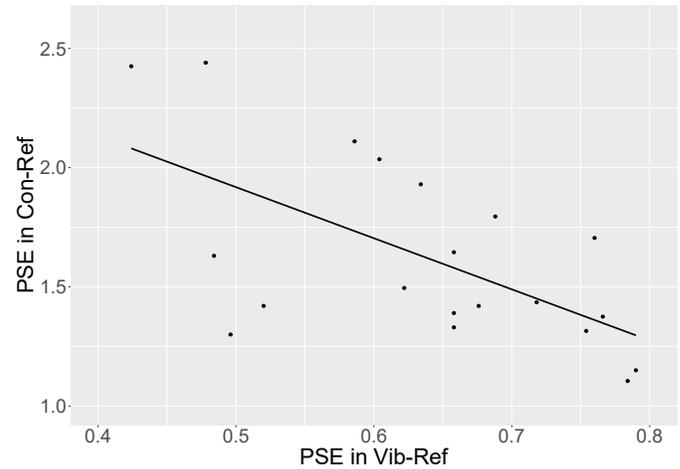


Fig. 9. Plots of the PSE results of each participant in the vib-ref and con-ref groups.

of 1.62 cancels its effect. Studies mentioned in the related work section have noted that tendon vibration increases the signal from muscle spindle and/or tendon organ, and this might lead to an increment of the sense of weight. However, the results had large variances. As shown in Fig. 9 and the results of the correlation test, participants had consistent PSE results between the vib-ref and con-ref groups. This indicates that the effect of the vibration on pseudo-weight sensation has individual differences. The results of the correlation test between the intensity of motion illusion at rest and PSE of the con-ref group support this.

6 GENERAL DISCUSSION

This study investigated whether tendon vibration can extend the effect of the pseudo-haptic technique. Our results suggest that the inner tendon vibration while lifting a virtual object can extend an applicable motion gain without being noticed by users (XP1) with the similar resolution of pseudo-weight sensation as without vibration (XP2). Our first experiment suggested that an unnoticeable, strict applicable gain was from 0.71 to 1.41 without tendon vibration and 0.74 to 1.53 with inner tendon vibration. In addition, the second experiment showed that the JND of pseudo-weight sensation was 0.20 and 0.19 for each condition. Here, we could roughly compute that visual motion gain could present at least four levels of weight sensation (by $(1.41 - 0.71)/0.20$), and visual motion gain with inner tendon vibration could present at least five levels of weight sensation (by $(1.53 - 0.74)/0.19$). This effect indicates that tendon vibration could increase the number of presentable levels of pseudo-weight sensation. In addition, to the best of our knowledge, this study is the first to show the possibility

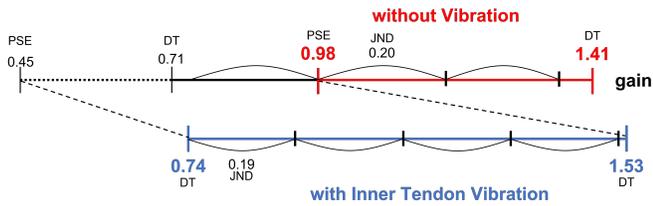


Fig. 10. Summary of results: The pseudo-haptic technique can present four steps of different weight sensation without the tendon vibration (the range: 0.71 - 1.41; the resolution: 0.20) while it can present five steps with the tendon vibration (the range: 0.74 - 1.53; the resolution: 0.19). The most efficient manner of combining visual motion gain and inner tendon vibration is using a gain of 0.74 to 1.53 with the tendon vibration and 0.98 to 1.41 without vibration. Then, the pseudo-haptic technique can present 7 steps in total.

of using tendon vibration as noise on somatosensory information to increase the contribution of visual information on pseudo-haptics sensation.

Moreover, this study is the first to compute the PSE of pseudo-weight sensation between tendon vibration and motion gain (XP3). With the PSE obtained in our experiment, developers can design a wider range of pseudo-weight sensation by combining tendon vibration and motion gain. Fig.10 summarizes our results. Practically, as the PSE was 0.64 and using the results of the first experiment, we could compute that the presentable range of weight sensation with tendon vibration and gain is to be theoretically the same as 0.45 ($= 0.64 * 0.74$) to 0.98 ($= 0.64 * 1.53$) without tendon vibration. Therefore, considering the resolution (results of XP2), the most efficient manner of combining techniques is to use 0.74 to 1.53 of gain with tendon vibration and 0.98 to 1.41 without tendon vibration. Then, we can present at least seven levels of weight sensation (by $(1.53 - 0.74)/0.19 + (1.41 - 0.98)/0.20$). We nearly double the capacity for simulating virtual weights: four steps only without vibration, and up to seven steps exploiting vibrations. However, because the effect of tendon vibration has individual differences, implementing a calibration step to map the effects of tendon vibration and motion gain for each user may be better in a practical application.

