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Original Article

Test-retest reliability of subjective visual vertical measurements with lateral head tilt in virtual reality goggles

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Abstract

Objective: The objective is to investigate the test-retest reliability of subjective visual vertical (SVV) in the upright position and with lateral head tilts through a computerized SVV measuring system using virtual reality (VR) goggles. **Materials and Methods:** Thirty healthy controls underwent SVV test in upright position, with the head tilted to the right 30°, and with the head tilted to the left 30°. Subjects wore SVV VR goggles, which contained a gyroscope for monitoring the angle of head tilt. Each subject completed 10 adjustments in each head position. The mean value of SVV deviations and SVV imprecision (the intra-individual variability of SVV deviations from the 10 adjustments) were recorded and compared across different head positions. The participants then repeated the same SVV protocol at least 1 week later. The test-retest reliability of SVV deviation and SVV imprecision were analyzed. **Results:** The SVV deviation (mean ± standard deviation) was 0.22° ± 1.56° in upright position, −9.64° ± 5.91° in right head tilt, and 7.20° ± 6.36° in left head tilt. The test-retest reliability of SVV deviation was excellent in upright position (intra-class correlation coefficient [ICC] = 0.77, $P < 0.001$), right head tilt (ICC = 0.83, $P < 0.001$) and left head tilt (ICC = 0.84, $P < 0.001$). The SVV values from the 10 adjustments made during right and left head tilts were less precise than when measured at upright ($P < 0.001$). The test-retest reliability of SVV imprecision was poor at upright (ICC = 0.21, $P = 0.26$) but fair-to-good in right head tilt (ICC = 0.72, $P < 0.001$) and left head tilt (ICC = 0.44, $P = 0.04$). **Conclusion:** The test-retest reliability of SVV deviation during lateral head tilts via VR goggles is excellent, which supports further research into the diagnostic value of head-tilt SVV in various vestibular disorders. In addition, the degree of SVV imprecision during head tilt has fair-to-good test-retest reliability, which suggests SVV imprecision may have clinical applicability.

Keywords: *Reliability, Subjective visual vertical, Vestibular perception, Vestibular test*

Introduction

The vestibular system senses and stabilizes body movements, ensuring freedom of action through several distinct neuro-anatomical pathways. The vestibular nuclei (VN) receive sensory inputs from the inner ear, and the VN project these vestibular signals to (i) the ocular motor nuclei for maintaining gaze stability, (ii) the spinal cofrd for maintaining postural balance, (iii) the vestibular cortex for establishing spatial orientation, and (iv) the cerebellum for modulating vestibular signals. These neural pathways serve the vestibulo-ocular reflex (VOR), vestibulo-spinal reflex (VSR), vestibular perception, and cerebellar feedback networks, respectively.

Each pathway that serves the vestibular system plays a critical role, but in the current clinical practice, vestibular testing is mostly used to evaluate the VOR. Such evaluations include caloric testing, rotary chair testing, the video head impulse test, dynamic visual acuity, video ocular counter-roll, and ocular vestibular evoked myogenic potentials [1-4]. In specialized neuro-otology units, several other tests play a role in evaluating the VSR, such as computerized dynamic posturography and cervical vestibular evoked myogenic potential [5,6]. Clinical tests of vestibular perception, by contrast, are not widely available and rarely met with in the hospital setting.

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The exception in some neuro-otology and neuro-vestibular units, however, is the test of vestibular perception called subjective visual vertical (SVV), which is used routinely [7].

