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Postural Adaptation in Elderly Patients with Instability and Risk of Falling After Balance Training Using a Virtual-Reality System

Hamlet Suárez,[1] Alejo Suárez,[1] and Luiz Lavinsky[2]

[1]*Laboratory of Audiology and Vestibular Pathophysiology, School of Medicine, Montevideo, Uruguay, and* [2]*Department of Otolaryngology, School of Medicine, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil*

Abstract: Our aim in this study was to assess postural control adaptation quantitatively in unsteady elderly patients at risk of falls in open spaces and given balance training with a virtual-reality system reproducing environmental stimulation. Using a balance rehabilitation unit based on a virtual-reality system that changes sensory information (visual, vestibular, and somatosensory), we treated 26 elderly, unsteady patients who were prone to falling (age range, 73–82 years) and who were enrolled in a customized vestibular rehabilitation program. We assessed postural responses by posturography before and after 6 weeks in the vestibular rehabilitation program under two conditions: (1) standing, eyes open, static visual field, and (2) standing, eyes open, dynamic visual field through virtual-reality goggles, generating horizontal optokinetic stimulation (70 degrees per second angular velocity). We recorded postural responses with a platform measuring the confidential ellipse of the center-of-pressure distribution area and sway velocity with a scalogram analyzing postural behavior by wavelets. After 6 weeks of treatment, postural response confidential ellipse and sway velocity values were lower, evincing decreased amplitudes and sway frequency contents in the scalogram by wavelet under both stimulation paradigm conditions. These findings suggest postural adaptation under the two perceptual conditions when patients had static and dynamic visual fields. The possibility of treating elderly fallers with balance disorders using a virtual-reality environmental stimulation reproduction system is discussed.

Key Words: balance disorders; falls; postural control; vestibular rehabilitation; virtual reality

Instability and falls are a major problem in older adults and frequently result in physical, socioeconomic, and sometimes fatal outcomes. Statistics show that 33% of the elderly population older than 65 years experiences falls and that two-thirds of accidental deaths are attributable to falls [1,2]. Although falls are elicited by many mechanisms, vestibuloocular and vestibulospinal disorders play a major role among the different factors involved in older adult instability.

Decreased information from the sensory end organs (visuovestibular and somatosensory) and the deficient central processing of these signals are specifically related to balance disorders and falls in elderly patients. Indoor and outdoor environmental factors can increase the risk of falls in the elderly, and indoor factors can be modified to decrease the risk (type of handrails, stairs with safety features, illumination, etc.). Nevertheless, balance training is the only method by which to reduce the risk of falls in patients older than 75 years [3] when outdoor environmental changes arising from modifications in the visual field, support surface, and the like are involved. Vestibular rehabilitation and prevention programs may be developed to ensure the quality of life in the elderly and reduce their health care costs [4,5].

In this study, we assessed the postural responses of 26 elderly patients prone to unsteadiness and falls in

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Reprint requests: Dr. Hamlet Suárez, Laboratory of Audiology and Vestibular Pathophysiology, School of Medicine, C. de Guayaquil 1332, Montevideo 11400, Uruguay. Phone: +598-9961-0606; Fax: +598-2487-4080; E-mail: hsuarez@chasque.apc.org

open spaces before and after participation in a vestibular rehabilitation program (VRP). A customized VRP was designed for each patient, mainly to stimulate the sensory conditions that caused the more significant postural disturbances measured by posturography. These changes in visual, vestibular, and somatosensory information were made with a balance rehabilitation unit that generates environmental visual and vestibular stimuli through a virtual-reality system, eliciting changes in the postural responses. To assess the postural adaptation after the VRP, we recorded the postural responses through posturography before and after 6 weeks of training under two different perceptual conditions with static and dynamic visual fields (optokinetic stimulation) using the balance rehabilitation unit system.

PATIENTS AND METHODS

We evaluated and treated in a VRP 26 patients who had balance disorders (age range, 73–82 years) and who had had more than two falls in 1 year while walking in open spaces. The patients had been assessed previously with clinical tests, electronystagmography, postural control measurements, and computed tomography. Patients with musculoskeletal disorders, dementia, neuropathy, or Parkinson's disease were excluded from this study. We obtained informed consent from all the patients.

Vestibular Rehabilitation Program

We used a balance rehabilitation unit (Medicaa, Montevideo, Uruguay) for designing a customized VRP for each patient, with postural responses (PR) under different sensory conditions, simulating environmental stimuli, in which the system elicited the following oculomotor responses: smooth pursuit, saccadic, optokinetic, vestibulo-ocular reflex, and visual vestibular interactions. Before starting the balance rehabilitation and after its completion, we measured the changes produced in the PR parameters (confidential ellipse [CE] and sway velocity [SV]). We also made changes to somatosensory input, changing the foot support surface (using foam on the platform).

The VRP consisted of a 40-minute daily trial for 6 weeks, mainly stimulating the sensory condition in which the patients showed the highest postural control parameters. With the use of virtual reality, we made changes in their angular velocity and visual target size and in volume perception during the training simulating environmental stimuli. Patients were supported by safety harnesses during training time.

