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Determining the preferred modality for real-time biofeedback during balance training☆

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ABSTRACT

Vestibular rehabilitation therapy has been shown to improve balance and gait stability in individuals with vestibular deficits. However, patient compliance with prescribed home exercise programs is variable. Real-time feedback of exercise performance can potentially improve exercise execution, exercise motivation, and rehabilitation outcomes. The goal of this study is to directly compare the effects of visual and vibrotactile feedback on postural performance to inform the selection of a feedback modality for inclusion in a home-based balance rehabilitation device. Eight subjects (46.6 $\pm$ 10.6 years) with peripheral vestibular deficits and eight age-matched control subjects (45.3 $\pm$ 11.1 years) participated in the study. Subjects performed eyes-open tandem Romberg stance trials with (vibrotactile, discrete visual, continuous visual, and multimodal) and without (baseline) feedback. Main outcome measures included medial–lateral (M/L) and anterior–posterior mean and standard deviation of body tilt, percent time spent within a no-feedback zone, and mean score on a comparative ranking survey. Both groups improved performance for each feedback modality compared to baseline, with no significant differences in performance observed among vibrotactile, discrete visual, or multimodal feedback for either group. Subjects with vestibular deficits performed best with continuous visual feedback and ranked it highest. Although the control subjects performed best with continuous visual feedback in terms of mean M/L tilt, they ranked it lowest. Despite the observed improvements, continuous visual feedback involves tracking a moving target, which was noted to induce dizziness in some subjects with vestibular deficits and cannot be used during exercises in which head position is actively changed or during eyes-closed conditions.

1. Introduction

Vestibular dysfunction affects 35% of the US population age 40 and older, corresponding to 69 million people [1]. Impairment of the vestibular system from disease or injury can greatly affect balance and is associated with physical symptoms, such as dizziness, imbalance, unsteady gait, and falls [2,3], and psychological symptoms, such as anxiety and depression [4]. Individuals with vestibular dysfunction have an eightfold increase in their risk of falling [1] and at least half of the US population is affected by a balance or vestibular disorder sometime during their lives [5].

The vestibular system plays an important role in the orientation of the body in space. Following acute loss of vestibular function, the central nervous system adapts by increasing reliance on other available sensory information from the visual and somatosensory systems to maintain postural control. Vestibular rehabilitation therapy (VRT) facilitates this compensation process and has been shown to improve balance, decrease physical and psychological symptoms, and improve quality of life [6–8]. VRT involves a series of balance exercises that progress in difficulty, such as transitioning from a wide to a narrow base of support, and incorporates head movements, manipulation of vision (e.g., eyes closed), and modification of support surfaces (e.g., compliant or inclined surfaces). Patients are instructed to perform exercises at home in parallel with and/or following the completion of the supervised in-clinic therapy. While repeated and consistent performance of these exercises is required to maximize compensation and habituation [9], at-home therapy compliance decreases over time due to lack of feedback on performance and consequent loss of motivation due to reduced results [10].

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In a clinical setting, physical therapists provide feedback to patients regarding performance (e.g., knowledge of performance, KP) through a combination of verbal instruction, visual demonstration, and physical guidance. KP has been shown to improve task performance and has further been implemented through real-time feedback of kinematics or kinetics [11]. Cakrt et al. [12] demonstrated that patients performing VRT while receiving visual feedback regarding their center of pressure had improved posturography results compared to a control group performing VRT without visual feedback. Providing feedback during rehabilitation has been proposed in the form of home-based technologies to increase patient compliance with prescribed rehabilitation and therapy treatments. For example, Nitz et al. [13] showed that women who trained at home for 10 weeks with the Nintendo Wii Fit, which provides real-time continuous visual feedback of center of pressure, improved their balance and lower limb muscle strength.