In addition to detecting linear accelerations, the otolith organs sense the static position of the head relative to gravity [8]. When the head is tilted, the utricle senses head position in the roll plane, while the saccule senses head position in the pitch plane. In the clinical setting, this physiology is made visible by the ocular tilt reaction, which can appear if the peripheral or central utricular pathway is damaged or malfunctioning. The ocular tilt reaction consists of four clinical signs: Deviation of the SVV, ocular torsion, skew deviation, and head tilt. Of these signs, SVV is the most sensitive for detecting brainstem lesions, e.g., in Wallenberg syndrome [9,10]. SVV is also quite sensitive in the case of acute unilateral peripheral vestibulopathy, such as vestibular neuritis [11-13]. However, it is important to note, however, that deviations of SVV gradually diminish over time, making SVV less sensitive for detection of chronic vestibulopathy compared to acute lesions [14]. This phenomenon of the SVV gradually returning to baseline may be attributable to vestibular adaptation of the otolith organs on the healthy side, or to compensation by other sensory systems (e.g., visual, proprioceptive). For these reasons, experimental modifications to traditional SVV testing, following rational neurophysiological principles, may enable researchers to enhance the sensitivity of SVV testing, with a view to broadening its clinical applicability.

One of the most important neurophysiological functions of the utricle is to detect and convey graviceptive signals during static head tilts in the roll plane. With this principle in mind, lateral head tilts may be helpful for the diagnosis of vestibular disorders if they can enhance SVV sensitivity. In other words, more subtle imbalances of vestibular signaling, resulting from varying degrees of compensation over time, may be disclosed by the results of careful SVV testing. The concept may seem novel, but SVV testing with lateral head tilts has long been known in the field of psychophysics. As early as the mid-19th century, it was found that at small head tilt angles, the SVV usually deviates in the opposite direction of the head tilt, reflecting an overestimation of upright orientation relative to the head position (i.e., E-effect) [7]. On the other hand, at large head tilt angles, SVV usually deviates in the same direction as the head tilt, reflecting underestimation (i.e., A-effect) [7]. These phenomena have been described experimentally, but to date SVV with lateral head tilts has not been widely investigated clinically [15]. Probably for technical reasons, the effects of head tilts on SVV in patients with various vestibular disorders remains largely unknown.

Traditional laboratory methods for SVV testing include standing in front of a wall-mounted hemi-dome to minimize attention to the peripheral visual fields, or sitting in a completely dark room adjusting the angle of a luminous line on a computer screen [9,16]. In 2009, Zwergal *et al*. reported the "bucket test," a portable inexpensive method for SVV assessment [17]. In recent years, another portable SVV method was developed using virtual reality (VR) goggles, and was subsequently shown to be more accurate than the bucket test [18]. These "next-generation" SVV VR goggles contain a gyroscope that facilitates active measurement and monitoring of the head tilt angle. With the availability of VR goggles, SVV testing with lateral head tilts may soon become applicable in clinical practice. VR goggles are portable, time-saving, and show promise for developing novel diagnostic methods. Nevertheless, before introducing any VR method for SVV testing with head tilts to the clinical field, the test-retest reliability of head-tilt SVV using VR goggles must be evaluated. The aim of this study is to evaluate the test-retest reliability of SVV with lateral head tilts via SVV VR goggles in healthy controls.

Materials and methods

Thirty healthy controls who were recruited between April 2020 and June 2020 underwent SVV testing in upright position and with head tilts in the neuro-vestibular laboratory of Taichung Tzu Chi Hospital. The study was performed in accordance with the guidelines of the Declaration of Helsinki. Ethical approval for this study (REC-109-06) was provided by the Research Ethics Committee of Taichung Tzu Chi Hospital, Taichung, on March 30, 2020. Written informed consent was obtained from all subjects prior to the study.

A single well-trained examiner (CHW) guided all participants through the experimental protocol. After becoming familiar with the testing equipment and SVV protocol, each participant completed three experimental sessions for a total of 30 adjustments. Each session consisted of 10 SVV adjustments.

SVV testing was performed with a commercial computerized system for measuring SVV (VertiSVV, Zehnit, Shanghai, China). The system consisted of VR goggles which occlude ambient light, a wireless controller, and a laptop computer connected to the VR goggles and controller thhrough Bluetooth.

