Manipulation of Body Sway Interpretation through Kinesthetic Illusion Induced by Ankles Vibration

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***Abstract*— Numerous studies have explored the body tilt and sway elicited by vibratory stimuli, which are thought to be related to reflex adjustments or kinesthetic illusions. However, prior studies have not thoroughly explored the conditions that change the interpretation of self and environmental factors. In the present study, a subjective body sway was induced through alternating vibrations that were applied to the antagonist ankle muscles. Results indicated that a low switching frequency inclined the interpretation of self-sway, while a high switching frequency favored the interpretation of environmental sway.**

Keywords*— *kinesthetic illusion, body sway, body tilting sensation

I. Introduction

Numerous studies have explored the induction of body tilt or sway through the application of vibrations to various body parts [1][2][3][4][5]. For example, the sensation of body tilt and sway can be utilized to simulate the experience of walking or swaying of a vehicle within a virtual reality environment. This body tilt phenomenon might be considered to be related to reflex adjustments or kinesthetic illusions, which are illusions of limb movement or misalignment caused by vibratory stimuli to tendons [6][7].

On the other hand, interpretation of this illusory phenomenon is not uniquely determined. Cases exist where the body tilt is interpreted as the participants' motion (self-factor), and it is interpreted as the motion of the floor or walls (environmental factor)[24]. Nonetheless, prior studies have not thoroughly explored the conditions that lead to these different interpretations of self- and environmental factors. The clarification of these conditions could enhance our understanding of the feasibility of incorporating this phenomenon into the design of applications such as those previously mentioned.

Vection is another example of a sensory input causing the body to tilt or sway. It is a phenomenon in which a stationary person feels as if he or she is moving when presented with a visual stimulus with motion in a particular direction. In vection, when the change in the direction of motion of the image is at a low frequency, the person tends to feel as if they are moving by themselves, and when the change is at a high frequency, the person feels as if the environment is moving[15][16].

Inspired by this example of vection, we speculated that in the presentation of body tilt and body sway by vibration presentation at the ankle, when the vibration is presented alternately to the antagonist muscles (extensor and flexor muscles), the switching frequency of the vibration may cause a change in the interpretation of one's own sway and that of the environment. Given that numerous studies on kinesthetic illusions are impacted by tactile stimuli, we also posited that the sensation of body tilt and sway may be affected by how body weight is exerted onto the sole (variation in the center of pressure of the foot).

In this study, we stimulate the antagonist muscles involved in foot extension and flexion at the ankle, and assess whether variations in the interpretation of intended sway occur when the stimulation conditions are altered. Furthermore, we investigate the robustness of this phenomenon by examining whether changes in interpretation occur under conditions where the center of pressure of the foot is varied.

II. Related Work

The phenomenon of kinesthetic illusion, which involves an illusion of limb movement or misalignment by vibratory stimulation of tendons [6][7], has garnered significant attention in the field of virtual reality as a means of eliciting the sensation of motion without actual movement [8][9][10][11]. As an example, it has been documented that applying a 100 Hz vibratory stimulus to the tendons of the biceps brachii muscle elicits the illusion of arm extension [6]. Despite the presence of a delay of several seconds before the illusion of movement is produced, and the limitations to its intensity [22], research has shown that the illusion is stronger and faster when alternating stimulation of the antagonist muscles is employed [23]. It has also been established that kinesthetic illusions can be elicited through electrical stimulation [12][13]. As a demonstration of this principle applied to the body tilt sensation, Takahashi et al. successfully induced subjective body tilt sensations via electrical stimulation of the tendons in the ankle [14].

There are numerous examples of illusory phenomena related to body motion that can be subjectively interpreted as either "self-motion" or "environmental motion". In the context of vection, which involves the perception of self-motion through visual stimuli, this interpretation can depend on the frequency of the stimuli. There is a latency for the onset of vection [15], during which time the discrepancy between visual information and the sense of balance is reconciled [16]. If the direction of motion of the image changes during the latency period, the sense of self-motion is not generated; instead, motion of the environment is perceived. On the other hand, if the change in motion direction of the viewed image is at low frequency, the motion is perceived as self-motion. Given that self-motion perception also arises from proprioception, a phenomenon analogous to vection may also occur in response to proprioceptive input. Research has demonstrated that visual input can produce percepts and motion illusions equivalent to those arising from proprioception [17][18].