Visual [12], auditory [14], vibrotactile [15,16,31,32], and electrotactile [17] feedback have been used to provide real-time feedback of body or head movement during quiet and perturbed stance and some locomotor activities. Visual feedback displays are the most common means of conveying KP [18]; however, there are practical considerations that must be taken into account for individuals with vestibular deficits who rely heavily on the visual system for postural cues and perform VRT exercises that alter visual conditions through head movements or closed eyes [7]. Auditory displays are problematic for the many individuals with vestibular deficits who also have hearing problems [19]. Torso-based vibrotactile feedback displays have been investigated for balance-related applications because they intuitively convey information, directly mapping stimuli to body coordinates (e.g., left is left, front is front, etc.) [20]. Recently, individuals with vestibular deficits completing a two-week training period with a vibrotactile feedback device demonstrated decreased body sway, as measured by Sensory Organization Test scores, and decreased dizziness, as measured by the Dizziness Handicap Inventory [21]. Multimodal feedback has also been shown to improve balance metrics in healthy young and older adults [22]. Burke et al. [23] found that visual-tactile multimodal feedback led to improved performance scores versus visual feedback alone during several tasks, and was most effective during multi-tasking.

Real-time KP offers the potential to increase exercise motivation and positively impact rehabilitation outcomes. However, there is currently a lack of understanding regarding the effect of feedback modality on balance performance as well as the preference of individuals with vestibular deficits for a given feedback modality. The goal of this study is to directly compare the effects of visual and vibrotactile feedback on balance performance during a representative VRT exercise. Results will be used to inform the design of a home-based vestibular rehabilitation assistive training aid.

2. Methods

2.1. Participants

Eight patients (two women and six men, age: 46.6 ± 10.6 years) were recruited through the University of Michigan Vestibular Testing Center (Table 1). Patients were eligible to participate in this study if they had a diagnosed peripheral vestibular deficit, caloric weakness of 25% or greater on either side, and recommendation by a physical therapist for balance rehabilitation. Subjects with vestibular deficits were excluded if they had severe visual impairment, history of fainting, idiopathic vestibulopathies, or neurological disease affecting balance (e.g., Parkinson's). Eight healthy age-matched control subjects (two women and six men, age: 45.3 ± 11.1 years) were recruited from the community. Control subjects were excluded if they self-reported prior balance problems, arthritis, frequent lower limb pain, or severe visual impairment.

2.2. Experimental protocol

The study protocol was approved by the University of Michigan Institutional Review Board, written informed consent was obtained from all subjects prior to the start of the experiment in accordance with the Helsinki Declaration, and the investigation conformed to ethical and humane principles of research. Subjects stood on a level floor in tandem Romberg stance (heel-to-toe) for 30 s with eyes open, arms crossed over the chest, and bare feet. The tandem Romberg task was chosen as a representative vestibular rehabilitation exercise because it was challenging, but capable of being performed without complete balance disruption by all subjects with vestibular deficits. Seven tandem Romberg training trials were completed without feedback as practice, after which three no-feedback ("baseline") trials were performed. Subjects then performed seven training trials and three testing trials for each of four feedback conditions: (1) discrete visual, (2) vibrotactile, (3) vibrotactile + discrete visual (multimodal), and (4) continuous visual. One of four testing orders was assigned to each subject based on a Balanced Latin Squares design with feedback modality as the primary factor. Following the completion of all feedback trials, subjects were given a comparative questionnaire (Table 2) and asked to rank the four feedback modalities based on their suitability for use in an at-home rehabilitation device.

2.3. Intervention

The vibrotactile feedback system (Fig. 1, right panel) consisted of an adjustable belt, inertial measurement unit (IMU, Xsens Motion Technologies B.V., Netherlands) to detect body tilt, and four vibrating actuators referred to as tactors (C2, Engineering Acoustics Inc., USA). The belt was wrapped tightly around the subject's torso, with the IMU positioned over the subject's spine at the L2–L4 level. The tactors were affixed to the inside of the belt at the positions of the navel, spine, and right and left sides of the torso [15]. The IMU signals were sampled at 100 Hz. The tactor driving circuit generated sinusoidal signals to actuate the tactors at a frequency of 250 Hz.

