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Short-term retention effect of rehabilitation using head position-based electrotactile feedback to the tongue: Influence of vestibular loss and old-age

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ABSTRACT

Our objective was to evaluate whether the severity of vestibular loss and old-age (>65) affect a patient's ability to benefit from training using head-position based, tongue-placed electrotactile feedback. Seventy-one chronic dizzy patients, who had reached a plateau with their conventional rehabilitation, followed six 1-h training sessions during 4 consecutive days (once on days 1 and 4, twice on days 2 and 3). They presented bilateral vestibular areflexia (BVA), bilateral vestibular losses (BVL), unilateral vestibular areflexia or unilateral vestibular losses and were divided into two age-subgroups (≤65 and >65). Posturographic assessments were performed without the device, 4 h before and after the training. Patients were tested with eyes opened and eyes closed (EC) on static and dynamic (passively tilting) platforms. The studied posturographic scores improved significantly, especially under test conditions restricting either visual or somatosensory input. This 4-h retention effect was greater in older compared to younger patients and was proportional to the degree of vestibular loss, patients with increased vestibular losses showing greater improvements. In bilateral patients, who constantly fell under dynamic-EC condition at the baseline, the therapy effect was expressed by disappearance of falls in BVL and significant prolongation in time-to-fall in BVA subgroups.

Globally, our data showed that short training with head-position based, tongue-placed electrotactile biofeedback improves balance in chronic vestibulopathic patients some 16.74% beyond that achieved with standard balance physiotherapy. Further studies with longer use of this biofeedback are needed to investigate whether this approach could have long-lasting retention effect on balance and quality of life.

1. Introduction

Supplying individuals with artificial sensory information on body position, orientation and displacements has been shown to improve balance performances [1–7]. Based on these findings many biofeedback systems have been developed employing either visual [1], auditory [2–4] or tactile [4–7] input. The BrainPort balance device (Wicab Inc., Middleton, WI, USA) is one of these systems [5,11]. It uses the tongue as an alternative sensory channel to convey afferent information relating to a patient's head position in real time. It is well known that head displacements are normally detected by the vestibular system [8]. Its role in head and body stabilization and orientation is well documented and explains gait and posture impairments in vestibular patients [9]. The BrainPort balance device was developed with the objective of enhancing postural-kinetic performances by substituting vestibular cues while freeing up the visual and auditory inputs normally involved in balance control and spatial orientation.

Previous studies demonstrated the ability of the CNS to efficiently integrate this head position-based, tongue-placed biofeedback for head stabilizing [5] and controlling upright posture [10] in vestibular-defective patients. Moreover, it was shown that stability improvements continue after disconnection of the device and this residual effect is linearly related to the time the device is used [5]. A specific training program was then proposed using the BrainPort balance device as a rehabilitation tool [11]. Its retention effect was observed in patients with moderate to severe balance dysfunction resulting from various sensorimotor impairments [5,11–13]. However, the extent to which the severity of vestibular loss and old-age (>65) interfere with the patient's potential to benefit from this therapy is still unknown. In the present study, the short-term retention effect of BrainPort-therapy was assessed in chronic dizzy patients with different degrees of vestibular losses, ranging from unilateral vestibular deficit to

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bilateral vestibular areflexia. Our objective was to determine whether the above mentioned factors, affecting the neuronal plasticity, influence therapy outcome.

2. Materials and methods

2.1. Subjects

After approval of the institutional review board, the files of 71 consecutive patients (37 women and 34 men) who underwent BrainPort-therapy were submitted for a retrospective review. Patients gave informed consent as required by the Helsinki declaration (1964). Their age ranged from 38 to 84 (mean 65.11 ± 11.99). 35 patients were 65 or under while 36 patients were over 65, thus forming two age-subgroups ($\leq$65 and >65). The studied sample was divided into the following four subgroups: bilateral vestibular areflexia (BVA), bilateral vestibular losses (BVL), unilateral vestibular areflexia (UVA) and unilateral vestibular losses (UVL). This classification was based on the bythermal-caloric and 0.25 Hz rotating-chair tests [14] performed by videonystagmography (VNG-Ulmer, Synapsys, Marseille, France). Demographic and vestibular test data are outlined in Table 1 for each vestibular-subgroup (Table 1).