The interpretation of 'self-motion' and 'environmental motion' can also be differentiated within vestibular sensation, which is directly tied to the sense of self-motion. Electrical stimulation has been demonstrated to control vestibular sensation, with numerous studies exploring its use in virtual reality applications [19][20]. It has been reported that switching stimuli between the left and right sides with a frequency of 1 Hz or greater is perceived as environmental oscillation [21].

In a seminal study by Lackner [24], the author report that when a vibratory stimulus was applied to the elbow, it generated the illusion of arm flexion. However, when the same stimulus was applied with the arm fixed to a wall, the resulting sensation was the rotation of the entire body. This alteration in perception was solely due to the modification in interpretation, whether the arm moved or the entire body moved, and not due to the perception of environmental motion. Yet, it is noteworthy that a minimal tactile cue impacted the interpretation of the nature of motion. This phenomenon has also been observed when making physical contact with the environment using the fingertips [25].

In the same study conducted by Lackner [24], a participant's experience of the illusion of a tilting wall or floor upon contact was documented. The stimulation of the Achilles tendon through vibration was found to result in an interpretation of environmental factors arising from both the stimulus and the physical contact with the environment.

Vibratory stimulation to the ankle has a more pronounced impact on postural stability in neutral standing positions than in postures where the stance surface is inclined forward or backward [2]. Such variations in stability can be attributed to potential changes in proprioception of posture, alterations in vibratory transmission due to muscle tension, and fluctuations in tactile awareness of the foot resulting from modifications in the center of pressure of the foot in a forward or backward inclined posture.

As previously stated, the body movement illusion phenomenon is subject to modification by two primary factors, namely the frequency of stimulus switching to the antagonist muscle and the provision of supplementary sensory cues. Thus, the focus of this investigation centers on these two factors, evaluating the influence of alterations in stimulus switching frequency and foot center of pressure on the interpretation of movement.

III. METHODS

The swaying sensation of the body is elicited by alternating stimulation of the antagonist muscles of the ankle through vibration. Experiment #1 examines how the interpretation of the sway is altered through changes in the frequency of the vibration switching, while Experiment #2 evaluates the impact of changes in the center of pressure of the foot on the interpretation of the sway.

A. Apparatus

Two vibrators (Acouve Lab Vp2 series Vp210) were affixed to the ventral and dorsal parts of the ankle with elastic ankle supporters (braces). The pressure exerted on the skin by the vibrators was maintained by the tension of the supporters. The frequency of the vibration utilized in the experiment was determined to be 70 Hz, as established in a study by Naito et al., which concluded that a strong kinesthetic illusion was elicited under this condition [26]. The 70 Hz sine wave was generated via software (Cycling '74 & MI7 Max 8), and the ventral and dorsal vibrators were driven alternately via an audio interface (Roland, OCTA-CAPTURE) and audio amplifier (FX-AUDIO-FX202A/FX-36A PRO).

The Wii Balance Board (Nintendo) was utilized to regulate the center of pressure in the foot.

B. Conditions

Experimental setup is as depicted in Fig. 1, in which the location of the vibrators is denoted by yellow circles. The vibrators were placed over the tendons near the ankle joint. The flexors on the ventral part and the extensors on the dorsal part were targeted for stimulation, as they correspond to antagonist muscles. The ventral vibrators generated an illusion of extension-oriented movement, while the dorsal vibrators elicited an illusion of flexion-oriented movement. The tibialis anterior tendon was utilized to foster the illusion of extension and the triceps surae tendon (Achilles tendon) for the illusion of flexion.

Experiment #1 was designed with seven conditions of switching frequency: 0 Hz (no switching, ventral stimulation only), 0 Hz (no switching, dorsal stimulation only), 1 Hz, 2 Hz, 3 Hz, 5 Hz, and 10 Hz. A total of 21 trials were conducted, with each set comprising three iterations of the seven conditions. The median value from the three repetitions was employed as the experimental data.