Postural Measurements

We assessed postural strategies before and after the VRP using a force platform with online recording of the center of pressure (COP) that measured two relevant parameters: SV and 95% CE of the COP distribution area. An 80-second trial was recorded producing two discrete signals of n = 4,000 samples (sampling frequency $f_s = 50$ Hz): *COPx* and *COPy*. Next, for each recording, the average speed of COP along its path ($\langle \upsilon \rangle$) was calculated at $t = 80$ seconds (n = 4,000) using:

$$\langle \upsilon \rangle = \frac{f_s}{N} \sum_{i=2}^{N} \left[(COPx_i - COPx_{i-1})^2 + (COPy_i - COPy_{i-1})^2 \right]^{1/2}$$

The CE of the bivariate distribution ($COPx_i$, $COPy_i$), $1 \le i \le n$, is the ellipse in which 95% of the COP samples are predicted to be enclosed. It can be shown that the area of the 95% confidential ellipse is:

$$Area = 2\pi F_{0.05[2,N-2]} \sqrt{\sigma_x^2 \sigma_y^2 - \sigma_{xy}^2}$$

where $F_{0.05[2,N-2]}$ is the F statistic at the 95% confidence level with n data points, σ_x^2 and σ_y^2 are the variances of the lateral and anteroposterior coordinates, respectively, and σ_{xy} is the covariance. For a large sample size ($n > 120$), $F_{0.05[2,N-2]}$ is 3.00. This is the case here (n = 4,000).

Time-Frequency Analysis (Scalogram)

To evaluate the fundamental oscillatory frequency, its amplitude, and temporal behavior of the responses, we performed a time-frequency analysis of COP in both directions (*COPx* and *COPy*) by computing its scalogram. As the Fourier transform is not adapted to the analysis of a nonstationary signal, such as the COP signal, its time-frequency representation must be considered. Because of its resolution properties, the scalogram is a widely used time-frequency energy density. The scalogram of the signal $x(u)$ is the energetic version of the wavelets transform, defined as the square magnitude of the wavelets transform:

$$SCAL_X(t,f) = \left| \int_{-\infty}^{+\infty} x(u) \cdot \sqrt{\frac{f}{f_0}} \cdot \psi^*\left(\frac{f}{f_0} \cdot (u - t)\right) \cdot du \right|^2$$

The mother wavelet [6] that was chosen was the Morlet wavelet:

$$\psi(u) = e^{-u^2/2} \cdot e^{j2\pi f_0 u}$$

These wavelets are the ones with the best time-frequency localization in the sense specified by the Heisenberg-Gabor uncertainty principle [6]. We assessed PRs using CE and SV measures and wavelet scalograms obtained under two stimulation paradigm conditions (Fig. 1) at the start of the VRP and 6 weeks

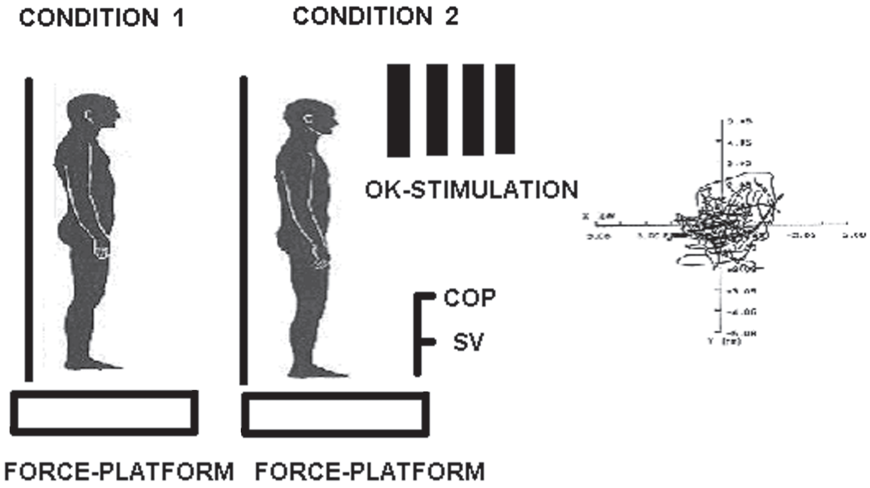

Figure 1. Stimulation paradigm conditions for postural assessment. Condition 1: static visual field, standing position, eyes open, staring at fixed mark, no movement of visual information. Condition 2: standing position, eyes open, looking at 70 degrees per second optokinetic (*OK*) stimulation delivered through virtual-reality goggles. (*COP* = center-of-pressure; *SV* = sway velocity.)

afterward: (1) static visual field (standing position, eyes open, staring at a fixed mark, without movement in the visual information), and (2) dynamic visual field (standing position, eyes open, looking at an optokinetic stimulation with an angular velocity of 70 degrees per second, delivered through virtual-reality goggles). The Wilcoxon rank sum test was used for statistical analysis of data.