All the patients presented balance disturbances for at least 1 year. They benefited from appropriate medical and/or surgical treatments, counseling, and changes in their medical prescriptions aiming to minimize the effect of polymedication on balance control. In addition, all the patients benefited from 20 to 50 sessions (mean 35.54 ± 6.98) of conventional rehabilitation. This traditional approach relieved the original symptoms. However, patients reported persistent dizziness and moderate to severe handicap as evaluated by the Dizziness Handicap Inventory (DHI) [15] and showed abnormal posturographic scores (SPS platform, Synapsys, Marseille, France) [16].

The studied sample does not include patients with acute vestibulopathies, severe neurological or psychiatric conditions, nor patients with contraindication for use of the BrainPort balance device (communicable diseases, open mouth or tongue sores, neuropathies of the tongue).

2.2. BrainPort balance device

The BrainPort balance device is a portable system including an intraoral device (IOD) placed on the tongue and a controller equipped with a computer. The IOD contains an electrotactile array and a 3-axis, digital output accelerometer detecting both anterior–posterior (AP) and medial–lateral (ML) head displacements. The system microprocessor acquires acceleration information, estimates head pitch and roll angles and consequently activates specific 2×2 arrays within a larger 10×10 array regrouping 100 gold-plated electrodes. The activated electrodes deliver the electrical stimulation (bursts of three 25 μs-wide pulses at 200 Hz repeated at 50 Hz) to the dorsum of the tongue. Mapping the data to the array causes "binning" of the output signal into 2.8° increments to individual tactor rows, to a maximum range of $\pm$14° in each direction. This allows a subject to detect the typical postural sway occurring in semi-static position [11]. When the head position temporarily exceeds the display's range limit, the stimuli pattern remains at the outer edge allowing the subject to not lose the position information. Therefore, users continuously perceive head position and displacements through "tingling" stimuli mapped onto the tongue.

The goal of training is to make corrective postural adjustments in order to center the stimulus on the tongue thus achieving better head stabilization and appropriate balance.

2.3. Training procedure

Two 1-h sessions, separated by 4 h, were conducted daily during 4 consecutive days. The first and last visits were used only for balance assessment. During the other six visits (once on days 1 and 4, twice on days 2 and 3) each patient followed an individualized training program including five 5-min and one 20-min trials separated by rest periods. During training, patients used the device while performing balance exercises. These were done eyes closed, in standard then sensitized Romberg positions on firm then various foam surfaces and were challenged by imposing dynamic postural-kinetic tasks depending on their ability. Patients progressed to the next level when they were able to perform a 5-min trial without needing assistance. For 20-min trials, the postural tasks were challenging but not tiring. A physiotherapist conducted this individualized program based on his own clinical evaluation.

2.4. Posturographic assessment

The patient's balance was assessed using the SPS posturography system allowing us to record AP and ML center of pressure (CoP) sway separately. A passively tilting platform, imposing a self-regulated balance task, was used to test dynamic balance [17]. It was placed on the static SPS platform with its axis oriented first in the pitch (DYNAP) then in the roll planes (DYNML). The patient's sway caused the platform to rotate, thus amplifying AP or ML sway selectively, requiring postural reactions in the plane of provoked postural disturbances.

Eyes opened and eyes closed trials were carried out on the static (ST-EO and ST-EC), DYNAP (DYNAP-EO and DYNAP-EC) then DYNML (DYNML-EO and DYNML-EC) support surfaces. Patients were instructed to maintain their balance without moving or standing stiffly. Two trials of 20 s were performed under each test condition without the device, 4 h before the first and 4 h after the last training sessions.