In Experiment #2, two switching frequency conditions were established, at 1 Hz and 10 Hz, due to their distinguishable effect on the interpretation of self and environmental sway factors identified in Experiment #1. The three conditions for center of foot pressure were categorized as anterior (toe-side), neutral (normal upright posture), and posterior (heel-side), which were regulated through measurement of the subject's center of foot pressure range in each condition prior to the experiment. In the measurement, the participants were instructed to sustain their

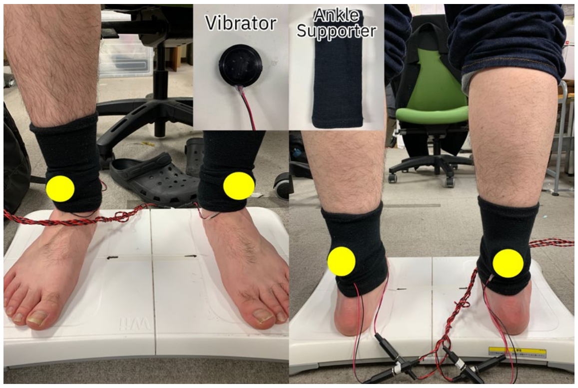

Fig. 1. Position of vibrators (the location of the vibrators is denoted by yellow circles.)

balance on the board for 10 seconds in each center of foot pressure condition, with recordings taken of their posture. In the neutral condition, participants were asked to maintain their natural stance, whereas on the toe and heel side, participants were asked to shift their center of pressure as far as possible while maintaining stability.

The experimenter monitored the results from the Wii Balance Board and instructed the participants to keep their readings within the range of values determined prior. The output from the Wii Balance Board was kept concealed from the participants during the experiment, but they were still instructed to retain their initial center of foot pressure as much as possible. The 18 trials were carried out, each consisting of three repetitions of the six conditions, including the frequencies and center of foot pressure conditions as one set. The median of the three repeated measures was used as the experimental data.

The sequence of experiments was pseudo-randomized such that the arrangement was counterbalanced among participants.

C. Experiment

Experiment #1 was performed with 12 participants, consisting of 2 females and 10 males, ranging in age from 22 to 27 years. Experiment #2 was carried out with 10 participants, consisting of 2 females and 8 males, with an age range of 22 to 27 years. Eight participants completed both experiments. The experiments were approved by the Ethics Committee of the authors' institution.

Following proper placement of the vibrators utilizing ankle supporters, calibration was performed utilizing an accelerometer (Sparkfun LIS331). The amplitude of vibration for each vibrator was regulated via software, ensuring a constant value of $80\ \mathrm{m/s^2}$ at a frequency of 70 Hz.

Prior to the stimulation, the experimenter adjusted the participants to face straight ahead by placing a finger in front of their eyes and instructing them to fix their visual attention to it. Throughout the stimulation, the participants were instructed to keep their eyes closed and maintain an upright stance on the apparatus. Meanwhile, the participants were outfitted with ear muffs designed to mask auditory cues, including the operating noise of the vibrator and other environmental noises.

The strength of the kinesthetics illusion, the interpretation of the produced sway (or tilt) and the confidence in this interpretation were evaluated during each trial. Participants were presented with alternating ventral and dorsal (or unilateral in 0 Hz conditions) vibration stimuli for 10 seconds. After the stimulation, participants responded on a 7-point Likert scale to the strength of the illusion (1: no illusion, 7: strong), their interpretation of the produced sway (or tilt) (1: completely environmental sway (or tilt), 7: completely their own sway (or tilt)), and their confidence in their interpretation (1: not at all confident, 7: very confident). The participants were instructed to take into consideration that the term "environmental sway (or tilt)" refers to the sway (or tilt) of the ground and not the vibration of the vibrators.

After each trial, participants were granted a 30-second rest. Additional 30-second rest was accorded between sets. Upon completion of all three sets, participants were prompted to provide comments.

In Experiment #1, participants were instructed to realign the center of pressure of their foot as closely as feasible to the center on the balance board prior to the initiation of the stimulus. Furthermore, they were advised to preserve this stance as possible as they can during the stimulus presentation.

In Experiment #2, participants were instructed to adjust their foot pressure center prior to stimulus presentation so as to align it within the range of values previously recorded during the experiment's pre-measurement phase.

In Experiment #2, the locus of the center of foot pressure was measured per trial. The data acquisition for this measurement began one second prior to the start of the stimulus.

In Experiment #1, the results were analyzed using Friedman tests and multiple comparisons with the Bonferroni correction. The statistical software utilized was IBM SPSS Statistics. The results of Experiment #2 underwent ART-ANOVA and multiple comparisons with the Bonferroni correction, with the aid of R and the ARTool package. A Paired-samples t-test was also conducted to assess the magnitude of the shift in the foot pressure center, utilizing the same software as Experiment #1. The significance level for all analyses was set at 0.05.