Future research may explore additional vibration parameters and interaction design that can further enhance the effect. One possible method for enhancing the effect is to utilize the aftereffect of tendon vibration [53]. For example, to increase the effect of motion illusion, activate one side of the tendon vibration until before lifting a virtual object and then switch it to the other side of the tendon vibration immediately after lifting. In addition, in the second and third experiments, several visual gains were used above the DT. The DT of the visual/physical motion discrepancy obtained in the first experiment is the strictest criterion for an applicable visual gain. However, we believe that manipulating the weight perception with gains above the DT is possible, and that the practical range of the applicable visual gain is greater than the DT obtained in the first experiment. First, in our experiment and in other psychological experiments that investigate this type of DT, the threshold would be stricter than in practical uses case because the tasks require participants to focus on the DT, thereby improving sensitivity to it.

Moreover, we consider that a visual gain with users feeling uncomfortable or without sensory integration occurring because of a large visual/physical motion discrepancy is not the same as the DT. Some studies have positively applied visual gain above the DT and succeeded in presenting a greater pseudo-weight sensation [5]. However, a method for measuring the range of this practical visual gain has not yet been established. Therefore, another study could propose an experimental method for investigating this practical range of pseudo-haptics with tendon vibration. Finally, the limitation of our use of tendon vibration is that it emits noise and may impair the VR experience. Although no participant mentioned that they felt uncomfortable or annoyed by the sound or vibration, using noise-cancelling headphone and avoiding long-duration uses may create better experiences.

7 CONCLUSION

This study investigated the possibility of using tendon vibration to extend pseudo-haptic sensations in VR. In particular, we evaluated the effect of tendon vibration on the DT of visual/physical motion discrepancy (XP1), the JND of pseudo-weight sensation induced by visual gain (XP2), and the sense of weight by computing the PSE with the pseudo-weight induced by visual gain (XP3). The results of the first and second experiments show the possibility of a new approach that uses tendon vibration as noise on somatosensory information to enable the pseudo-weight sensation to rely more on visual information, and the PSE obtained in the third experiment helps developers design a wider range of pseudo-weight sensation. Our results suggest that tendon vibration nearly doubles the capacity for simulating virtual weights. In summary, our results show that tendon vibration has a potential to extend pseudo-haptic techniques in VR.

ACKNOWLEDGMENTS

This work was partially supported by the MEXT Grant-in-Aid for Scientific Research (S) (19H05661), JSPS Grant-in-Aid for Scientific Research (A) (21H04883), and Grant-in-Aid for JSPS Fellows (21J12284).

REFERENCES

- [1] A. Pusch and A. Lécuyer, "Pseudo-haptics: from the theoretical foundations to practical system design guidelines," in *Proceedings of the 13th international conference on multimodal interfaces*, 2011, pp. 57–64.
- [2] Y. Ujitoko and Y. Ban, "Survey of pseudo-haptics: Haptic feedback design and application proposals," *IEEE Transactions on Haptics*, vol. 14, no. 4, pp. 699–711, 2021.
- [3] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, "Pseudo-haptic feedback: can isometric input devices simulate force feedback?" in *Proceedings IEEE Virtual Reality 2000 (Cat. No. 00CB37048)*. IEEE, 2000, pp. 83–90.
- [4] Y. Taima, Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose, "Controlling fatigue while lifting objects using pseudo-haptics in a mixed reality space," in *2014 IEEE Haptics Symposium (HAPTICS)*. IEEE, 2014, pp. 175–180.
- [5] M. Rietzler, F. Geiselhart, J. Gugenheimer, and E. Rukzio, "Breaking the tracking: Enabling weight perception using perceivable tracking offsets," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 2018, pp. 1–12.