Before therapy, the limits of stability (LoS) were additionally defined for each patient as their maximum possible straight body

Table 1
Age and sex repartition and data from videonystagmography tests in subgroups of patients with bilateral vestibular areflexia (BVA), bilateral vestibular losses (BVL), unilateral vestibular areflexia (UVA) and unilateral vestibular losses (UVL).

Patients subgroups	Number total (men; women)	Age mean ± standard deviation (range)	Videonystagmography data	
			Responses to bythermal caloric test	VOR gain to rotary chair test
BVA	17[a] (12; 5)	59.35 ± 8.34 (49–75)	Bilaterally absent	$\leq$0.05
BVL	11 (4; 7)	74.82 ± 10.74 (48–83)	Bilaterally reduced	<0.4
UVA	20[b] (5; 15)	59.55 ± 14.49 (38–83)	Unilaterally absent, 100% asymmetry	$\geq$0.4
UVL	23 (13; 10)	65.17 ± 12.82 (39–84)	Unilaterally reduced, 34–92% asymmetry	$\geq$0.4

No patients presented cerebellopontine angle tumors outside the internal auditory meatus.
[a] 3 patients had a bilateral vestibular neurectomy (VN) for disabling Menier's disease (MD).
[b] 14 patients had a unilateral VN for disabling MD ($n = 11$) and vestibular schwannoma ($n = 3$).

tilt in AP then ML directions without loss of balance. The maximum ranges (mm) of the AP and ML CoP displacements as recorded under LoS test (R_{Limit}) were then used for calculating the patient's pre and post therapeutic equilibrium scores (ESs) separately for AP and ML sway, as follows:

$$\text{ES} = \frac{R_{\text{Limit}} - R_{\text{Test}}}{R_{\text{Limit}}} \times 100$$

where $R_{(\text{Test})}$ represents the maximum range (mm) of the CoP sway in the corresponding direction as recorded under a test condition. In this way, large postural sway occurring under a test condition reduced the corresponding ES to zero. ES was set at zero when it was negative or when a patient was unable to perform a test without falling or needing external aid. In this last case, time-to-fall (TTF) was measured as the lapse of time standing before falling.

2.5. Statistical analysis

Three-way analyses of variances (ANOVAs) were used to examine the effect of the therapy (before/after), vestibular loss (four vestibular-subgroups) and old-age ($\leq$65/>65) on the ESs. Post hoc analyses by Least Significant Difference (LSD) Fisher tests were performed whenever necessary. Statistica 9.1 (StatSoft Inc., Tulsa, OK, USA) was used. Results were considered significant for $P < 0.05$.

3. Results

Fig. 1 illustrates pre- and post-therapeutic AP CoP displacements from a representative BVA patient recorded under ST-EO, ST-EC, DYNAP-EO and DYNAP-EC conditions (Fig. 1). Similar therapy effects were observed on their ML sway under ST-EO, ST-EC, DYNML-EO and DYNML-EC conditions.

Table 2
Significant F statistics and levels of significance ($^*P < 0.05$) for main effects of therapy (before versus after therapy), vestibular loss (subgroups of patients with different degrees of vestibular losses) and age ($\leq$65 versus >65 age-subgroups) revealed by the ANOVAs of equilibrium scores (ES) and time-to-fall (TTF). Note that the axis of the rotational platform was oriented in the pitch plane under DYNAMIC-AP and in the roll plane under DYNAMIC-ML conditions.