IV. Results

A. Experiment #1: Changes of ratings with switching frequency

Fig. 2(a) depicts the assessment of the perceived strength of the illusion for each of the switching frequency conditions in Experiment #1. It is evident that the alternate switching of vibration produced a stronger illusion compared to the continuous presentation of either the ventral or dorsal side. As the switching frequency increases, the variability in the ratings of strength of the illusion also increases. The Friedman test indicated a significant difference among the effects of the switching frequency conditions. However, no significant differences were found in the post-hoc analysis.

Fig. 2(b) presents the assessment of sway interpretation for each switching frequency condition. As previously stated, a rating of 1 means that the participant perceives complete environmental sway, while a rating of 7 indicates complete self-sway. The Friedman test indicated a significant difference among the effects of the switching frequency conditions, and Post-hoc analysis indicated that there were significant differences between 0 Hz (ventral) and 10 Hz ($p = 0.012$), 1 Hz and 5 Hz ($p = 0.038$), 1 Hz and 10 Hz ($p = 0.001$), and 2 Hz and 10 Hz ($p = 0.003$).

Fig. 2(c) illustrates the assessments of confidence for each of the switching frequency conditions. the differences among the conditions appear to be modest. The outcome of the Friedman test revealed no significant difference.

The correlation between strength of illusion and confidence, as quantified by the Pearson's correlation coefficient, was found to be 0.42 ($p = 8.2e-5$), which reflects a weak positive relationship.

B. Experiment #2: Changes of ratings with position of the center of foot pressure

Fig. 3(a) depicts the assessment of the illusion's strength for each foot pressure center and switching frequency condition in Experiment #2. The median strength of the illusion appears to be somewhat higher in the neutral condition as compared to the other conditions. An ART-ANOVA test revealed significant main effects of switching frequency ($Pr(>F) = 0.00051$) and foot pressure center ($Pr(>F) = 0.011$), but no interactions were detected. Post-hoc analysis indicated that there were significant differences between 1 Hz-neutral and 10 Hz-anterior ($p = 0.00034$), 1 Hz-neutral and 10 Hz-posterior ($p = 0.013$), and 1 Hz-posterior and 10 Hz-anterior ($p = 0.022$).

Fig. 3(b) presents the assessment of the interpretation of the sway for each foot pressure center and switching frequency condition. There appears to be little median difference between the foot pressure center conditions for each switching frequency condition. from ART-ANOVA, the main effect was significant only for switching frequency ($Pr(>F) = 1.7e-11$) and not for foot pressure center or interaction.

Fig. 3(c) illustrates the assessments of confidence for interpretation for each center of foot pressure and switching frequency condition. There appears to be little median difference between center of foot pressure conditions for any switching frequency condition; ART-ANOVA showed no significant main effects for any of the conditions.

The correlation between strength of illusion and confidence, as quantified by the Pearson's correlation coefficient, was found to be 0.38 ($p = 0.0031$), which reflects a weak positive relationship.

C. Experiment #2: Changes in center of foot pressure during stimulation

Fig. 4(a) and Fig. 4(b) show the changes in the center of pressure at 1 Hz-neutral and 10 Hz-neutral for one participant during Experiment #2. The positive y-axis represents the anterior direction (toe side), and the negative y-axis denotes the posterior direction (heel side). The center of pressure was captured at a frequency of 100 Hz, and linear interpolation was applied to a few missing values. 1 Hz-neutral (Fig. 4(a)) and 10 Hz-neutral (Fig. 4(b)) both appear to have periodic fluctuations in values. This trend was observed for all participants. In terms of amplitude, the 1 Hz-neutral appears to be larger than the 10 Hz-neutral.

A root mean square (RMS) comparison was performed to quantify the difference in amplitude between the 1 Hz-neutral and 10 Hz-neutral. The center of pressure was extracted for a duration of 8 seconds, starting from 1 second after the initiation of vibration. The extracted signal was subjected to DC component removal, followed by calculation of the RMS value. These steps were performed on a total of 30 signals from 3 repeated measurements and 10 participants in each condition.

Fig. 4(c) showcases the results of the computed RMS values, which indicate that the 1 Hz-neutral appears to have a higher RMS value than the 10 Hz-neutral. A paired t-test indicated a significant difference between the two conditions ($p < 0.001$).