- [6] M. Samad, E. Gatti, A. Hermes, H. Benko, and C. Parise, "Pseudo-haptic weight: Changing the perceived weight of virtual objects by manipulating control-display ratio," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–13.
- [7] T. Honda, N. Hagura, T. Yoshioka, and H. Imamizu, "Imposed visual feedback delay of an action changes mass perception based on the sensory prediction error," *Frontiers in psychology*, vol. 4, p. 760, 2013.
- [8] N. L. Williams and T. C. Peck, "Estimation of rotation gain thresholds considering fov, gender, and distractors," *IEEE transactions on visualization and computer graphics*, vol. 25, no. 11, pp. 3158–3168, 2019.
- [9] N. Ogawa, T. Narumi, and M. Hirose, "Effect of avatar appearance on detection thresholds for remapped hand movements," *IEEE Transactions on Visualization and Computer Graphics*, vol. 27, no. 7, pp. 3182–3197, 2020.
- [10] U. Proske and S. C. Gandevia, "The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force," *Physiological reviews*, 2012.
- [11] M. W. Taylor, J. L. Taylor, and T. Seizova-Cajic, "Muscle vibration-induced illusions: review of contributing factors, taxonomy of illusions and user's guide," *Multisensory Research*, vol. 30, no. 1, pp. 25–63, 2017.
- [12] U. Proske and T. Allen, "The neural basis of the senses of effort, force and heaviness," *Experimental Brain Research*, vol. 237, no. 3, pp. 589–599, 2019.
- [13] K. Hagbarth, "Motor effects of vibratory muscle stimuli in man," in *Noble Symposium I. Muscular afferents and motor control*. Almqvist & Wiksell, 1966, pp. 177–186.
- [14] F. A. Sanz, 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*, vol. 10, no. 3, pp. 17–1, 2013.
- [15] S. Takamuku and H. Gomi, "What you feel is what you see: inverse dynamics estimation underlies the resistive sensation of a delayed cursor," *Proceedings of the Royal Society B: Biological Sciences*, vol. 282, no. 1811, p. 20150864, 2015.
- [16] T. Narumi, Y. Ujitoko, Y. Ban, T. Tanikawa, K. Hirota, and M. Hirose, "Resistive swipe: Visuo-haptic interaction during swipe gestures to scroll background images on touch interfaces," in *2017 IEEE World Haptics Conference (WHC)*. IEEE, 2017, pp. 334–339.
- [17] Y. Ujitoko, Y. Ban, and K. Hirota, "Presenting static friction sensation at stick-slip transition using pseudo-haptic effect," in *2019 IEEE World Haptics Conference (WHC)*. IEEE, 2019, pp. 181–186.
- [18] —, "Modulating fine roughness perception of vibrotactile textured surface using pseudo-haptic effect," *IEEE Transactions on Visualization and Computer Graphics*, vol. 25, no. 5, pp. 1981–1990, 2019.
- [19] A. Lécuyer, J.-M. Burkhardt, and L. Etienne, "Feeling bumps and holes without a haptic interface: the perception of pseudo-haptic textures," in *Proceedings of the SIGCHI conference on Human factors in computing systems*, 2004, pp. 239–246.
- [20] T. Hachisu, G. Cirio, M. Marchal, A. Lécuyer, and H. Kajimoto, "Virtual chromatic percussions simulated by pseudo-haptic and vibrotactile feedback," in *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology*, 2011, pp. 1–5.
- [21] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415, no. 6870, pp. 429–433, 2002.
- [22] M. O. Ernst and H. H. Bühlhoff, "Merging the senses into a robust percept," *Trends in cognitive sciences*, vol. 8, no. 4, pp. 162–169, 2004.
- [23] D. M. Wolpert, Z. Ghahramani, and M. I. Jordan, "An internal model for sensorimotor integration," *Science*, vol. 269, no. 5232, pp. 1880–1882, 1995.
- [24] G. Ariff, O. Donchin, T. Nanayakkara, and R. Shadmehr, "A real-time state predictor in motor control: study of saccadic eye movements during unseen reaching movements," *Journal of neuroscience*, vol. 22, no. 17, pp. 7721–7729, 2002.
- [25] R. Shadmehr and F. A. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *Journal of neuroscience*, vol. 14, no. 5, pp. 3208–3224, 1994.
- [26] S. Runeson and G. Frykholm, "Kinematic specification of dynamics as an informational basis for person-and-action perception: expectation, gender recognition, and deceptive intention," *Journal of experimental psychology: general*, vol. 112, no. 4, p. 585, 1983.
- [27] D. C. Knill and A. Pouget, "The bayesian brain: the role of uncertainty in neural coding and computation," *TRENDS in Neurosciences*, vol. 27, no. 12, pp. 712–719, 2004.
- [28] K. Friston, "The free-energy principle: a rough guide to the brain?" *Trends in cognitive sciences*, vol. 13, no. 7, pp. 293–301, 2009.
- [29] Y. Ban and Y. Ujitoko, "Enhancing the pseudo-haptic effect on the touch panel using the virtual string," in *2018 IEEE Haptics Symposium (HAPTICS)*. IEEE, 2018, pp. 278–283.
- [30] P. B. Matthews, "Mammalian muscle receptors and their central actions," 1972.
- [31] G. M. Goodwin, D. McCloskey, and P. Matthews, "The contribution of muscle afferents to klesesthesia shown by vibration induced illusionsof movement and by the effects of paralysing joint afferents," *Brain*, vol. 95, no. 4, pp. 705–748, 1972.
- [32] D. McCloskey, P. Ebeling, and G. Goodwin, "Estimation of weights and tensions and apparent involvement of a "sense of effort"," *Experimental neurology*, vol. 42, no. 1, pp. 220–232, 1974.
- [33] L. Jones and I. Hunter, "Effect of muscle tendon vibration on the perception of force," *Experimental neurology*, vol. 87, no. 1, pp. 35–45, 1985.
- [34] S. Le Franc, M. Fleury, M. Cogne, S. Butet, C. Barillot, A. Lecuyer, and I. Bonan, "Influence of virtual reality visual feedback on the illusion of movement induced by tendon vibration of wrist in healthy participants," *Plos one*, vol. 15, no. 11, p. e0242416, 2020.
- [35] K. Ushiyama, A. Takahashi, and H. Kajimoto, "Modulation of a hand-held object's property through proprioceptive stimulation during active arm movement: Proprioceptive modulation of a hand-held object's property," in *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–6.
- [36] E. Naito, H. H. Ehrsson, S. Geyer, K. Zilles, and P. E. Roland, "Illusory arm movements activate cortical motor areas: a positron emission tomography study," *Journal of Neuroscience*, vol. 19, no. 14, pp. 6134–6144, 1999.
- [37] R. Kitada, E. Naito, and M. Matsumura, "Perceptual changes in illusory wrist flexion angles resulting from motor imagery of the same wrist movements," *Neuroscience*, vol. 109, no. 4, pp. 701–707, 2002.
- [38] A. Sittig, J. van der Gon Denier, and C. Gielen, "The contribution of afferent information on position and velocity to the control of slow and fast human forearm movements," *Experimental Brain Research*, vol. 67, no. 1, pp. 33–40, 1987.
- [39] J. Inglis and J. Frank, "The effect of agonist/antagonist muscle vibration on human position sense," *Experimental Brain Research*, vol. 81, no. 3, pp. 573–580, 1990.
- [40] D. Burke, K.-E. Hagbarth, L. Löfstedt, and B. G. Wallin, "The responses of human muscle spindle endings to vibration of non-contracting muscles." *The Journal of physiology*, vol. 261, no. 3, pp. 673–693, 1976.
- [41] M. Tsuge, M. Izumizaki, K. Kigawa, T. Atsumi, and I. Homma, "Interaction between vibration-evoked proprioceptive illusions and mirror-evoked visual illusions in an arm-matching task," *Experimental brain research*, vol. 223, no. 4, pp. 541–551, 2012.
- [42] G. Fusco, G. Tieri, and S. M. Aglioti, "Visual feedback from a virtual body modulates motor illusion induced by tendon vibration," *Psychological Research*, vol. 85, no. 3, pp. 926–938, 2021.
- [43] C. A. Porro, M. P. Francescato, V. Cettolo, M. E. Diamond, P. Baraldi, C. Zuiani, M. Bazzocchi, and P. E. Di Prampero, "Primary motor and sensory cortex activation during motor performance and motor imagery: a functional magnetic resonance imaging study," *Journal of Neuroscience*, vol. 16, no. 23, pp. 7688–7698, 1996.
- [44] C. Thyriion and J.-P. Roll, "Perceptual integration of illusory and imagined kinesthetic images," *Journal of Neuroscience*, vol. 29, no. 26, pp. 8483–8492, 2009.
- [45] E. Cafarelli and C. E. Kostka, "Effect of vibration on static force sensation in man," *Experimental neurology*, vol. 74, no. 2, pp. 331–340, 1981.
- [46] B. L. Luu, B. L. Day, J. D. Cole, and R. C. Fitzpatrick, "The fusimotor and reafferent origin of the sense of force and weight," *The Journal of physiology*, vol. 589, no. 13, pp. 3135–3147, 2011.
- [47] E. Cafarelli and J. Layton-Wood, "Effect of vibration on force sensation in fatigued muscle." *Medicine and Science in Sports and Exercise*, vol. 18, no. 5, pp. 516–521, 1986.
- [48] J. B. Fallon and V. G. Macefield, "Vibration sensitivity of human muscle spindles and golgi tendon organs," *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine*, vol. 36, no. 1, pp. 21–29, 2007.