The VR goggles displayed a yellow luminous line at the middle of the screen against a totally dark background. The luminous line appeared to be tilted to the right or to the left at a random computer-generated angle, ranging from 20° to 90°. Each participant adjusted the angle of the line by turning a rotary knob on the wireless controller. When the line was adjusted to the perceived vertical, the participant pressed the confirm button on the controller to end the adjustment. When one adjustment was finished, the next adjustment started immediately with appearance of a new luminous line tilted at a random angle.

The three SVV test sessions were performed in upright position (0°), then with the head tilted to right side (+30°) and finally with the head tilted to left side (−30°) [Figure 1]. Each participant completed 10 adjustments in each session, with a 1-min interval between sessions. During the head-tilt sessions, participants were asked to tilt the head on the neck to ±30°, while maintaining the trunk as upright as possible. The gyroscope of the VR goggles allowed head position in the roll and pitch plane to be monitored in real-time by the examiner via the laptop. The examiner gave oral feedback to participants, maintain the head tilt in the roll plane as close as possible to 30° throughout SVV testing,

without tilting forward or backward in the pitch plane. After participants completed all three sessions (i.e., 30 adjustments), the degree of SVV deviation for each adjustment was recorded and saved in to the laptop automatically. SVV deviations to right side were recorded as positive values, and deviations to left side were recorded as negative values.

More than 1 week later, all 30 participants underwent a second set of SVV measurements under the same examiner's instructions using the same protocol described above.

For each participant, the SVV deviation for a given session (upright, right head tilt, or left head tilt) was defined as the mean of the SVV values from the 10 consecutive adjustments of that session. The SVV imprecision was defined as the intra-individual variability of the 10 consecutive values among the 30 subjects, similar to a parallel design with replicates [19]. The SVV deviation in each head position was calculated, respectively. A-effect and E-effect in lateral head tilts were also identified. The inter-individual variabilities between upright and head-tilt positions were compared by Levene's test. Levene's test was used to measure the equality of the inter-subject variances of the SVV deviation for the 30 subjects in the three head positions. $P < 0.05$ was considered that the inter-subject variances in different head positions were statistically unequal.

SVV imprecision represents the intra-subject variability among the 10 repeated adjustments. Individual SVV imprecision is defined as the intra-subject variability of the 10 adjustments for a single subject, calculated as the SD of the 10 adjustments. Across-subjects SVV imprecision (σ) is defined as intra-subject variability of the 10 adjustments across all 30 subjects, calculated through parallel design with replicates [19]:

$$\sigma = \sqrt{\frac{1}{n(m-1)}\sum_{j=1}^{n}\sum_{k=1}^{m}(xijk - aij)^2}$$
$$= \sqrt{\frac{1}{30(10-1)}\sum_{j=1}^{30}\sum_{k=1}^{10}(xijk - aij)^2}$$

xijk is the single result of th replicate ($k = 1,\ldots m$) of the *j*th subject ($j = 1,\ldots, n$) from the *i*th session (i = upright, right head tilt, left head tilt) *aij* is the mean of the total replicates of the *j*th subject from the *i*th session.

We analyzed the correlation of SVV deviations in the first (SVV-1) and second (SVV-2) measurements through Pearson's correlation coefficient. We assessed the test-retest reliability between SVV-1 and SVV-2 via intra-class correlation coefficient (ICC). We also used ICC to evaluate the test-retest reliability of the SVV imprecision between the first (SVVi-1) and second (SVVi-2) measurements. A two-way random-effect model, absolute agreements, and average measures were used for analysis. ICC values above 0.75 represent excellent reliability, values between 0.4 and 0.75 represent fair-to-good reliability, and values below 0.4 represent poor reliability [20]. The statistical analysis was performed through SPSS version 23.0 (IBM, Armonk, NY, USA).

Figure 1: The three subjective visual vertical test sessions in upright position (0°), with the head tilted to right side (+30°) and with the head tilted to left side (−30°)

Results

Thirty healthy controls were included in this study. Mean age was 33 (range 25–51) and 16 subjects (53.3%) were female. Twenty-six subjects (86.7%) were right-handed and four were left-handed.