V. Discussion

A. Strength of illusion

In Experiment #1, Significant differences were not revealed in the illusion's intensity as a function of the switching frequency.

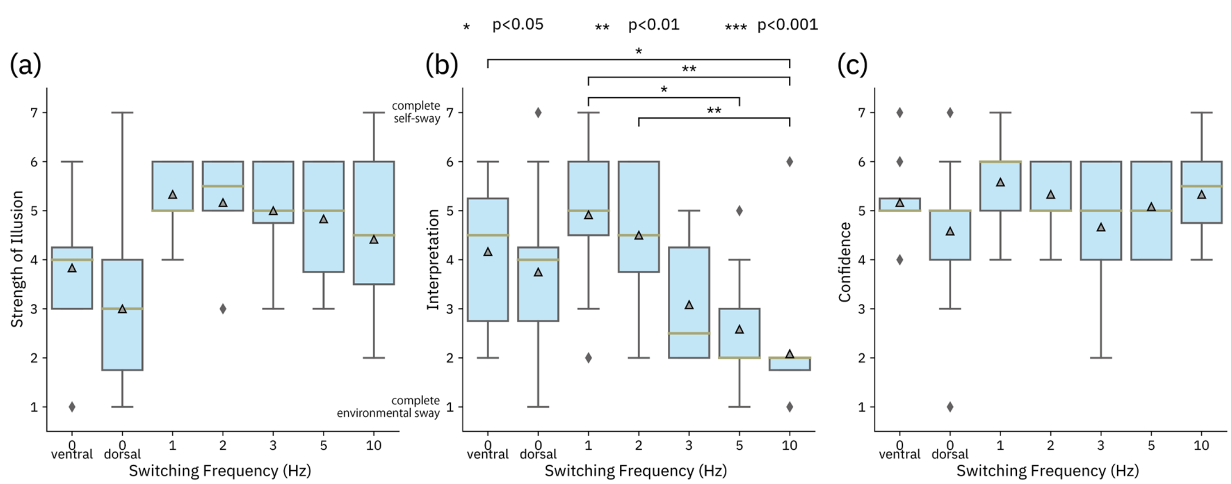

Fig. 2. Evaluation of (a) illusion strength, (b) sway interpretation (1: completely environmental sway (or tilt), 7: completely their own sway (or tilt)), and (c) confidence in interpretation for different switching frequency conditions.

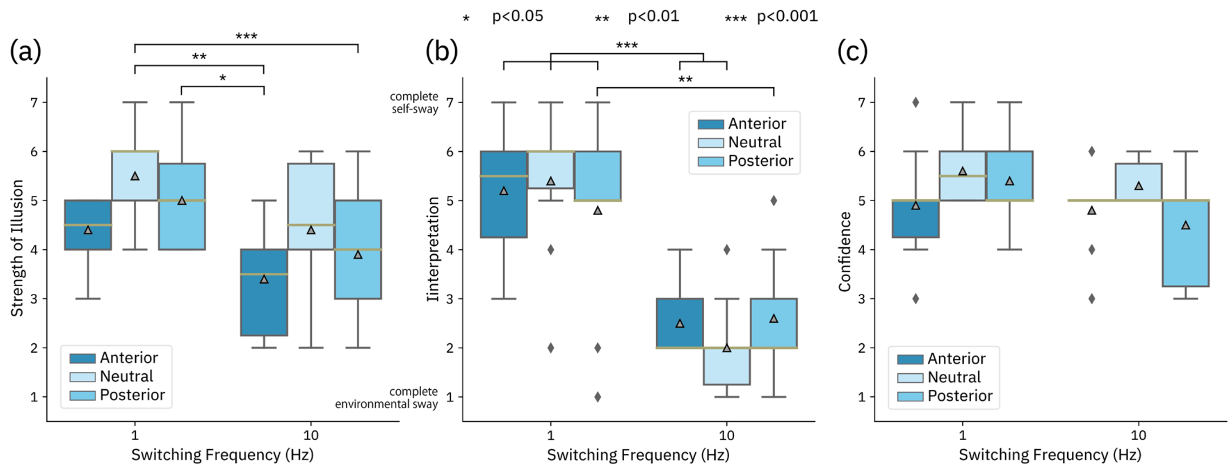

Fig. 3. Evaluation of (a) illusion strength, (b) sway interpretation (1: completely environmental sway (or tilt), 7: completely their own sway (or tilt)), and (c) confidence in interpretation for different center of foot pressure and switching frequency conditions.

