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Effect of head roll-tilt on the subjective visual vertical in healthy participants: Towards better clinical measurement of gravity perception

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Abstract

Objective: Gravity perception is an essential function for spatial orientation and postural stability; however, its assessment is not easy. We evaluated the head-tilt perception gain (HTPG, that is, mean perceptual gain [perceived/actual tilt angle] during left or right head roll-tilt conditions) and head-upright subjective visual vertical (SVV) using a simple method developed by us to investigate the characteristics of gravity perception in healthy participants.

Methods: We measured the SVV and head roll-tilt angle during head roll-tilt within ±30° of vertical in the sitting and standing positions while the participant maintained an upright trunk (sitting, 434 participants; standing, 263 participants). We evaluated the head-upright SVV, HTPG, and laterality of the HTPG.

Results: We determined the reference ranges of the absolute head-upright SVV (<2.5°), HTPG (0.80-1.25), and HTPG laterality (<10%) for the sitting position. The head-upright SVV and HTPG laterality were not influenced by sex or age. However, the HTPG was significantly greater in women than in men and in middle-aged (30-64 years) and elderly (65-88 years) participants than in young participants (18-29 years). The HTPG, but not the head-upright SVV or HTPG laterality, was significantly higher in the standing vs sitting position.

Conclusion: The HTPG is a novel parameter of gravity perception involving functions of the peripheral otolith and neck somatosensory systems to the central nervous system. The HTPG in healthy participants is influenced by age and sex in the sitting position and immediately increases after standing to reinforce the righting reflex for unstable posture, which was not seen in the head-upright SVV, previously considered the only parameter.

Level of Evidence: 4.

KEYWORDS

gravity perception, head-tilt perception gain, healthy participants, subjective visual vertical

1 | INTRODUCTION

Living on Earth requires special orientation and postural stability with reference to gravity vectors. The magnitude and direction of gravity are perceived by the central nervous system, specifically by the brainstem,[1] thalamic,[2] and cortical areas,[3,4] which integrate information from peripheral gravity sensors comprising otolith organs[5] and the somatosensory system.[6] A type of dizziness involving a floating sensation is thought to arise from gravity perception disturbance (GPD).[7] However, verifying the relationship between dizziness and GPD remains challenging, as no clinical examination is available for easily evaluating gravity perception, except for estimating the subjective visual vertical (SVV).[8-10]

The SVV, proposed by Aubert,[11] is a psychophysical paradigm for measuring the visually perceived direction of the gravitational vertical using a visual line stimulus. Many studies have investigated SVV, including the threshold of body tilt and its age-related change,[12,13] body balance in healthy individuals,[14] relationship to vestibular migraine and vestibulopathy patients,[15,16] and so on. The SVV has been used to characterize gravity perception under various gravity conditions, such as microgravity,[17] hypergravity,[18,19] and whole-body tilt.[20] However, these methods are not suitable for clinical examinations due to the bulky equipment, high costs, and complex protocols involved. Thus, in clinical settings, the SVV is now measured only in the head-upright condition, which limits its ability to detect abnormalities in gravity perception.

This study aimed to establish a simple, quantitative examination method for clinically evaluating gravity perception, using the head-tilt perception gain (HTPG), the new parameter of perceptual gain (perceived/actual tilt angle) calculated by data during multiple head-upright and head roll-tilt conditions, in addition to the head-upright SVV (HU-SVV), which is just the conventional SVV. Using this method, we determined the characteristics of gravity perception in healthy participants, as a first step towards understanding GPD.

2 | MATERIALS AND METHODS

We conducted four experiments in total: two preliminary experiments, one principal experiment, and one additional experiment. During measurements, participants who had no history of vertigo and hearing loss in the principal experiment were in the sitting position, whereas participants in the additional experiment were in the standing position. The experimental conditions are summarized in Table 1.

All experiments were approved by the Ethics Committee of Nara Medical University (Notification Nos. 356 and 916) and were conducted according to the Helsinki Declaration. All participants provided informed consent. The participant shown in Figure 1B,C provided consent for using the image.

