Available online at www.sciencedirect.com
ScienceDirect
Gait & Posture 27 (2008) 303–308
GAIT & POSTURE
www.elsevier.com/locate/gaitpost

The potential applications of a virtual moving environment for assessing falls in elderly adults

Pamela S. Haibach [a,b,*], Semyon M. Slobounov [a], Karl M. Newell [a]

[a] Department of Kinesiology, The Pennsylvania State University, United States
[b] Department of Physical Education and Sport, State University of New York at Brockport, United States

Received 30 October 2005; received in revised form 9 March 2007; accepted 10 April 2007

Abstract

The purpose of this study was to investigate whether the moving room paradigm could be used to assess fall risk in older people. A group of young adults (18–29 years) and two groups of elderly adults (60–79 years) with and without a history of falls were placed into a simulated moving room. Participants stood still facing an oscillating three dimensional virtual room moving in the antero-posterior plane with three types of room movement conditions, continuous oscillatory, discrete anterior and discrete posterior. The young adults performed with less postural motion and coherence with the virtual motion than the older age groups. The group of elderly fallers exhibited more postural motion [center of pressure (COP) length, $p < 0.05$], a trend towards higher coherence with the object motion ($p = 0.07$), and the greatest amount of time-to-stability ($p < 0.05$). A virtual moving room incorporating measures of time-to-stability and egomotion appears useful in predicting risk for falls.

Keywords: Aging; Falls; Posture; Virtual environment; Vision; Balance; Egomotion; Time-to-stability

Falls are one of the leading causes of injury-related deaths in the United States [1]. Tinetti et al. found that nearly half of a group of community dwelling older adults experienced one or more falls over a 3-year period, with nearly a quarter of the fallers incurring a serious injury [2]. Injuries resultant to falls can lead to fear of future falls and a loss of functional independence [3].

Assessment of fall risk has not previously included the influence of the visual control of posture. Age-related changes in sensory systems contribute to postural instability in older adults. Visual deficits include reduced visual acuity [4–6], contrast sensitivity [5,6], depth perception, dark adaptation [6], visual sensitivity to motion [4], loss in the size of the visual field [5], decreased peripheral vision and poor color discrimination [7]. These deficits in elderly people contribute to an increase in the time required to regain stability in posture, increasing fall risk [8].

The strong influence of vision on the control of posture has previously been shown using the moving room paradigm [9,10]. Individuals placed in a dynamic environment, such as a room which oscillates towards or away from the individual, have been found to move in the opposite direction of the moving stimulus. Motion detected by the retina provides information about the position of the environment relative to the body. It can either inform the observer of self-motion, also known as egomotion, or motion occurring in the environment [11]. The sensory systems work together to detect egomotion [9,10] however, in the case of the moving room studies, the visual system predominates [10]. The moving room provides no additional information to the vestibular or somatosensory system to induce the illusion of motion [12]. The sensory conflict is solely upon the visual system. The participant is often not even aware of their postural transitions in response to the room movements.

It has been shown that elderly people respond to the moving room with enhanced postural motion as assessed by

* Corresponding author at: SUNY Brockport, 350 New Campus Dr., Brockport, NY 14420, United States. Tel.: +1 585 395 5427; fax: +1 585 395 2771.
E-mail address: phaibach@brockport.edu (P.S. Haibach).

0966-6362/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2007.04.004

properties of the center of pressure [13]. The present investigation examined whether the moving room paradigm would have the potential to predict falls by placing participants in a virtual moving room and comparing healthy elderly adults with and without a history of falls. Virtual reality provides a unique opportunity to manipulate properties of the optic array in the motion of the virtual room [14] and provides a potential avenue for postural research and rehabilitation [15,16].

Two main properties of postural control were examined: egomotion and time-to-stability. Egomotion was determined by the amount of postural motion induced by the motion of the screen. Higher coherence with the virtual screen motion combined with a greater amount of center of pressure motion is indicative of an adaptive performance, while longer time-to-stability implies an increased risk for postural instability [8].

1. Methods

1.1. Participants

The present investigation included 45 volunteer participants separated into 3 groups of 15 adults, including a young adult (18–29 years), a healthy elderly group (60–79 years) and an age parallel elderly group of fallers. Each participant signed an informed consent form reviewed by the university Institutional Review Board and received US $10 h^{-1} for their participation. Table 1 displays the descriptive statistics for the participants.

Exclusion criteria for the healthy elderly adults included neuromuscular diseases, diabetes, vertigo, CVA or TIA, use of an aid while walking, difficulty with standing upright, falls within the past year, visible tremor and uncorrected visual deficits. The participants were also asked whether they felt the effects of motion sickness as these can be induced by the movement displayed on the virtual reality screen [17]. The inclusion criteria for the elderly faller group included adults who have experienced two or more falls in the previous year.