During all trials, subjects were located 3.35 m from a standard projection screen and were instructed to stand in an upright position and use the feedback to stay within the no-feedback zone. All modalities provided feedback in the direction of tilt and activated only when body tilt approximately exceeded a "no feedback zone" threshold of 1° in that direction. Feedback was deactivated when the subject moved his or her body back within the no-feedback zone. During vibrotactile feedback trials, the nearest tactor provided vibrations [15]. For discrete visual feedback trials, one of four red squares, which corresponded to the four tactor locations, was projected onto the screen and filled to indicate the direction in which the threshold value had been exceeded (Fig. 1). Multimodal trials (discrete visual + vibrotactile) provided vibrations and illuminated squares simultaneously. Continuous visual feedback trials were identical to discrete visual feedback trials, with the addition of a moving circle that gave a continuous, real-time depiction of the subject's amplified body tilt as measured by the IMU. This circle was presented regardless of whether the subject was in the no-feedback zone. The projection screen update rate was 30 Hz.

2.4. Outcome measures

The primary metrics used to quantify performance were the mean and standard deviation (SD) of body tilt in the medial–lateral (M/L) and anterior–posterior (A/P) directions, the percent time spent in the no-feedback zone (PZ), and the mean rank on the comparative survey. Mean body tilt was calculated for each trial as the absolute value of the average of the body tilt; SD also was calculated for each trial. PZ was calculated as the percentage of time during the trial that the tilt was in the no-feedback zone. The rank of each feedback modality for all eight questions of

Table 1
Vestibular group demographics.

Subject no.	Age	Sex	Diagnosis	Affected side (% caloric weakness)
1	49	F	Intratympanic gentamicin injection, Meniere's disease	Right (36%)
2	39	M	Acoustic neuroma resection	Right (100%)
3	43	M	Severe bilateral peripheral vestibular weakness	Both
4	54	M	Vestibular neuritis	Right (26%)
5	56	M	Severe bilateral peripheral vestibular weakness	Both
6	63	F	Acoustic neuroma resection	Right (100%)
7	36	M	Acoustic neuroma resection	Left (100%)
8	33	M	Vestibular neuritis	Right (94%)

Table 2
Comparative questionnaire given to subjects to rank the four feedback modalities based on their suitability for use in an at-home rehabilitation device.

1.Which feedback type do you prefer? 1: least preferred and 4: most preferred
2.Which feedback type was most helpful in performing the exercise? 1: least helpful, 4: most helpful
3.Which feedback type would you be most likely to use to aid in performing the exercise at home? 1: least likely, 4: mostly likely
4.Which feedback type do you most enjoy using for performing the exercises? 1: least enjoyable, 4: most enjoyable
5.Which feedback type best helps you maintain your balance during the task? 1: least helpful in balancing, 4: most helpful in balancing
6.Which feedback type was most sensitive to your body motions? 1: least sensitive, 4: most sensitive
7.Which feedback type resulted in your best performance? 1: worst performance of the exercise, 4: best performance on the exercise
8.Which feedback type was the easiest to learn? 1: hardest to learn, 4: easiest to learn

the survey was averaged over all subjects, with four being the highest (e.g., "most preferred" or "most helpful in maintaining balance").

2.5. Statistical analysis

Data analysis was performed using PASW (SPSS Inc.). All metrics except PZ and mean rank were normalized for all conditions by dividing by each subject's mean baseline value. A linear mixed model using a compound symmetric covariance matrix with a Fischer's least significant difference post hoc analysis was used to determine statistical significance. Feedback condition and repetition were used as the independent factor and repeated measure, respectively. The outcome metrics described above were used as dependent variables. No correction was made for multiple comparisons. Significance is reported for $p < 0.05$.