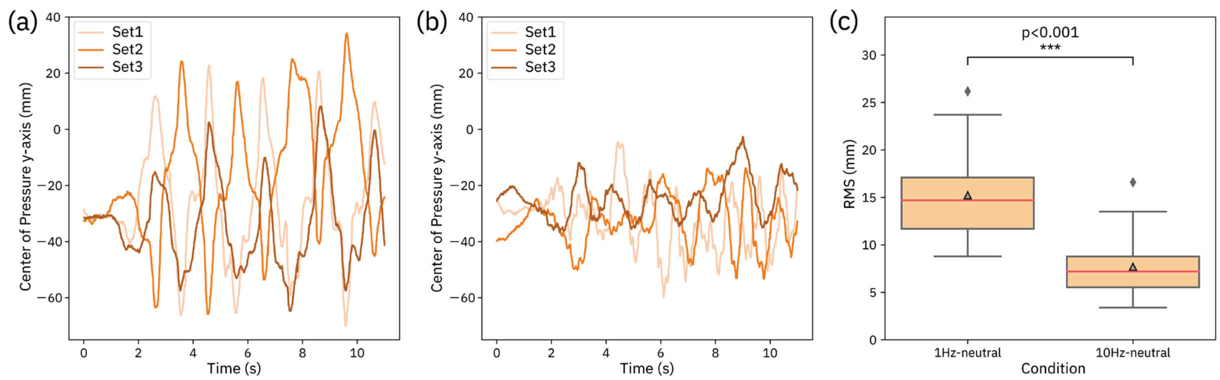

Fig. 4. Changes in center of foot pressure at (a) 1 Hz-neutral and (b) 10 Hz-neutral in one participant. (c) RMS values of the center of foot pressure at switching frequencies of 1 Hz and 10 Hz.

Even when applying a rapid switching frequency of 10 Hz, no significant difference was detected when compared to the frequency of 1 Hz. There appears to be a presence of frequency dependence, but not enough to make a significant difference in multiple comparisons. The finding that a switching frequency of 10 Hz can be perceived as a bodily vibration is noteworthy. It has been observed that there is a delay of several seconds before the illusion occurs [22], but it is thought that this delay was reduced by the alternating vibration[23] and that the illusion was produced even at the 10 Hz switching frequency. It is thought that the illusions produced by muscle A were accelerated by the combination of the aftereffect, which is the sensation of reversal from the direction of the illusion produced at the end of the vibration of muscle B, which is antagonistic to muscle A (i.e. the same direction of illusion as muscle A)[23].

The switching frequencies of 1 Hz seems to give higher intensity of the illusion relative to 0 Hz, although no statistically significant difference was observed in this study. This may be due to the enhancement of illusion's intensity by alternating vibrations shown in the previous study[23]. This experimental investigation compared the strength of tilt with that of sway, recognizing that a qualitative equivalence between the two may be debatable. Nevertheless, since the main purpose of the experiment was to evaluate the vividness of the illusion regardless of its type, the comparison seems to be a valid.

The present experiments did not elucidate the upper limit of the switching frequency in which the kinesthetic illusion is perceived. Previous research suggests that the illusion may not occur when the alternating stimulation of antagonist muscles is synchronized [27]. This indicates that the illusion may not take place at frequencies that are too high to be perceived as alternating vibrations.

In Experiment #2, statistically significant differences in the illusion's intensity were detected between 1 Hz-neutral and 10 Hz-anterior, as well as between 1 Hz-neutral and 10 Hz-posterior. This implies that, when the switching frequency is set to 10 Hz, the shift of the center of foot pressure to either the anterior or posterior direction could have decreased the illusion. The tilt of the center of pressure forwards or backwards concentrates tactile sensations on the toes or heels, respectively, which may have made participants focus on these sensations, thus reducing the intensity of the illusion as in previous research[25]. It is also possible that ankle muscles tense when the center of pressure shifts to the toes or heels, which could impact the illusion's intensity; however, this cannot be confirmed by this experiment.

In both Experiments A and B, a weak positive correlation was observed between the intensity of the illusion and the confidence in the sway interpretation, indicating that a clear interpretation can be made when the illusion is robustly perceived.