2.1 | Preliminary experiment 1: Whole-body roll-tilt to 90°

Seven men, aged 30-49 (mean 36.6) years, participated in the experiment. We used a flight simulator (GYROLAB GL-4000; Environmental Tectonics Corporation, Southampton PA, USA),[21] located at the Aeromedical Laboratory of the Japan Air Self-Defense Force, to control whole-body roll-tilt safely and precisely (Figure 1A). During the experiment, the participant sat on a chair in the cockpit of the flight simulator, at a distance of 91 cm from the simulator screen. The participant wore goggles (SK11 DG-12B; Fujiwara Sangyo, Hyogo, Japan) that covered the visual field except for the central 15-20° of each eye, so that the screen edges were not visible. To fix the whole body firmly to the chair, the participant's trunk was secured using a five-point harness, and cushions were positioned between the participant and the cockpit's sides. The participant's head was immobilized using a custom-made head-holder and neck brace (Figure 1B).[22] For each trial, the participant was instructed to close his eyes. The cockpit was then tilted leftward to one of eight angles (−90, −75, −60, −45, −30, −20, −10, or 0°) at an angular velocity <1.00°/second and an angular acceleration <5.00°/second^2. The cockpit was maintained in the rolled position for at least 30 seconds, and the participant was then instructed to open his eyes and record his SVV using a bar presented on the screen in a random orientation. The participant adjusted the bar clockwise or counterclockwise to match his perceived direction of gravity, using a keypad programmed to change the line orientation by 1° per keystroke. Then, the participant was instructed to again close his eyes in preparation for the next SVV measurement. The SVV was measured 24 times, that is, three times in each of the eight tilt conditions, in a pseudo-random order.

TABLE 1 Summary of experimental conditions

	Number of subjects	Conditions	Tilt angle (°)
Preliminary experiment 1	7 (all M)	Whole-body roll-tilt (sitting position)	−90, −75, −60, −45, −30, −20, −10, 0
Preliminary experiment 2	66 (all M)	Head roll-tilt (sitting position)	−30, −20, −10, 0, 10, 20, 30
Principal experiment	434 (224 M, 210 F)	Head roll-tilt (sitting position)	−30, 0, 30
Additional experiment	263 (192 M, 71 F) selected subjects from the principal experiment	Head roll-tilt (standing position)	−30, 0, 30

Abbreviations: M, male; F, female.

FIGURE 1 Apparatus. A, Preliminary experiment 1: The flight simulator used to generate conditions of whole-body tilt around a front-to-back axis ("roll") at various angles. B, The participant in the cockpit of the flight simulator. C, Preliminary experiment 2 and principal experiment: The examination system used to measure the subjective visual vertical and head roll-tilt angle under static, head-tilted conditions

2.2 | Preliminary experiment 2: Head roll-tilt in the range of −30 to 30°

Sixty-six healthy men, aged 20-38 (mean 21.8) years, participated in the experiment. To ensure clinical relevance, we previously developed a simple, compact examination system (Figure 1C; head-tilt subjective visual vertical [HT-SVV] examination system, UNIMEC, Tokyo, Japan) to simultaneously measure the SVV and head roll-tilt angle (HTA), with no flight simulator needed, and then analyze the data.[23] During the experiment, the participant sat on a chair approximately 60 cm from a bar-display box and wore goggles, to exclude visual information except for that of a bar (7 cm long × 0.2 cm wide) on the display. Concurrently, the HTA was monitored using a linear accelerometer attached to goggles. At the beginning of each trial, the participant was instructed to tilt the head slowly rightwards or leftwards until the experimenter told them to stop (approximately −30, −20, −10, 0, 10, 20, or 30°), to keep the trunk upright, and to keep the eyes closed. After the head had been maintained in a static tilted condition for 5-10 seconds, the SVV was measured under static head-tilted conditions in the same manner as in preliminary experiment 1. The SVV was measured 14 times (twice in each tilt condition) in a pseudo-random order.