RESULTS

A previous report [7] showed different behaviors between elderly persons prone to fall and normal elderly people when different visual stimulation was used. In accordance with that study, our patients' PR data suggested that they had marked instability and were at risk of falls. The PR values measured for those prone to fall improved after the VRP. CE and SV values decreased under the two stimulation paradigm conditions (Table 1; Fig. 2). A greater reduction in PR values after VRP was evident in condition 2.

We processed PR records with the wavelet scalogram before the beginning of VRP. All 26 patients had a significant increase in the amplitude of slow-frequency and sway-frequency contents of up to 2 Hz under condition 2 (visual optokinetic stimulation). The wavelet scalogram after 6 weeks of VRP also showed adapted changes, with the PR amplitude and the sway-frequency contents down to below 0.5 Hz (Fig. 3). The decrease in the slow-frequency amplitudes and sway-frequency contents showed an improvement in postural control parameters [8].

Table 1. Mean and Standard Deviation Values for Center-of-Pressure (COP) Distribution Area and Sway Velocity (SV) in Two Paradigm Conditions

	Condition 1		Condition 2	
	Pre-VRP	Post-VRP	Pre-VRP	Post-VRP
COP (cm^2)				
MV	10.4	3.5	22.4	10.2
σ	2.3	1.4	4.3	4.2
SV (cm/s)				
MV	3.2	2.4	4.87	2.9
σ	0.5	0.4	1.4	0.3

VRP = vestibular rehabilitation program; MV = mean value.

Note: Condition 1: before balance rehabilitation (COP and SV values). Condition 2: after balance rehabilitation (COP and SV values). A significant decrease in values ($p < .001$) was found in both conditions and for both parameters (Wilcoxon rank sum test).

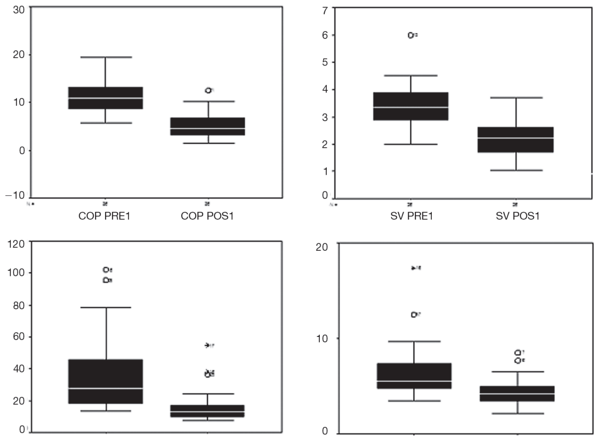

Figure 2. Box plot of recorded values. White line is median of recorded values; box limits are first and third quartiles, with 50% of values within box limits; circles are records classified as outliers. Condition 1 (top) and condition 2 (bottom) data for center-of-pressure (*COP*) records (left) and for sway velocity (*SV*) records (right), before (*PRE*) and after (*POS*) a vestibular rehabilitation program.

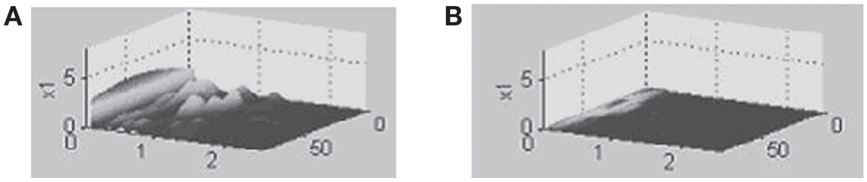

Figure 3. Wavelet scalogram representative of an elderly patient who falls. (A) Scalogram before balance rehabilitation. (B) Scalogram 6 weeks after balance rehabilitation. In (B), sway-frequency contents and response amplitudes decreased, which indicates improvement in postural control.

DISCUSSION

Age-related changes in the neural, sensory, and musculoskeletal system can lead to balance impairments that affect ability to move around safely. Specifically, the deficit in control of the support base, with compensatory arm and leg movements elicited by environmental changes, is regarded as an important issue in the postural disturbance repertoire of the elderly population. The 26 patients who showed "sensitivity" when exposed to optokinetic stimuli suggested that a visual field with a moving target could elicit postural disturbances and put these patients at risk of falling. This issue can be reproduced and analyzed by means of virtual reality, using the platform to measure the postural skill disturbances when changes in visual flow occur.

The goal in developing a vestibular rehabilitation system using virtual reality is to recreate environmental changes in the visual, vestibular, and somatosensory inputs, generating the adjusted vestibuloocular and vestibulospinal reflexes involved in postural control and gait strategies. Because the virtual-reality system allows different kinds and sequences of stimulation to be designed, according to the vestibuloocular and vestibulospinal disturbances, all patients received customized training to improve their postural skills.

Further information, such as a longitudinal study over time with patients who fall, will be necessary to evaluate the impact on the decreased risk of falling. However, these findings showed an adaptation in the postural control parameters after rehabilitation and suggest that virtual reality could be a tool for designing customized VRPs to prevent instability and falling in the elderly population, usually elicited in open spaces or due to sudden changes in environmental visual, vestibular, and somatosensory stimulation.

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