3. Results

3.1. Subjects with vestibular deficits

Fig. 2 shows postural sway data with and without vibrotactile feedback from a representative subject. Repetition was not found to have a significant effect on PZ or the mean or SD of M/L or A/P body tilt. Feedback condition was found to have a significant effect on each balance outcome measure: PZ ($p < 0.0001$), mean body tilt (M/L: $p = 0.0002$; A/P: $p < 0.0001$), and body tilt SD (M/L: $p = 0.01$; A/P: $p < 0.0001$). Post hoc analysis showed no significant differences for any metric among the discrete visual, vibrotactile, and multimodal feedback conditions. With respect to baseline, the discrete visual (A/P: $p < 0.0001$), vibrotactile (A/P: $p < 0.0001$), multimodal (M/L: $p = 0.009$; A/P: $p < 0.0001$), and continuous visual (M/L: $p < 0.0001$; A/P: $p < 0.0001$) feedback conditions had significantly lower mean tilt values (Fig. 3a). Furthermore, mean M/L body tilt was significantly lower during continuous visual feedback than during any other feedback modality (all $p < 0.05$); however, mean A/P body tilt during continuous visual feedback was only significantly lower than that during multimodal feedback ($p = 0.02$). M/L body tilt standard deviation (Fig. 3b) was significantly lower than baseline ($p = 0.001$) during continuous visual feedback. A/P body tilt SD was significantly lower than baseline during vibrotactile ($p = 0.02$), multimodal ($p = 0.02$), and continuous visual feedback ($p < 0.0001$); furthermore, A/P body tilt SD was significantly lower during continuous visual feedback than during each other feedback modality (all $p < 0.01$).

Fig. 3c shows the results for mean PZ. Each feedback condition demonstrated higher mean PZ than baseline (all $p < 0.0001$), and continuous visual feedback had a significantly higher PZ than discrete visual feedback ($p = 0.01$). Discrete visual and vibrotactile feedback modalities ranked lowest in surveys, and continuous visual feedback ranked highest.

3.2. Healthy age-matched control subjects

Normalized M/L body tilt mean and SD are shown in Fig. 3d and e, respectively. Repetition was found to have a significant effect only on mean M/L body tilt ($p = 0.02$). Feedback condition was found to have a significant effect on mean body tilt (M/L: $p = 0.0002$; A/P: $p < 0.0001$), body tilt SD (M/L: $p = 0.0005$; A/P: $p < 0.0001$), and PZ ($p < 0.0001$). Post hoc analysis showed the mean body tilt to be significantly higher during baseline than during discrete visual (M/L: $p = 0.005$; A/P: $p < 0.0001$), vibrotactile (A/P: $p < 0.0001$), multimodal (M/L: $p = 0.007$; A/P: $p < 0.0001$), and continuous visual (M/L: $p < 0.0001$; A/P: $p < 0.0001$) feedback trials. Mean body tilt was significantly lower with continuous visual feedback than with vibrotactile (M/L: $p = 0.001$; A/P: $p = 0.237$) or multimodal (M/L: $p = 0.094$; A/P: $p = 0.003$) feedback. Body tilt SD was significantly higher during baseline trials than during discrete visual