- [49] D. McCloskey, "Differences between the senses of movement and position shown by the effects of loading and vibration of muscles in man," *Brain research*, vol. 61, pp. 119–131, 1973.
- [50] F. Monjo, J. Shemmell, and N. Forestier, "The sensory origin of the sense of effort is context-dependent," *Experimental brain research*, vol. 236, no. 7, pp. 1997–2008, 2018.
- [51] O. Bock, K. Pipereit, and A. Mierau, "A method to reversibly degrade proprioceptive feedback in research on human motor control," *Journal of neuroscience methods*, vol. 160, no. 2, pp. 246–250, 2007.
- [52] C. Brun and M. Guerraz, "Anchoring the "floating arm": Use of proprioceptive and mirror visual feedback from one arm to control involuntary displacement of the other arm," *Neuroscience*, vol. 310, pp. 268–278, 2015.
- [53] T. Kito, T. Hashimoto, T. Yoneda, S. Katamoto, and E. Naito, "Sensory processing during kinesthetic aftereffect following illusory hand movement elicited by tendon vibration," *Brain research*, vol. 1114, no. 1, pp. 75–84, 2006.
- [54] J. S. Schofield, M. R. Dawson, J. P. Carey, and J. S. Hebert, "Characterizing the effects of amplitude, frequency and limb position on vibration induced movement illusions: Implications in sensory-motor rehabilitation," *Technology and Health Care*, vol. 23, no. 2, pp. 129–141, 2015.
- [55] E. Burns and F. P. Brooks, "Perceptual sensitivity to visual/kinesthetic discrepancy in hand speed, and why we might care," in *Proceedings of the ACM symposium on Virtual reality software and technology*, 2006, pp. 3–8.
- [56] D. Finney, "Probit analysis (3rd edition)," 1971.
- [57] W. A. Johnston and V. J. Dark, "Selective attention." *Annual review of psychology*, 1986.