Outcome measures	Main effect		
	Therapy	Vestibular loss	Age
Anterior–posterior sway			
$\text{ES}_{(\text{STATIC Eyes Opened})}$	3.82*	–	–
$\text{ES}_{(\text{STATIC Eyes Closed})}$	7.72*	–	–
$\text{ES}_{(\text{DYNAMIC-AP Eyes Opened})}$	9.06*	6.86*	11.67*
$\text{ES}_{(\text{DYNAMIC-AP Eyes Closed})}$	15.74*	11.88*	5.01*
$\text{TTF}_{(\text{DYNAMIC-AP Eyes Closed})}$	271.22*	489.17*	15.67*
Medial–lateral sway			
$\text{ES}_{(\text{STATIC Eyes Opened})}$	7.69*	2.72*	–
$\text{ES}_{(\text{STATIC Eyes Closed})}$	14.24*	2.99*	–
$\text{ES}_{(\text{DYNAMIC-ML Eyes Opened})}$	15.54*	3.07*	9.02*
$\text{ES}_{(\text{DYNAMIC-ML Eyes Closed})}$	22.07*	9.03*	3.64*
$\text{TTF}_{(\text{DYNAMIC-ML Eyes Closed})}$	268.22*	427.31*	13.24*

Table 2 indicates the main effects of therapy, vestibular loss and age revealed by the ANOVAs (Table 2).

As shown in Fig. 2, pre-therapeutic ESs were lower under dynamic compared to static test conditions, bilateral patients having the poorest performances. After therapy, significant improvements were observed in ESs characterizing the BVA, BVL and UVA patients' balance under static-EO, static-EC and dynamic-EO conditions. In addition, unilateral patients showed improvement in ESs recorded under dynamic-EC conditions (Fig. 2). It is notable that before therapy 100% of bilateral and 30% of UVA patients constantly fell under these conditions. After therapy, all of them were able to perform dynamic-EC tests without falling