2.3 | Principal experiment: Head roll-tilt at approximately 30° in the sitting position

The experiment was conducted using the HT-SVV examination system in 434 healthy participants, including volunteers, such as college students, factory workers, members of the elderly club, parent-teacher association members, and persons undergoing medical examinations [224 men and 210 women; age range 18-88 (mean 36.4) years], who were also divided into three age groups (young: 18-29 years, 114 men, 103 women; middle-aged: 30-64 years, 81 men, 82 women; elderly: ≥65 years, 29 men, 25 women). The participant's position and SVV and HTA measurements were the same as in preliminary experiment 2, except that the rightward or leftward tilt angles were approximately −30, 0, or 30°. The SVV was measured 14 times (four times in each of the −30 and 30° conditions and six times in the 0° condition) in a pseudo-random order.

2.4 | Additional experiment: Head roll-tilt at approximately 30° in the standing position

The experiment was conducted using the HT-SVV examination system on 263 healthy participants [192 men and 71 women; age range 19-71 (mean 28.2) years] who were randomly selected in the principal experiment, to further investigate gravity perception. Measurements were recorded while participants maintained a standing position, using the same procedure as in the principal experiment.

2.5 | Statistical analysis

Independent variables were primarily within-subject variables, whereas age and sex constituted between-subject variables. Statistical significance was assessed using the Wilcoxon signed-rank test for comparing paired data, the Mann-Whitney *U* test for comparing non-paired data, and the Kruskal-Wallis test with a post hoc Steel-Dwass test for multigroup comparisons. A *P* value <.05 was considered statistically significant. All analyses were performed using Statcel 4 (OMS, Saitama, Japan).

3 | RESULTS

3.1 | Estimation of gravity perception

We calculated the head-tilt perception (HTP) using the following equation:

$$\mathrm{HTP} = \mathrm{HTA} - \mathrm{SVV} \quad (1)$$

Accordingly, when the SVV shifts in a direction opposite to that of the HTA, the HTP becomes larger than the HTA and is overestimated (known as Müller effect or the E-effect) (Figure 2A). In contrast, when the SVV shifts in the same direction as that of the HTA, the HTP becomes smaller than the HTA and is underestimated (known as Aubert effect or the A-effect).

The results of preliminary experiments 1 and 2 are superimposed in Figure 2B, where the average HTP across participants is plotted vs the average HTA. The HTP of preliminary experiment 1, measured in the simulator, demonstrated the A-effect at −20°, the E-effect at −45°, and the A-effect at −90°, producing an S-shaped curve versus HTA. In contrast, the average HTP of preliminary experiment 2, measured using a much simpler setup, demonstrated a linear dependence on the average HTA (slope = 1.025, intercept = 0.564°, R^2 = 1.000) in the range −30 to 30°. Based on this observation, we calculated the slope and intercept of the regression lines fitted to the HTP data of