1.2. Apparatus

An AMTI (OR6-1000) force platform was used to assess postural sway. The force platform records the postural dynamics with three force components: the medio-lateral force (Fx), antero-posterior force (Fy) and the vertical force (Fz) and three respective moment components: Mx, My and Mz. The force platform data were sampled at a rate of 100 Hz filtered at a low cutoff frequency of 20 Hz. The excitation voltage was set to 5 V. Biometrics goniometers were placed on the ankle (SG110), knee (SG110) and hip (SG150) with accuracy being defined as $\pm 2^{\circ}$ and repeatability was 1°.

The virtual reality (VR) system provided a semi-immersive environment. The VR environment was developed using the following hardware: ImmersaDeskR2 (distributed by Fakespace Systems is a stereo capable rear-projection system with a 4 in. × 5 in. screen at a 60° angle with respect to the floor); CrystalEyes stereo glasses (3.3 oz) and a DELL PRECISION 530 linux PC workstation. Software synchronizing all devices and hardware drivers and generating graphics was written in C/C^{++}/OpenGL/CAVELib. The participant stood close to the screen providing visual information to approximately 110° of horizontal field of view. The frame rate of the ImmersaDesk was set at 30 frames/s and the resolution was 1024 × 768 pixels. The graphical part of the program generated on the screen the visual representation of a moving room with two lateral walls, a front wall, a ceiling and floor covered with high contrast black and white parallel stripes (vertical for the lateral walls and horizontal for the ceiling and floor).

Table 1
Descriptive statistics (mean and S.D.) for participants ($n = 45$)

	Group ($n = 15$)		
	Young	Nonfallers	Fallers
Sex	6 M, 9 F	7 M, 8 F	8 M, 7 F
Age (years)	22.2 (3.3)	67.8 (3.1)	70.1 (5.5)
Weight (lbs)	161 (35.6)	162.3 (26.0)	170.5 (29.3)
Height (in.)	67.1 (4.9)	66.1 (2.2)	66.8 (4.3)
Right visual acuity	24.05 (5.0)	38.3 (15.7)	62.3 (58.0)
Left visual acuity	25.0 (6.6)	36.3 (12.0)	45.3 (20.6)
Peripheral vision	1 (0)	1.4 (0.74)	1.6 (0.63)
Activity (number of times/week)	4.3 (1.7)	4.3 (1.1)	3.9 (1.8)
Duration of activity	62.7 (21.7)	49.7 (14.7)	40.3 (19.3)
Number of falls	0.07 (0.3)	0.07 (0.26)	2.6 (1.1)

1.3. Procedures

Prior to testing, each participant completed two vision assessments, a visual field test, oculokinetic perimetry [18] and a visual acuity test (the Snellen eye chart). Goniometers were also placed on the participants' ankle, knee and hip with self-adhesive tape. Participants were then fitted into a harness supported by 2 × 6 wooden boards. Each participant stood on the force platform with a comfortable foot position facing the VR screen. Foot position was recorded to maintain the same stance throughout the experiment. The participants were asked to fixate upon a focal point on the screen. Participants were instructed to stand still with their arms to their sides, however, if they felt the movement of the screen causing them to sway to refrain from opposing the movement.

During a trial, the visual image on the screen gave the appearance that the virtual room was oscillating at 0.3 Hz and one of five amplitudes (1, 2, 4, 8 and 16 cm). There were three types of room movements, continuous oscillatory (CO), in which the screen moved in an antero-posterior direction throughout the entire trial; discrete anterior (DA), the screen moved in one discrete movement towards the participant after 5 s and discrete posterior (DP). During the DA and DP conditions, the screen moved 1/2 the distance of the amplitude. The center of pressure was recorded during the entire trial. There were three 25 s trials per condition, totaling 45 trials, plus 6 control trials. The control trials measured the postural motion of standing still without room oscillations, three with eyes open and three with eyes closed.

The amplitude conditions were randomly presented to the participants to avoid practice or fatigue effects. Participants were allowed to take breaks as often and as long as necessary and were encouraged to bend the joints at their arms and/or legs between trials. Following each condition, participants were asked to rate the amount of simulated motion they noticed on the screen, virtual motion, and how much motion they perceived their body moving, termed vection, from one (no motion) to seven (maximum motion).

1.4. Data analyses

The center of pressure (cm) was used as the measure of postural motion. Center of pressure length was used as a measure of the total center of pressure displacement in both the x and y directions. Statistical analyses of the data included descriptive statistics of the dependent variables as well as analysis of variance. The dependent variables were placed independently in a within subject 3-way (group $\times$ amplitude $\times$ movement condition) repeated measure ANOVA.