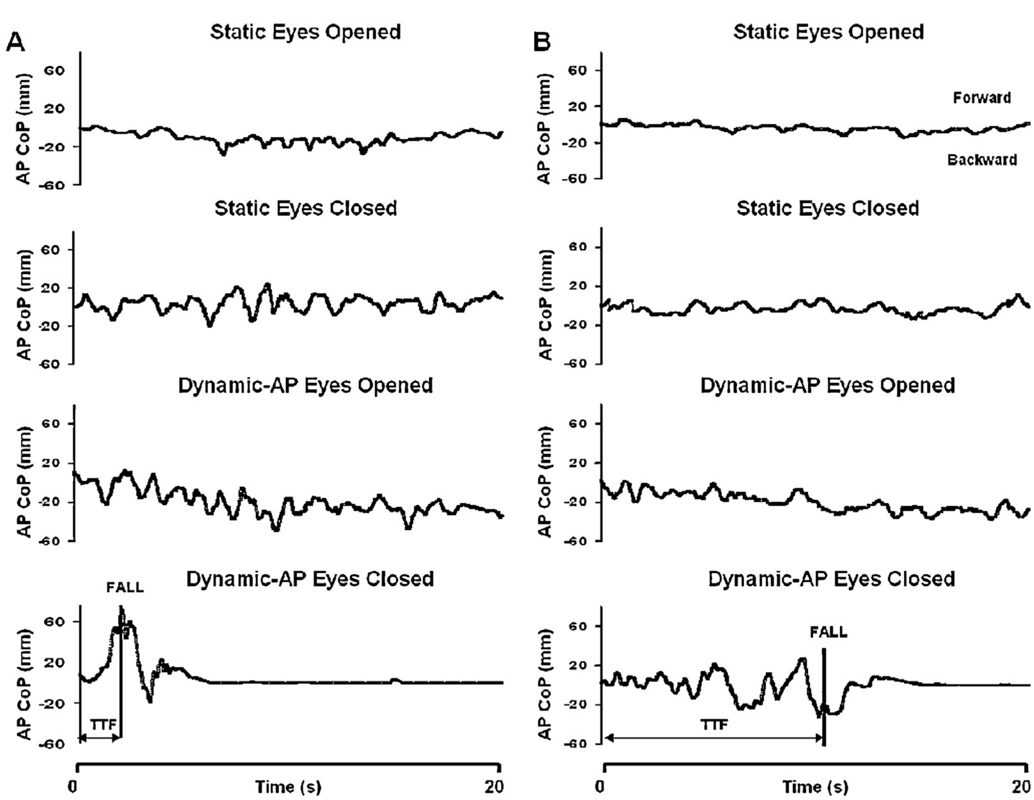

Fig. 1. Anterior–posterior (AP) center of pressure displacements (CoP) from a representative patient presenting bilateral vestibular areflexia, before (A) and 4 h after training (B). Note that in the Dynamic-AP conditions, the axis of the passively tilting platform was oriented in the pitch plane, thus amplifying the patient's spontaneous AP sway selectively. Time-to-fall (TTF) indicates the lapse of time standing before falling.