Anatole Lécuyer is director of research and head of Hybrid team at Inria, Renne, France. He is currently Associate Editor of IEEE Transactions on Visualization and Computer Graphics, Frontiers in Virtual Reality and Presence. He was Program Chair of IEEE VR 2015-2016 and General Chair of IEEE ISMAR 2017. Anatole Lécuyer obtained the IEEE VGTC Technical Achievement Award in Virtual/Augmented Reality in 2019.



Yutaro Hirao received his B.S. and M.S. in engineering from Waseda University (2018 and 2020) in Japan. He is currently working toward the PhD degree in engineering from the University of Tokyo. His research topics are mainly virtual reality (VR) and cross-modal interaction.



Tomohiro Amemiya is an associate professor at the Graduate School of Information Science and Technology, the University of Tokyo. He received BS and MS degrees in mechano-informatics from the University of Tokyo in 2002 and 2004. From 2004 to 2019, he was a research scientist at NTT Communication Science Laboratories. He received his Ph.D. from Osaka University in 2008. His research interests include somatosensory perception and human-computer interaction technologies.



Takuji Narumi is an associate professor at the Graduate School of Information Science and Technology, the University of Tokyo. His research interests broadly include perceptual modification and human augmentation with virtual reality and augmented reality technologies. He received BE and ME degree from the University of Tokyo in 2006 and 2008 respectively. He also received his Ph.D. in Engineering from the University of Tokyo in 2011.



Ferran Argelaguet is an Inria research scientist at the Hybrid team (Rennes, France) since 2016. He received his PhD degree from the Universitat Politècnica de Catalunya (UPC), in Barcelona, Spain in 2011. His main research interests include 3D user interfaces, virtual reality and human-computer interaction. He was program co-chair of the IEEE Virtual Reality and 3D User Interfaces conference track in 2019 and 2020, and the journal track in 2022.