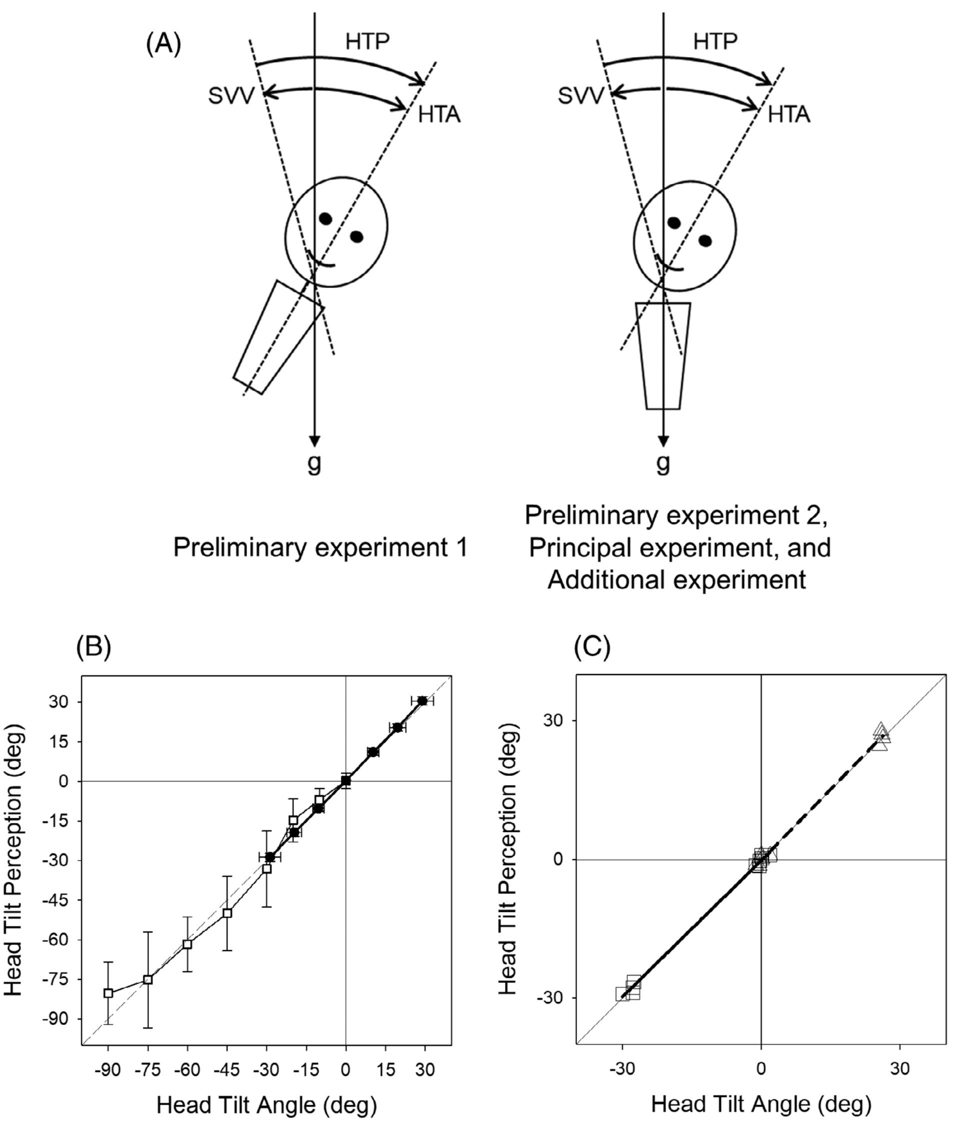

FIGURE 2 Head-tilt perception (HTP) results and illustration of experimental variables. A, HTP was calculated as the difference between the head roll-tilt angle (HTA) and the subjective visual vertical (SVV) in all experiments. B, The average HTPs vs the average HTAs in preliminary experiments 1 (□; *n* = 7) and 2 (■; *n* = 66), superimposed. C, Representative individual data from the principal experiment. The HTP gain (HTPG) is the slope of the regression line fitted to the left or right head-tilt data (solid and dotted lines, respectively). Left HTPG, 0.984; right HTPG, 1.025

the principal experiment. This slope, which is dimensionless, is herein termed the head-tilt perception gain, or HTPG. Figure 2C is based on a representative participant in the principal experiment and shows the left and right HTPG values calculated using HTP data with the head tilted to the left and right, respectively. The intercept is equivalent to the HTP with zero HTA, which, according to Equation (1), is the negative of the SVV obtained when the head is upright. The SVV in the head-upright condition is herein termed the head-upright SVV, or HU-SVV. Based on the above results, we expressed gravity perception during head roll-tilt in the range −30 to 30° as the left and right HTPGs, which were measured while the participants kept their trunk upright.

3.2 | HU-SVV in healthy participants

The key results from the principal experiment, namely, the age and sex dependences of the three gravity perception parameters, are presented in Table 2. Also, the results from the additional experiment, namely, the differences in the three gravity perception parameters between the sitting and standing positions, are presented in Table 3.