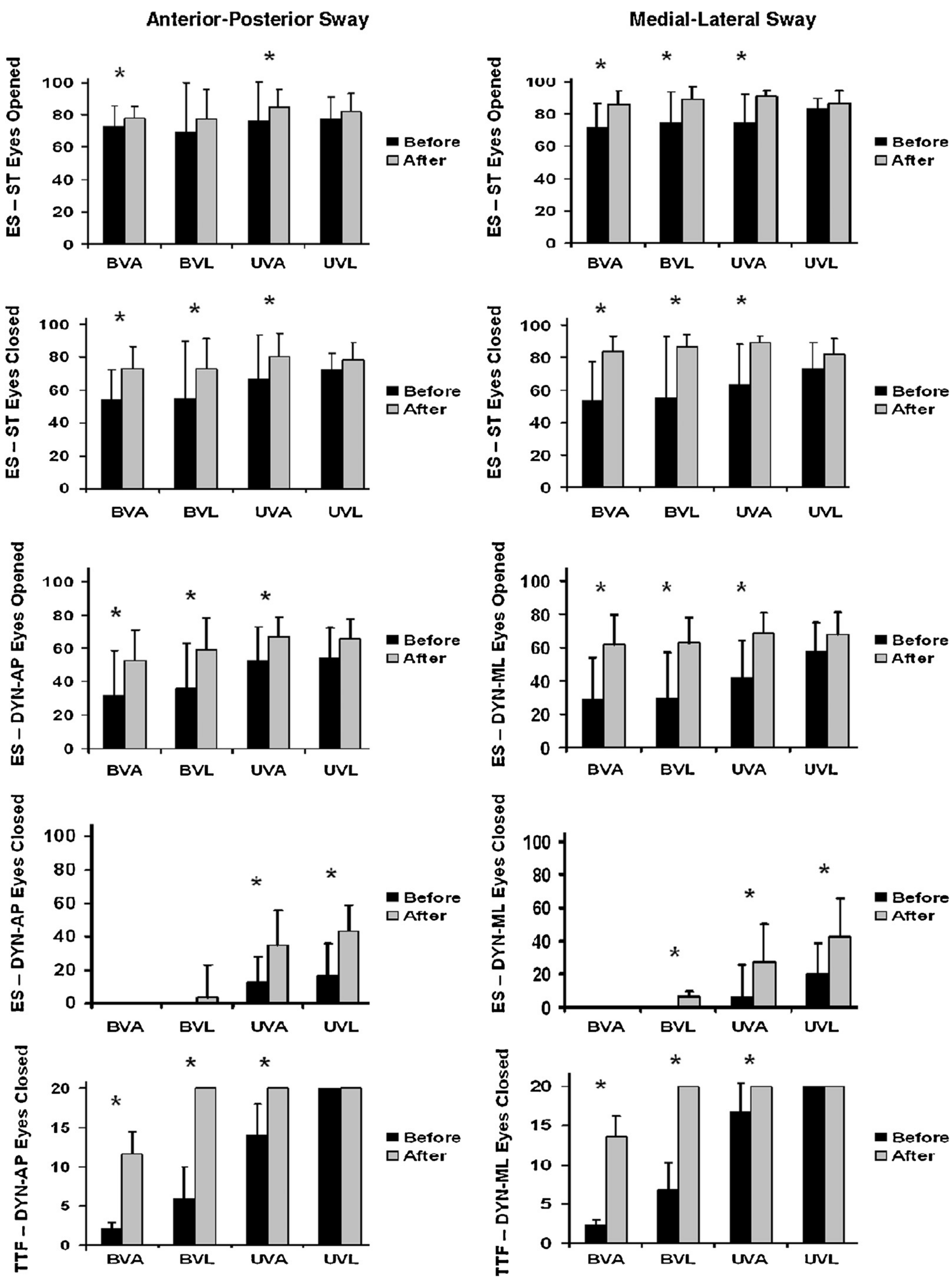

Fig. 2. Mean equilibrium scores (ES) and time-to-fall (TTF) measured before (black columns) and after therapy (gray columns) in subgroups of patients presenting bilateral vestibular areflexia (BVA), bilateral vestibular losses (BVL), unilateral vestibular areflexia (UVA) and unilateral vestibular losses (UVL). The standard deviation of each mean is indicated by a vertical bar on the column. Significant therapy effects as determined by the LSD Fisher test are indicated by * ($P < 0.05$). Note that dynamic balance was assessed using a passively tilting platform placed on the static (ST) posturography platform with its axis oriented in the pitch (DYN-AP) then in the roll planes (DYN-ML).

except the BVA subjects, who however, showed a significant prolongation in time-to-fall under these conditions (Fig. 2).

Before therapy, ESs characterizing ML balance under ST-EO, ST-EC, DYNML-EO and DYNML-EC conditions were lower in >65 compared to ≤65 Age-subgroups (respectively $P < 0.05$, $P < 0.05$, $P < 0.05$ and $P < 0.05$). Similar trends were observed when analyzing AP sway under DYNAP-EO and DYNAP-EC conditions (respectively $P < 0.05$ and $P < 0.05$). After therapy, ESs improved significantly in both age-subgroups, >65 patients showing greater improvements (Fig. 3A).

As illustrated in Fig. 3B, the amount of the post-therapeutic changes was proportional to the degree of vestibular loss, patients with increased vestibular losses showing greater improvements. In addition, in all the studied subgroups, the improvement was greater for dynamic-EO and static-EC than static-EO tests (Fig. 3). These trends were seen in ESs characterizing both AP and ML balance and were more evident when analyzing ML sway.

The mean improvement of all our patients' ESs recorded under static-EO, static-EC and dynamic-EO conditions was 16.74%.

4. Discussion

The present study aimed at investigating whether the severity of vestibular loss and old-age (>65) influence the