During the first measurement, the SVV deviation in upright position was 0.22° ± 1.56° (mean ± standard deviation). Twenty-four (80%) out of 30 subjects' SVV deviations were within ±2°. When the head was tilted to the right 30°, the SVV deviation was −9.64° ± 5.91°. When the head was tilted to the left 30°, the SVV deviation was 7.20° ± 6.36°. All 30 subjects presented with E-effect during right head tilt. During left head tilt, 28 (93.3%) subjects presented with E-effect, while 2 had A-effect. Inter-individual variations were greater in head-tilt SVV than in upright SVV [$P < 0.001$, Levene's test, Figure 2].

Across-subjects SVV imprecision was 0.82° at upright, 3.03° in right head tilt and 2.35° in left head tilt. The SVV values from adjustments made at right and left head tilts were less precise than those at upright ($P < 0.001$, test of equality of variance based on parallel design of replicates [19]).

The mean interval between the first measurement (SVV-1) and second measurement (SVV-2) was 24 days (all ≥7 days). The correlation between SVV-1 and SVV-2 is shown in

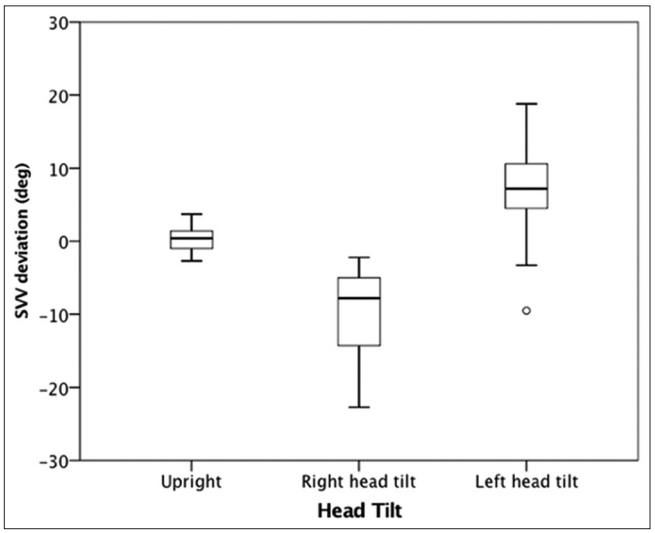

Figure 2: Subjective visual vertical deviation at upright, right head tilt, and left head tilt during the first measurement. Positive values denote deviation to the right, and negative values denote deviation to the left. Median deviation (center line), upper and lower quartiles, upper and lower extremes, and outliers are shown

Figure 3. SVV-1 and SVV-2 were moderately correlated in upright position (r = 0.62, P < 0.001), but highly correlated with head tilts to the right (r = 0.72, P < 0.001) and left side (r = 0.77, P < 0.001). The two subjects who exhibited A-effect in left head tilt in the first measurement presented with E-effect in left head tilt in the second measurement. None of the E-effects reversed to A-effect.

The test-retest reliability of SVV deviation was analyzed via ICC. The SVV had excellent reliability in upright position (ICC = 0.77, P < 0.001), right head tilt (ICC = 0.83, P < 0.001), and left head tilt (ICC = 0.84, P < 0.001).

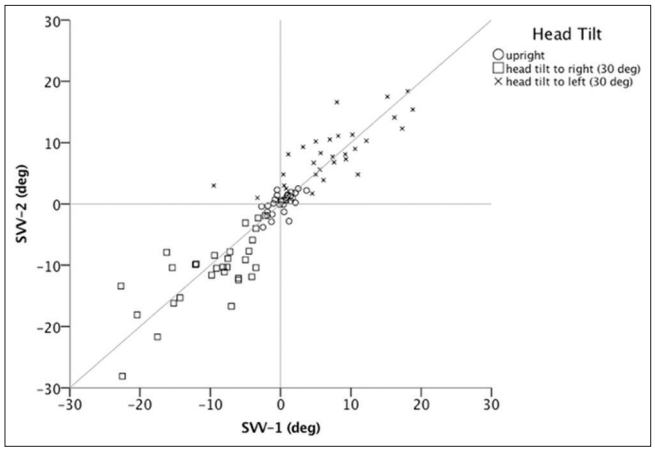

Figure 3: Correlation of subjective visual vertical deviation between the first measurement (SVV-1) and the second measurement (SVV-2). Gray lines: reference lines