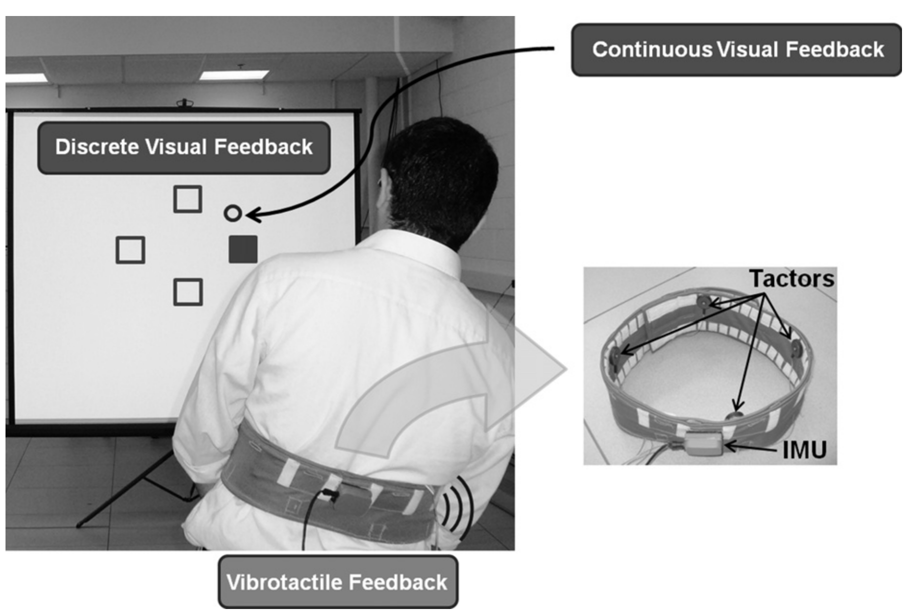

Fig. 1. Left panel: Experimental setup including discrete visual feedback display, continuous visual feedback display and vibrotactile feedback device. Right panel: Instrumented vibrotactile feedback belt consisting of four tactors and an IMU.

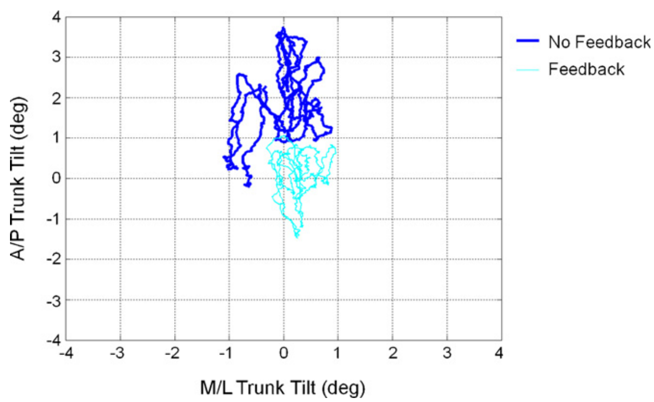

Fig. 2. Bird's-eye view of one subject's body tilt trajectory without feedback (darker, thicker line) and with vibrotactile feedback (lighter, thinner line) illustrating the reduction in sway area and shift to a more upright posture observed when vibrotactile feedback was applied.

(M/L: $p = 0.003$; A/P: $p = 0.0004$), vibrotactile (M/L: $p = 0.001$; A/P: $p < 0.0001$), multimodal (M/L: $p < 0.0001$; A/P: $p < 0.0001$), or continuous visual (M/L: $p = 0.03$; A/P: $p < 0.0001$) feedback trials. M/L body tilt SD was significantly higher during continuous visual feedback trials than during multimodal feedback trials ($p = 0.044$). There were no significant differences in PZ among the four feedback conditions, but the PZ with each feedback condition was significantly larger than baseline PZ ($p < 0.0001$) (Fig. 3f). Control subjects ranked continuous visual feedback the lowest on average; no difference in ranking was observed among discrete visual, vibrotactile, and multimodal feedback conditions.

4. Discussion

All feedback modalities improved most metrics in comparison to the baseline condition in both groups. No differences were observed in balance performance among discrete visual, vibrotactile, and multimodal feedback modalities for the vestibulopathic group. This group showed greatest improvement when using continuous visual feedback, and ranked it highest. The control group did not show the same level of improvement for continuous visual feedback versus other modalities and ranked it lowest.

The discrete visual and vibrotactile feedback displays convey the same information; both provide 90° spatial resolution and bimodal tilt magnitude (on/off). Although previous studies comparing visual and vibrotactile feedback have reported task-dependent differences in reaction time and performance [23], no differences in performance for these modalities were found here. Multiple resource theory suggests that the redundancy provided by multimodal feedback should improve performance in comparison to single-mode feedback [25,26]. However, we did not observe improvements in performance beyond single-mode feedback when discrete visual + vibrotactile feedback was used. Such improvements could potentially arise in even more challenging tasks. Our results indicate that vibrotactile feedback is as effective as discrete visual or discrete visual + vibrotactile feedback for individuals with vestibular deficits.