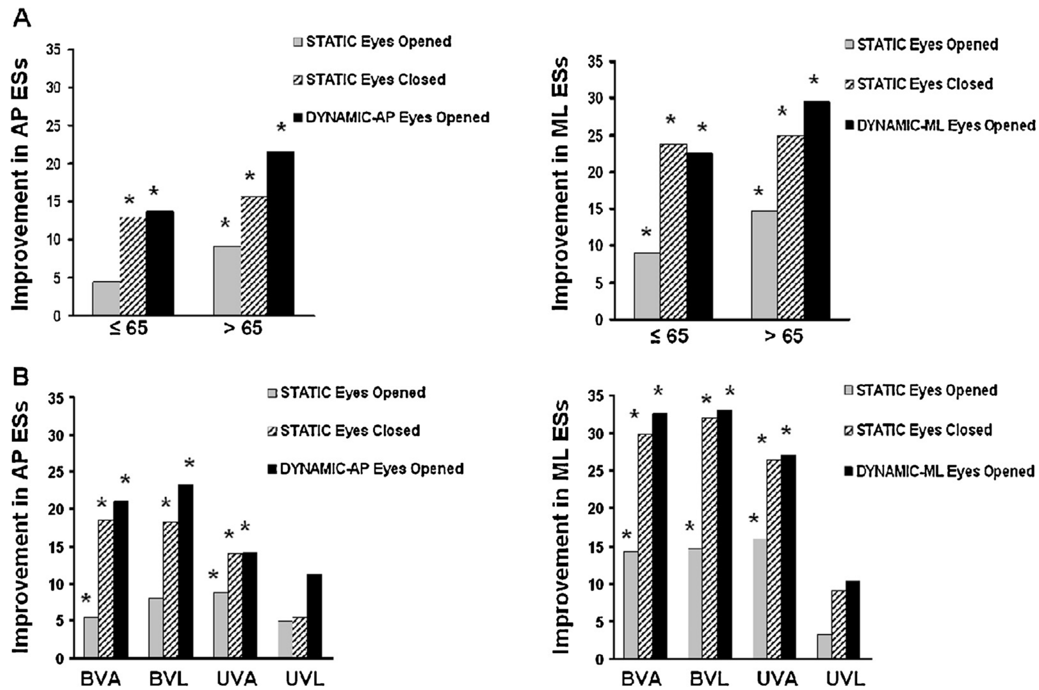

Fig. 3. Mean improvement (difference between post- and pre-therapeutic equilibrium scores) as anterior–posterior (AP ESs) and medial-lateral sway (ML ESs) for ≤65 and >65 age-subgroups (panel A) as well as for patients presenting bilateral vestibular areflexia (BVA), bilateral vestibular losses (BVL), unilateral vestibular areflexia (UVA) and unilateral vestibular losses (UVL) (panel B). The * indicates significant therapy effects ($P < 0.05$) as determined by the LSD Fisher test.

patients' ability to benefit from training with the BrainPort balance device providing an artificial vestibular signal. For this, we studied the immediate retention effect of six training sessions on chronic dizzy patients, who had reached a plateau with their conventional rehabilitation. They presented various degrees of vestibular losses ranging from unilateral deficit to bilateral vestibular areflexia and were divided into two age-subgroups (≤65 and >65).

Analysis of pre-therapeutic equilibrium Scores revealed a characteristic pattern of underutilization of vestibular input for postural compensation [17] pointing to the insufficiency of the conventional treatments for our patients. We demonstrated that training with the BrainPort balance device offers a possibility to improve their postural performances beyond the level achieved with standard balance physiotherapy. Our data has shown that the amount of the post-therapeutic changes is proportional to the degree of vestibular loss, patients with profound deficits benefiting more from this therapy than those with unilateral losses. This is in line with previously reported findings showing that body sway-based auditory [18,19] and multi-modal [20] biofeedback have a greater stabilizing effect in vestibular patients than in healthy subjects.

Consistent with data on the effect of postural audio-feedback [1,19], we further demonstrated that the therapy effect is greater under test conditions selectively limiting the reliable sensory information for balancing. Indeed, in our study, minor changes were observed under static-EO condition. In contrast, the therapy effect was better under the static-EC condition suppressing the visual input, as well as the dynamic-EO condition provoking important distortion of somatosensory input from ankle joints [17]. In unilateral patients, significant improvements were observed under dynamic-EC conditions restricting both visual and somatosensory input, thus imposing an effective use of the available egocentric and gravitational references provided via surviving proprioceptive and vestibular cues. BVA patients, differentiating from the others by a complete loss of vestibular sensors, still demonstrated a characteristic fall pattern under this condition. We did not find publications confirming that supplying BVA patients with any kind of biofeedback could allow them to remain standing for 20 s EC without assistance on tilting platforms. In contrast, a possibility to prolong the time-to-fall was previously reported in BVA patients tested with EC on a sway-referenced platform (Equitest, Neurocom) while supplying them with vibrotactile biofeedback [21]. Consistent with this data, the present study showed a significant prolongation of time-to-fall in the BVA subgroup. It is also notable that in our experience, the therapy effect in BVL subjects was expressed by a complete disappearance of falls under dynamic-EC condition. This is a substantial benefit that had been impossible to achieve even after several sessions of conventional rehabilitation.