Figure 4 shows Bland–Altman plots for SVV-1 and SVV-2 in upright position [Figure 4a], right head tilt [Figure 4b] and left head tilt [Figure 4c]. The mean difference between SVV-1 and SVV-2 was 0.037° ± 1.38° at upright, 1.27° ± 4.33° with right head tilt, and −1.27° ± 4.09° with left head tilt. Five subjects fell outside the 95% limits of differences – two at upright, two at right head tilt, and one at left head tilt.

Figure 5 shows the correlation of SVV imprecision between the first measurement (SVVi-1) and second measurement (SVVi-2). The test-retest reliability was fair to good at right head tilt (ICC = 0.72, P < 0.001) and left head tilt (ICC = 0.44, P = 0.04), but poor at upright (ICC = 0.21, P = 0.26).

The results of test-retest reliability of SVV deviation and SVV imprecision are summarized in Table 1.

Discussion

This study shows that the test-retest reliability of SVV deviation is excellent in upright position, as well as right head tilt and left head tilt. Therefore, utilization of SVV VR goggles to test SVV deviation is a reliable method for assessment of verticality perception in the upright position, but also in lateral head tilts. This result suggests that VR goggle-guided head-tilt SVV testing is applicable in clinical practice. In addition, our

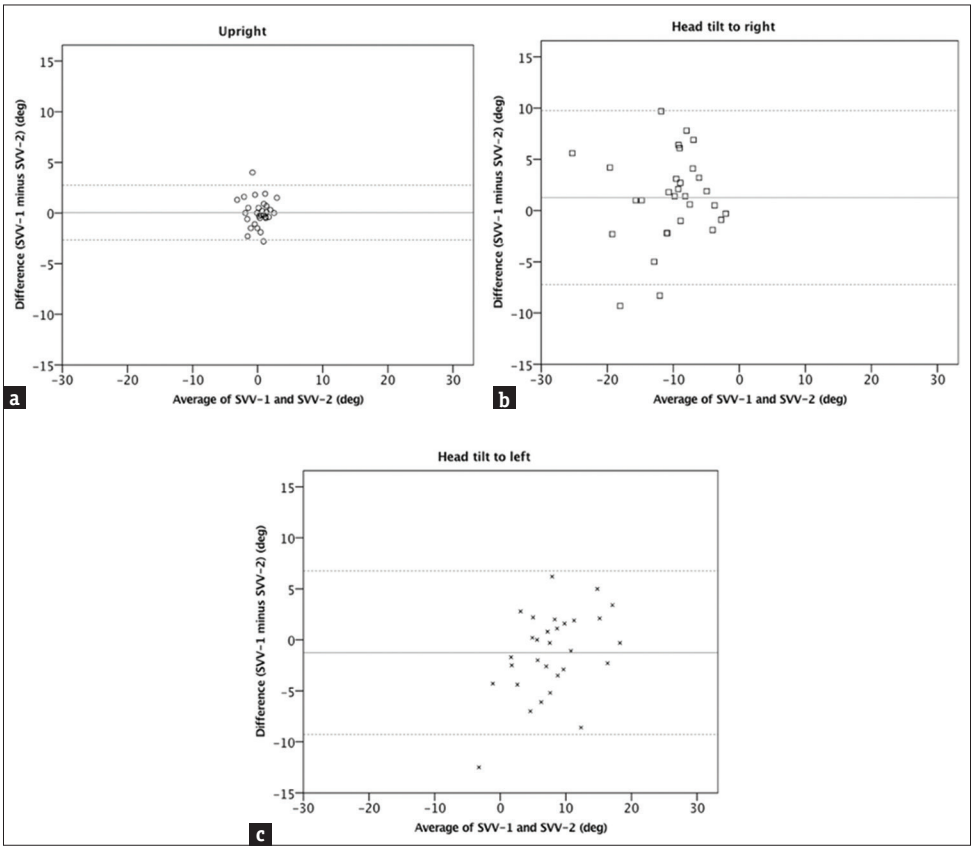

Figure 4: Bland–Altman plots for the subjective visual vertical deviations at upright (a), right head tilt (30°) (b), and left head tilt (30°) (c) in the first measurement (SVV-1) and the second measurement (SVV-2). Solid horizontal line: mean of differences; dotted lines: 95% upper and lower limits of differences

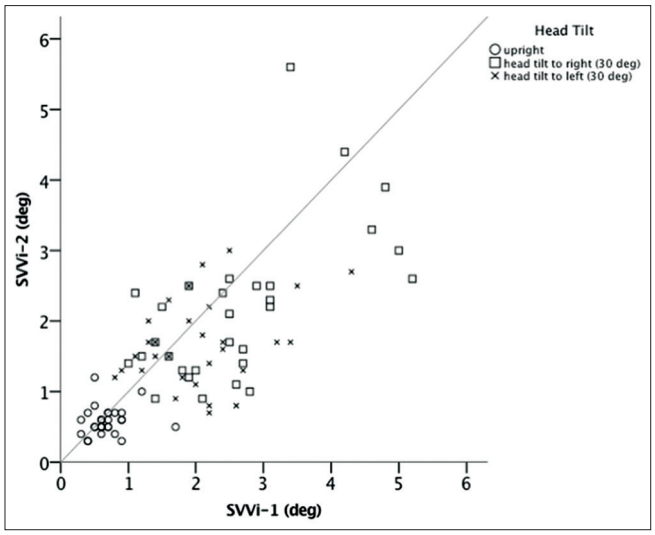

Figure 5: The correlation of subjective visual vertical imprecision between the first measurement (SVVi-1) and the second measurement (SVVi-2). Gray line: reference line