The means and standard deviations (SDs) of the signed values (ie, deviations to the left and right) and absolute values (ie, error) of the HU-SVV in 434 healthy participants in the sitting condition, as collected in the principal experiment, were 0.06 ± 1.31° and 1.04 ± 0.79°, respectively. No significant differences were found in the signed (*P* = .453) or absolute (*P* = .116) values of the HU-SVV between men and women. The absolute values of the HU-SVV in both men and women did not differ across age groups (*P* > .141; Figure 3A), in agreement with previous reports.[24] The absolute values of the HU-SVV did not change (*P* = .961) between sitting and standing positions (Figure 4A).

3.3 | HTPG in healthy participants

Since there was no overall significant difference (*P* = .407) between the left and right HTPGs, we pooled the HTPG directions (1.038 ± 0.120). In contrast, the HTPG was significantly larger (*P* = .002) in women (1.051 ± 0.112) than in men (1.026 ± 0.126) (Figure 3A). The HTPGs were significantly influenced by age group in both men and women. The HTPG in men was significantly larger in the middle-aged (1.068 ± 0.121) and elderly (1.053 ± 0.143) groups than in the young group (0.989 ± 0.114; *P* < .001 for both), but no significant difference was observed between the middle-aged and elderly groups (*P* = .947). As with men, the HTPG in women was significantly larger in the middle-aged (1.059 ± 0.100) and elderly (1.091 ± 0.137) groups than in the young group (1.034 ± 0.112; *P* = .037 and *P* = .035, respectively), but no significant difference was detected between the middle-aged and elderly groups (*P* = .438). The HTPG was significantly higher (*P* < .001) in the standing position (1.041 ± 0.126) than in the sitting position (1.010 ± 0.117) (Figure 4B).

3.4 | HTPG laterality

Then, we assessed the HTPG laterality in each participant using the following index:

$$\text{HTPG laterality}\ (\%) = 100 \times (\text{left HTPG} - \text{right HTPG}) / (\text{left HTPG} + \text{right HTPG}) \quad (2)$$

TABLE 3 Results of the additional experiment: sitting and standing positions

	Sitting position	Standing position	P value
HU-SVV (°)	1.01 ± 0.77	1.01 ± 0.76	.961
HTPG	1.010 ± 0.117	1.041 ± 0.126	<.001
HTPG laterality (%)	4.73 ± 3.61	4.43 ± 3.52	.205

Note: HTPG laterality and HU-SVV are presented as absolute values. The *p* values were calculated using the Wilcoxon signed-rank test.
Abbreviations: HTPG, head-tilt perception gain (dimensionless); HU-SVV, head-upright subjective visual vertical.

TABLE 2 Results of the principal experiment: age and sex effects

Sex effect	All subjects	Men	Women	P value
HU-SVV (°)	1.04 ± 0.79	0.96 ± 0.74	1.12 ± 0.86	.116
HTPG	1.038 ± 0.120	1.026 ± 0.126	1.051 ± 0.112	.002
HTPG laterality (%)	4.62 ± 3.54	4.63 ± 3.55	4.60 ± 3.54	.910
Age effect	**Young**	**Middle-aged**	**Elderly**	**P value**
HU-SVV (°)	0.99 ± 0.75	1.03 ± 0.77	1.22 ± 1.07	.723
HTPG, men	0.989 ± 0.114	1.068 ± 0.121	1.053 ± 0.143	<.001
HTPG, women	1.034 ± 0.112	1.059 ± 0.100	1.091 ± 0.137	.009
HTPG laterality (%)	4.75 ± 3.42	4.16 ± 3.19	5.48 ± 4.68	.021

Note: HTPG laterality and HU-SVV are presented as absolute values. The *p* values for sex were calculated using the Mann-Whitney *U* test and those for age by the one-way Kruskal-Wallace test.
Abbreviations: HTPG, head-tilt perception gain (dimensionless); HU-SVV, head-upright subjective visual vertical.