B. An interpretation of sway

Experiment #1 demonstrated a tendency among participants to attribute their sway to the environment when the switching frequency was high, and to their own movements when the frequency was low. Participants reported feeling an "earthquake-like shaking" and a stronger sensation of contact with the ground at high frequencies, while attributing their movements to themselves at low frequencies. These observations suggest that higher-order interpretations in the brain play a role in determining the source of sway. When sensory information cannot be accounted for by one's own movement, it may be perceived as originating from the environment through a process of elimination.

The amplitude of the center of foot pressure shift along y-axis during stimulation was less pronounced at 10Hz compared to 1Hz. This is an expected physical phenomenon as the amplitude decreases at higher frequencies while vibrating with the same energy; however, it might also have implications on the interpretation of "sway." When the switching frequency was elevated, participants encountered conflicting information, where their foot pressure center swayed less, but the sensation of sway was still perceived, which could have contributed to the belief that the ground was actually swaying.

Within the scope of the present experiment, it is not possible to conclude whether the body swaying at high switching frequencies was interpreted as environmental sway because it was 'inherently impossible', or whether it was interpreted as environmental sway because the body did not actually sway much at high switching frequencies. Nevertheless, the findings imply that in situations of alternating vibrations, it is possible to provide an interpretation of whether the body itself or the environment is swaying, depending on the situation, by adjusting the switching frequency. When the frequency was at 0 Hz, the participants were not biased towards attributing the inclination to either their own movement or that of the environment. Participants reported experiences such as "I perceived the floor to be tilting when the vibration was on one side" and "I felt my body tilt towards the source of vibration when it was situated on one side".

C. Future work

A noticeable shift in interpretation was observed upon transitioning from a switching frequency of 2 Hz to 3 Hz. Further investigation is required to determine the frequency at which this perceptual alteration takes place. There were individual differences in the switching frequency, thus it is important to explicate the correlation between these variations and personal attributes such as height, weight, and muscle mass.

Experiment #2 was executed within the context of this experiment with the hypothesis that variations in weight distribution upon the soles of the feet might alter both body inclination and sensations of body sway. Many previous literatures on kinesthetic illusion have revealed that slight cues, such as hand-wall contact, can result in fluctuations in the kinesthetic illusion state. It is imperative to verify the effect of simultaneous hand-desk or hand-wall contact and ankle vibration presentation.

In applications of the kinesthetic illusion, it is improbable that the users will be asked to close their eyes, as was the case in the present study. It is, instead, more probable that the kinesthetic illusion will be used in conjunction with visual stimuli. This could result in an enhancement of the illusion, but further investigation is required to determine whether the interpretation of the sway itself is altered, as observed in the present study. Distinguishing between body sways is thought to improve the understanding of the experience in VR applications. For example, self-sway could be applied to express effects such as wind pressure and dizziness. Ground (environmental) sway is thought to be applicable to expressing the sway of vehicles, earthquakes, and the shaking of the ground when dinosaurs or giant creatures walk on it.

VI. Conclusion

This study aimed to explore the factors underlying the shift in the interpretation of sway between self-motion and environmental motion when a kinesthetic illusion is created through applying of vibrations to the ankle. Inspired by the phenomenon that the perception of self-motion or environmental motion induced by vection can vary based on the switching frequency of visual cue, we sought to examine the relationship between the switching frequency of presentation of the kinesthetic illusion and the interpretation of sway. To induce the illusion, alternating vibrations were applied to the tendons in the ankle, leading to a pendular motion.

In the experiments, the interpretation of the sway being attributed to self-motion or environmental motion was explored in terms of the switching frequency of the vibration and the center of foot pressure. The results demonstrated that the participants exhibited a tendency to regard the sway as their own at lower switching frequencies and as the environment's sway at higher switching frequencies. Despite the absence of a robust impact of the center of foot pressure on interpretation, it was inferred that the illusion was somewhat diminished at higher switching frequencies when the center of foot pressure shifted towards the toe or heel.

The present findings offer indications as to the frequency bandwidths that can be utilized to differentiate between an individual's own sway and that of the environment through a kinesthetic illusion, specifically in the context of virtual reality and similar applications.

In forthcoming studies, we aim to delve deeper into the switching frequency conditions, the impact of contact on other bodily regions, and the alterations that arise when vision is incorporated. Additionally, we seek to explore whether actual body sway plays a role in distinguishing self-motion from environmental motion, as well as the potential involvement of other factors beyond the parameters assessed in this investigation.

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