study reveals that SVV imprecision is increased in lateral head tilts compared to upright position, and that the degree of SVV imprecision is reliable at the retest after 1 week. In other words, an individual with high SVV imprecision in the first test will be similarly imprecise when adjusting the SVV angle in the second test 1 week later. Accordingly, SVV imprecision during lateral head tilt may be a useful parameter to be added to clinical assessments of verticality perception.

The test-retest reliability of SVV has been evaluated in several studies, but these studies have had heterogeneous experimental protocols and study populations. For example, one study testing SVV in stroke patients showed excellent test-retest reliability [21]. However in healthy subjects, study results for reliability vary depending on study methodology. In one study, using a computerized SVV system in a dimly lit room, test-retest reliability was excellent in younger people but fair-to-good in older people. Yet another study testing SVV in a totally dark room found that reliability was poor [22,23]. Importantly, in a study comparing SVV VR goggles to the bucket test, the test-retest reliability for the bucket was poor, but fair-to-good in VR goggles [18]. This same study also showed fair-to-good reliability in right head tilt (45°), and excellent reliability in left head tilt (45°). However, since the test and retest interval in this study was 30 min, which raises the possibility of bias due to training effects. Furthermore, maintaining the head tilted 45° throughout SVV testing can be difficult, particularly for older people with limited neck range of motion, which may restrict applicability of this method in clinical practice. In our study, we sought to minimize training effects by using a prolonged test-retest interval, of 1 week or longer, and to improve the comfort of study subjects by reducing the head tilt angle to 30°. Another strength of our study is the analysis of SVV imprecision, which could prove to be a useful clinical parameter in the future.