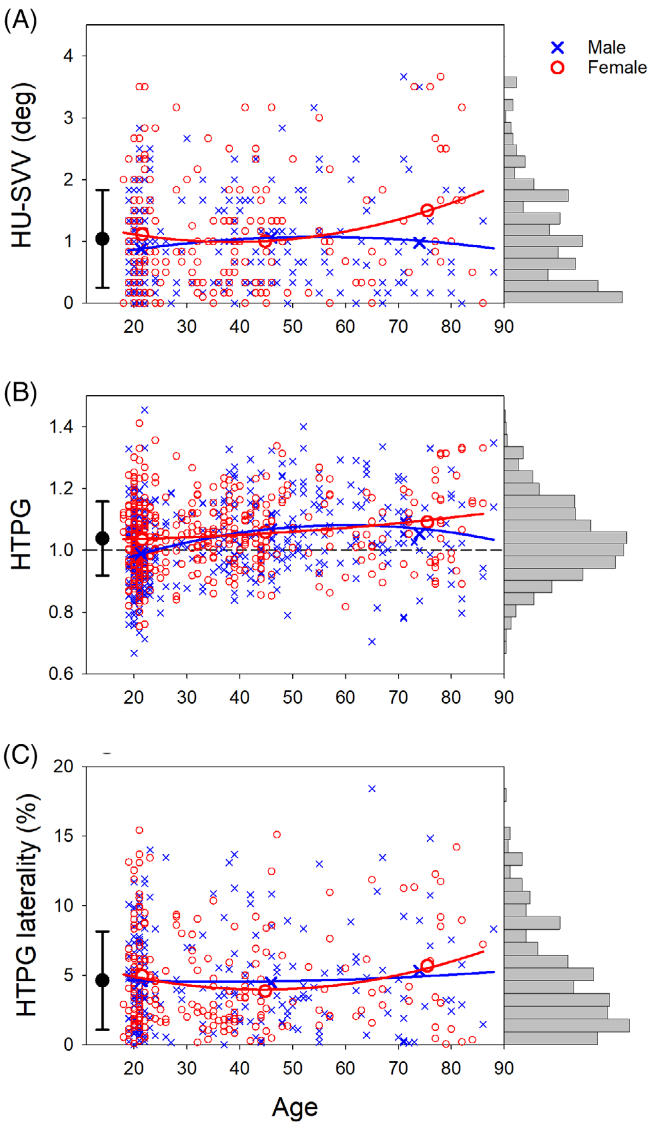

FIGURE 3 Effects of age and sex on gravity perception. Raw absolute values of the head-upright subjective visual vertical (HU-SVV), A, head-tilt perception gain (dimensionless) HTPG, B, and HTPG laterality, C, in 434 healthy participants (×, men; ◦, women), plotted by age. The means of each age group ("young": 18-29 years, 114 men, 103 women; "middle-aged": 30-64 years, 81 men, 82 women; "elderly": ≥65 years, 29 men, 25 women) and model fits (quadratic curve) are superimposed. The means ± *SD* and frequency distribution histograms of the aggregated data are presented on the left and right sides of each figure, respectively

The mean and SD of the signed and absolute values of HTPG laterality across all participants were −0.25 ± 5.82% and 4.62 ± 3.54%, respectively. We found no significant differences between men and women (signed, $P = .293$; absolute, $P = .910$).

The absolute value of HTPG laterality did not depend on age in either men or women ($P > .075$) (Figure 3C). The absolute value of HTPG laterality did not change ($P = .205$) between sitting and standing positions (Figure 4C).

3.5 | Reference ranges of gravity perception parameters

Based on the results from 434 healthy participants in the principal experiment, we determined reference ranges (ie, ranges of values containing 95% of the results from a reference population) of gravity perception parameters for future clinical use. The absolute value of the HU-SVV was less than 2.5°, the HTPG ranged between 0.80 and 1.25, and the absolute value of the HTPG laterality was less than 10%.