The continuous visual feedback modality was included in this study due to its high information content. As expected, the knowledge of current and future (rate of change in) body position provided by this display resulted in the best performance in the vestibulopathic population; several cited this added information as a motivation for ranking this modality highest, while others commented that the moving circle was distracting and difficult to track (due to its high speed), sometimes even causing dizziness (3 out of 8 subjects). Visual biofeedback should be used with caution with individuals with vestibular deficits because they may have unstable vision due to an impaired vestibular ocular reflex, and visual inputs can be destabilizing in certain situations. Furthermore, visual feedback is limited to a subset of exercises that do not require altered vision conditions (e.g., eyes closed). Based on these constraints, vibrotactile feedback may be a more appropriate modality for providing feedback in some cases. Individuals with vestibular loss differ in their reliance on visual or somatosensory information for postural control depending upon many intrinsic and extrinsic factors [28]. The results of this study suggest that individuals with vestibular deficits are able to use both discrete feedback modalities with equal effectiveness, therefore feedback type may be selected for rehabilitative training programs based on the desired outcome or other individual needs or preferences.

In the control group, we found improvements with all feedback conditions compared to baseline, but few differences among feedback conditions, potentially due to a ceiling effect. Many healthy subjects had little difficulty with the tandem Romberg stance; they achieved nearly perfect PZ scores. Individuals with vestibular deficits, however, exhibited a non-normalized baseline M/L body tilt (0.86°) that was more than twice that of healthy subjects (0.39°). The patient group, therefore, had a much larger opportunity for potential improvement in balance metrics than the controls.

Control subjects had greater mean M/L body tilt with vibrotactile feedback than with other feedback modalities, in particular continuous visual feedback. Cues mapped directly to the body may disrupt the performance of well-practiced skills significantly more than external cues (such as visual feedback) [27]. This disruption is less likely in vestibulopathic subjects who are more reliant on the cues due to sensory loss. The study results suggest that feedback displays (in particular vibrotactile) should be evaluated in the intended patient population rather than a healthy population, which may be more readily available, because of differences in preferences and performance. Future work should include the combination of continuous visual with vibrotactile feedback and the evaluation of continuous vibrotactile feedback alone and as part of multimodal feedback.

4.1. Study limitations

This experiment was performed on a small sample size of subjects as an exploratory study, and a large number of statistical tests were conducted without controlling the type I error. However, all subjects followed expected trends and improved performance with feedback. Only one patient population was included, although visual, vibrotactile, and multimodal feedback previously have been shown to be effective for older adults and those with Parkinson's disease or stroke [22,29,30]. Only one static task was used in this study, but this task provides an adequate balance challenge to the subjects with vestibular deficits thereby allowing performance to be compared across feedback display modalities. However, results may be different with dynamic tasks. We did not evaluate the short- or long-term effects of training with the biofeedback system. Instead, this study was focused on comparing the effects of several real-time feedback modalities. We chose to use visual feedback because it is common in rehabilitation, despite the fact that it is unsuitable during certain VRT exercises. Vibrotactile feedback was discrete rather than continuous in this study. While positioning the IMU on the trunk did not allow us to discriminate among lower body, upper body, or whole body motions, the trunk positioning maps directly to the body segment that primarily