Table 1: Test-retest reliability of subjective visual vertical deviation and subjective visual vertical imprecision in three head positions

SVV parameter	Head position	ICC	95% CI
SVV deviation	Upright	0.77	0.52-0.89
	Right head tilt (+30°)	0.83	0.64-0.92
	Left head tilt (-30°)	0.84	0.66-0.92
SVV imprecision	Upright	0.21	-0.58-0.61
	Right head tilt (+30°)	0.72	0.41-0.87
	Left head tilt (-30°)	0.44	-0.09-0.72

SVV: Subjective visual vertical, ICC: Intra-class correlation coefficient, CI: Confidence interval

Our study demonstrates that most subjects present with E-effect in VR goggles with lateral head tilts of 30°. These results are consistent with most previous studies, which generally show E-effects with lateral head tilts at angles <60°, and gradual reversal to A-effect with head tilts >60°. Peak A-effect has been shown to occur when the head is tilted in the roll plane around 130°, with gradual return to E-effect when the tilt angle is increased further [24-26]. Nevertheless, a number of studies show A-effect at small tilt angles [27,28]. These contradictory results may be attributable to differences in study design with respect to head and body position [29]. In some studies showing A-effect at small tilt angles (e.g., <60°), subjects were seated on a tilted chair but the neck was maintained straight, in line with the body. In this straight posture, "tilt signal" from the neck proprioceptors may be minimized or essentially eliminated, which overall results in A-effect, as has been suggested by mathematical models of verticality perception [24,30]. By contrast, in our study, we instructed healthy subjects to sit upright and tilt the neck by themselves. Thus, the effect of muscle contraction during the neck tilt may have been the driver of a strong proprioceptive "tilt signal," causing an apparent E-effect.

In addition to testing SVV deviation, we also evaluated SVV imprecision, which represents intra-individual variability among repeated measurements. In our study, the SVV imprecision during lateral head tilt was much greater than in the upright position. This finding is compatible with previous studies, which have showed that SVV imprecision increases with increasing angle of head tilt, reaching a maximum at angles of 120°–150° [26,30-32]. It has been suggested that SVV imprecision is related to internal models of sensory processing that update verticality perception by integrating vestibular and somatosensory signals [28]. Accordingly, SVV imprecision could theoretically be helpful for diagnosis of certain disorders related to sensory integration, such as vestibular migraine or persistent postural-perceptual dizziness. However, SVV imprecision is seldom measured in clinical practice, probably due to lack of appropriate equipment in the clinical setting, plus its reliability in such a context is still unknown. Our study proves that SVV imprecision with lateral head tilt can be easily measured by means of SVV VR goggles and that the result is reliable. We submit that SVV imprecision may be a potentially useful added diagnostic parameter for beside SVV evaluation.

There are several limitations in our study. First, when we asked subjects to tilt the head and maintain the trunk upright, we did not use any restraint equipment (e.g., bite bars) to ensure fixed posture. Thus most of the subjects could not have maintained the head tilted exactly to 30°, or kept their trunk perfectly upright throughout the testing procedures. To address this problem, we used real-time monitoring and consistent oral feedback by the examiner, which reasonably controlled the head tilt bias within ±3°. Second, because we utilized the method of active adjustment to measure SVV, the initial orientation and angle of the adjusted line may have affected the result of the SVV deviations [23,33]. Since the orientation in which the line initially appears was randomly selected by the SVV software, we did not control for this to be equal across all subjects. Third, the time interval between the first and second measurements was different among the subjects. All time intervals between testing sessions were 7 days or longer, so the bias of training effect is eliminated.

Conclusion

We conclude that the test-retest reliability of SVV deviation during lateral head tilt via VR goggles is excellent. This result supports further research into the diagnostic value of head-tilt SVV in various vestibular disorders. Moreover, although the SVV is less precise with lateral head tilts than in the upright position, the degree of imprecision is reproducible with fair-to-good test-retest reliability. This added finding suggests that besides SVV deviation, SVV imprecision may also have clinical relevance.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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