4 | DISCUSSION

The study findings propose that the HTPG can be used as a novel parameter for measuring gravity perception generated by functions from the peripheral otolith and neck somatosensory systems to the central nervous system in addition to the HU-SVV, which has been widely used in clinical settings.[25,26] To simplify, the HTPG represents gravity perception during head roll-tilt, whereas the HU-SVV means gravity perception only when the head is upright. Although the perceptual gain (HTP/HTA) of a head-roll condition has been reported in a previous study,[27] the HTPG is unique in that it expresses the perceptual gain during multiple left or right head roll-tilt conditions as a single parameter. The decisive factor in favor of using the HTPG was the linearity between the HTP and HTA during head roll-tilt at approximately 30° when keeping an upright trunk condition, since in the principal experiment the HTPG was slightly larger than 1, that is, the E-effect was observed. Conditions resulting in a linear relationship between the HTP and HTA were limited. For example, the whole-body roll-tilt condition in preliminary experiment 1 exhibited an S-shaped relationship, that is, the HTP was smaller than that in preliminary experiment 2 at 20° of the HTA as shown in Figure 2B. There were two possible reasons for the difference between them. The first reason was whether the head tilt was passive (preliminary experiment 1) or active (preliminary experiment 2). However, this reason is negative, because Van Beuzekom et al. reported that passive and positive head tilts exhibited the same characteristics of the subjective vertical.[28] It would seem to depend on the second reason, the type of somatosensory input. That is, the body somatosensory input (preliminary experiment 1) inhibited the HTP more than that of the neck (preliminary experiment 2), considering that otolith inputs were the same in both conditions. Further, a head roll-tilt greater than 30° in the upright-trunk condition produced a nonlinear relationship because of the increase in the E-effect.[9,29] Fortunately, a head roll-tilt less than 30° in the upright trunk condition is a natural and easy position for participants; thus, we were able to establish a simple method to evaluate the HTPG within 10 minutes and in a few steps, using a low-cost and compact device.

Similar trials measuring the SVV during head roll-tilt whereas maintaining an upright trunk condition have been reported. In 17 healthy participants, Kim and Kim showed that a 30° head roll-tilt tilts the SVV in the opposite direction (E-effect), whereas a 60° head roll-tilt tilts the SVV in the same direction (A-effect).[30] Luyat et al. reported that a 30° head roll-tilt tends to tilt the SVV in the opposite

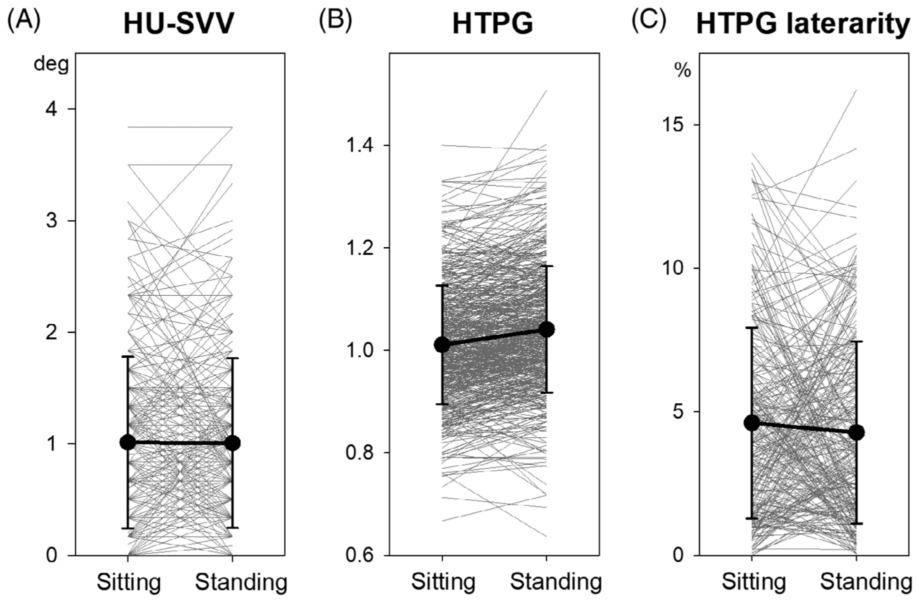

FIGURE 4 Effects of posture on gravity perception. Comparisons between the sitting and standing positions for the absolute values of the head-upright subjective visual vertical (HU-SVV), A, head-tilt perception gain (dimensionless) (HTPG) B, and HTPG laterality, C, in 263 healthy participants. Fine lines: individual data; coarse lines, averages ± *SD*