Furthermore, the present study showed significant improvements in both age-subgroups, highlighting potentials offered by brain plasticity even in elderly subjects. Therapy effect was greater in older patients presenting lower posturographic scores at the baseline, confirming that patients with the largest initial balance deficits benefit most from postural biofeedback [25]. These results corroborate bibliography data demonstrating that aging is not a limiting factor in benefiting from electrotactile [11], vibrotactile [26] or haptic sensory supplementation [27].

On the other hand, our data showed that training with the BrainPort balance device providing multi-directional head-tilt electrotactile biofeedback, improved both AP and ML balance. In accordance with findings on the directional specificity of the postural biofeedback effect [7,22] this corroborates previously reported data demonstrating that use of multi-axis vibrotactile feedback significantly reduces postural sway in all directions [7]. It is notable that in our study, the greatest improvements were observed in ESs characterizing the patients' ML sway, known to be less likely to reduce in vestibular subjects than those occurring in the AP plane [23]. Identical changes were reported in BVL patients tested with EO in one-leg stance, while supplying them with auditory postural biofeedback [24].

It is notable that use of the BrainPort balance device involves balance exercises known to enhance postural performances [2,3,6,28]. However, our patients had reached a plateau with their conventional rehabilitation that comprised the same exercises. Additionally, significant improvements were observed under dynamic test conditions that were not included in the training program. This suggests that training with biofeedback results in a carry-over effect leading to general balance changes. Nevertheless, the lack of a control group prevents us from claiming the superiority of this approach over training alone. Several controlled studies have elucidated this point, suggesting that biofeedback and training affect motor performance via different, complimentary mechanisms [6]. Furthermore, it was shown that in selected tasks, postural biofeedback have a fundamental effect which consistently increases stability beyond the effects of training alone [2,3,6,28].

In the present study, analysis of the therapy effect in posturographic scores revealed similarities with those observed in patients wearing auditory [2,3,18,19,24,25], vibrotactile [6,21,25,26] or multi-modal [20,22] biofeedback devices providing a real-time postural signal. Our patients, however, were tested without feedback, 4 h after the last use of the BrainPort balance device. We speculate that these immediate post-effects are partially due to its neuromodulating action. Indeed, in addition to head position-based biofeedback, this device provides powerful electrical stimulation of the tongue exciting the natural flow of neural impulses to the brainstem and cerebellum. Recent neuroimaging studies have highlighted that electrotactile tongue stimulation enhances postural stability in vestibular patients and induces neuromodulation of the balance-processing network [29,30]. The latter probably initiates and sustains the newly calibrated and integrated postural control signal and acts as an enhancer of neuroplastic changes resulting from targeted training with biofeedback.

Therefore, the short-term retention effect of BrainPort-therapy could be due to the association of training, biofeedback and neuromodulation effects. Having speculated that these factors would affect our subgroups similarly, the present study was limited in investigating the influence of vestibular loss and aging on the therapy outcome.

5. Conclusion

Our data showed that six 1-h training sessions with the BrainPort balance device improve both AP and ML balance in chronic dizzy patients presenting various degrees of vestibular losses. Significant improvement of posturographic scores was observed 4 h after cessation of therapy in subjects tested without the device. This short-term retention effect was proportional to the degree of vestibular loss, patients with increased vestibular losses showing greater improvements. It was larger in older compared to younger patients and was better when testing patients under test conditions limiting either visual or somatosensory input for balancing.

Globally, the present study confirmed that training with the BrainPort balance device enhances postural performances in chronic dizzy patients who had reached a plateau with their conventional rehabilitation. Further studies with longer use of this device are needed to investigate its possible long-lasting retention effect.

Conflict of interest statement

None declared.

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