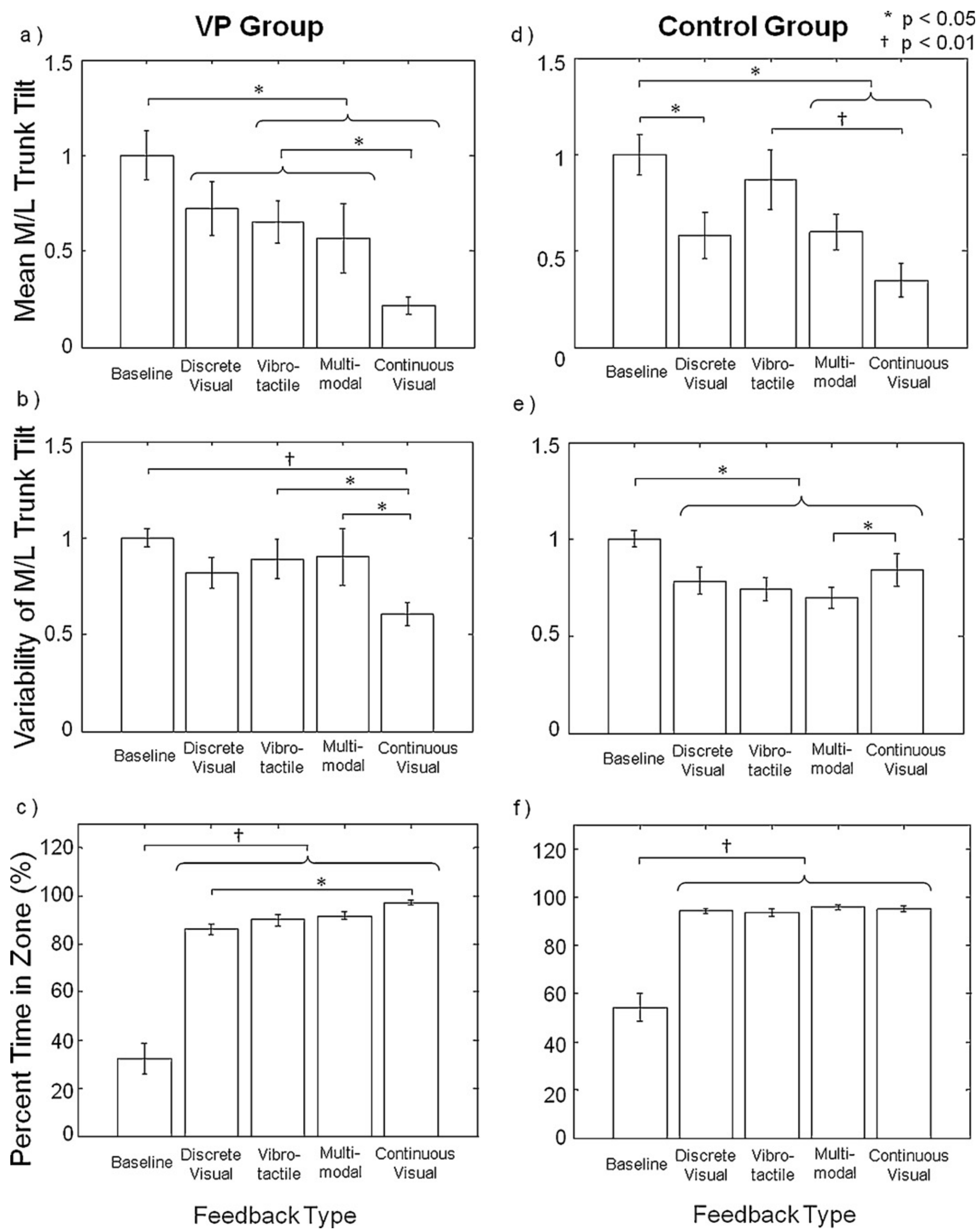

Fig. 3. Results for individuals with vestibular deficits (VP Group): (a) normalized mean M/L body tilt, (b) normalized SD of M/L body tilt, and (c) percent time spent in the no-feedback zone (PZ). The same metrics are shown for healthy age-matched control subjects in (d)–(f). Decreases in mean and SD of body tilt and increases in PZ indicate improved performance. Error bars represent standard error of the mean, with statistical significance represented by * for $p < 0.05$ and † for $p < 0.01$.

dictates the location of the center-of-mass with respect to the base-of-support.

5. Conclusion

In this study we have directly compared the effects of discrete visual, vibrotactile, multimodal, and continuous visual feedback on the performance of vestibulopathic and healthy age-matched control groups during a given static balance rehabilitation exercise. The group with vestibular deficits showed the most improvement in PZ and mean M/L tilt performance and the highest qualitative ranking for continuous visual feedback. However, the healthy age-matched control group showed no differences in PZ performance among the feedback modalities, and while they performed best with continuous visual feedback in mean M/L tilt performance, they ranked it lowest.

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Conflict of interest

We certify that none of the authors have a financial or personal relationship with other people or organizations that could inappropriately influence (bias) this work.

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