direction (E-effect) in 20 healthy men, whereas the opposite was found in 20 healthy women.[31] Otero-Millan and Kheradmand demonstrated that a 20° head roll-tilt tilts the SVV in the same direction (A-effect) in 12 healthy participants and is not associated with the change in ocular torsion.[32] However, the number of participants in these previous reports was rather small, not exceeding 40, whereas our study included 434 healthy participants. Thus, we were able to present reference ranges of gravity perception parameters based on a large sample size to aid evaluating GPD, which may underlie dizziness.

The HU-SVV and HTPG laterality indicated the left-right balance of gravity perception in head upright and head roll-tilt conditions, respectively. The HU-SVV was not influenced by age, as reported previously,[33,34] and HTPG laterality demonstrated similar characteristics. In contrast, the HTPG, indicating the magnitude of gravity perception, was significantly larger in middle-aged and elderly than in young participants. We hypothesize that the HTPG increases after middle age to adapt to postural instability, common in middle-aged and elderly people.[14,35-37] An increase in the HTPG reinforces the righting reflex to maintain postural balance. A similar mechanism was reported by Zu Eulenburg et al.[38] based on a functional magnetic resonance imaging study. The authors proposed that the central sensitization of otolith perception in elderly participants counterbalances the age-related functional decline in peripheral vestibular and somatosensory systems. In addition, our hypothesis is strongly supported by our current result that the HTPG was significantly higher in the standing than in the sitting position. This is because the standing position is unstable and increases the HTPG to reinforce the righting reflex. As the HTPG changed just after the position change, it can be used to accurately and immediately reflect central compensation for postural conditions. In other words, age and standing position-related increase in HTPG is a reasonable physiological function and would account for the appropriateness of HTPG as a parameter of gravity sensing.

Regarding sex differences, the HTPG was significantly smaller in men than in women, but the HU-SVV and HTPG laterality were not influenced by sex. According to our hypothesis, posture is more stable in men than in women, but conflicting results have been reported on this issue. For example, Kollegger et al.[39] reported that men exhibit greater spontaneous postural sway than women. Conversely, Rogind et al.[40] reported no differences in postural sway between sexes. Lee and Petrofsky[41] reported that postural sway in men is smaller than that in women at ovulation but is the same as that in women at menstruation. Moreover, the HTPG in the young male group was remarkably lower than that in the other groups, probably due to sex differences, as young men with sufficient muscular strength do not require an excessive righting reflex to maintain postural stability.

This study was limited by the fact that semicircular canals, that is, the sensors for angular acceleration of the head, could have also been stimulated by the head-tilting step. Graybiel et al.[42] previously reported that the stimulus threshold of semicircular canals is between 0.2 and 4.0°/s^2. Thus, the effects of semicircular canals' stimulation may have been included in both the SVV and HTPG, even during preliminary experiment 1, during which the head was tilted with the slowest speed (<5.0°/s^2). To reduce this effect as much as possible, the SVV was measured more than 30 seconds after head tilting in preliminary experiment 1. In other experiments, however, it was necessary to measure the HTP 5-10 seconds after head tilting to shorten the examination time for practical reasons. Regardless, it is clear that the examiner must be careful not to tilt the participant's head quickly.

Further studies using the present method in patients with dizziness are necessary for further validation and to understand the relationship between dizziness and GPD.

5 | CONCLUSION

We evaluated the HTPG using a simple method that we developed to investigate the characteristics of gravity perception in healthy participants. Unlike the HU-SVV, the HTPG was influenced by age and sex and was sensitive to central compensations for posture. Further studies in patients with dizziness are required to support clinical applications.

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CONFLICT OF INTEREST

The authors declare no conflict interests.

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