The data were filtered to 20 Hz prior to analyses. Time series of whole body postural movement along the anterior–posterior direction was obtained from the Force Plate AMTI system. The time series of moving room oscillations along the y-axis were obtained by VRML preprogrammed for different frequencies and magnitudes of virtual room motion. These two time series, oscillation of the virtual room and postural responses over time, were used to obtain coherence values between quantities of moving room and postural responses using a specially developed m-code in MATLAB 6.5. Coherence was calculated at the modulation frequency at 0.3 Hz. Coherence measures the linear correlation between the two components of the bivariate process at frequency w and is analogous to the square of the usual correlation coefficient [19,20]. Only the magnitude of coherence was calculated based on values relative to baseline, to reduce the inter-subject variability of absolute coherence. The baseline of coherence measures was relative to the first three time windows. The auto-spectra for each signal were calculated by using Welsh's averaged periodogram method [21]. Coherence was calculated based on the cross-spectra f_{xy} and auto-spectra f_{xx}, f_{yy} with the spectra estimated from segments of data and the coherence R_{xy} estimated from the combined spectra [22]:

$$\frac{R_{xy}(\lambda)|2 = |f_{xy}(\lambda)|2}{(f_{xx}(\lambda)f_{yy}(\lambda))} \quad (1)$$

The significance of coherence was also calculated. That is the confidence limit for zero coherence at the $\alpha\%$, and L is the number of disjoint segments: $\text{sig}(\alpha) = 1 - (1 - \alpha)^{1/(L-1)}$.

Time-to-stability was determined from the velocity of the center of pressure. Velocity profiles were constructed for individual trials. MATLAB Version 6.5 was used to differentiate the center of pressure values with respect to time. These values were then squared and the square root of the sum was then calculated, representing the velocity of the center of pressure vector. Time-to-stability was determined by plotting the velocity vector on the ordinate and time as the abscissa. The participant was considered to have returned to stability when the center of pressure velocity remained below three standard deviations from the mean.

2. Results

2.1. Center of pressure (COP)

COP length exhibited a group effect, F (2, 1980) = 52.67, $p < 0.05$, with the faller group displaying the greatest COP length. Tukey's post hoc analysis revealed differences across each group (ps < 0.05), with the young adults exhibiting the least amount of postural motion and the fallers with the greatest amount of postural motion. The different movement conditions also revealed a significant effect, F (2, 1980) = 11.03, $p < 0.05$. The continuous oscillatory condition induced the largest postural response (ps < 0.05).

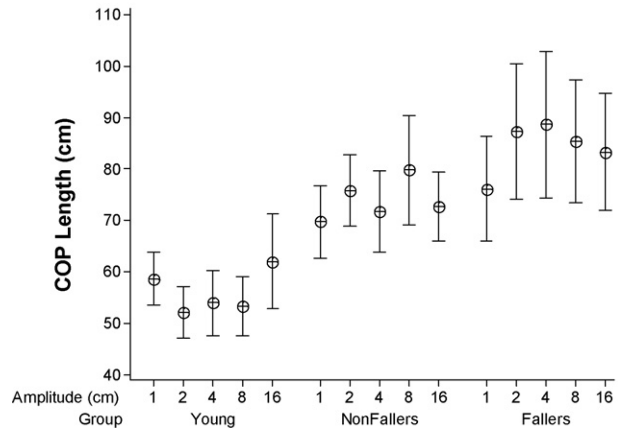

Fig. 1. Length of center of pressure motion across the magnitude of motion for each group. Significantly more motion was found in the faller group; ($p < 0.05$).

Main effects were found across the amplitude conditions, F (4, 1980) = 3.05, $p < 0.05$. The young adults displayed differences in the amplitude condition, however, both of the elderly adult groups displayed similar responses across the amplitude conditions (Fig. 1). The 1 cm amplitude caused greater postural motion than the 2 cm, 4 cm, or 8 cm conditions (ps < 0.05), but not the 16 cm condition. Differences were also found between the 16 cm condition and the 4 and 8 cm conditions (ps < 0.05).

2.2. Vection

Main effects for the subjective evaluation of the virtual motion were found for amplitude and type of room movement, F (4, 630) = 23.56, $p < 0.05$ and F (2, 630) = 85.08, $p < 0.05$, respectively. Amplitudes were rated as incrementally greater with the highest amplitude having the greatest perceived amount of motion. Participants rated the continuously oscillating conditions as having greater motion than the two discrete conditions for both room motion and perceived postural motion (ps < 0.05). A near group effect was found (p = 0.062) with the group of fallers rating the room motion as higher than the other two groups.

Analyses of vection revealed similar findings for amplitude and type of virtual motion, F (4, 630) = 2.88, $p < 0.05$ and F (2, 630) = 11.61, $p < 0.05$, respectively, but there were no group effects. Participants perceived their postural motion to be greater during the continuously oscillatory conditions than either of the discrete conditions. Perceptions of postural motion were also greater for the 8 and 16 cm amplitudes than the 1 cm amplitude (ps < 0.05).

Thus, there was no difference between age groups in their perception of postural motion, vection.

2.3. Frequency analysis

The frequency coupling was analyzed for the continuous oscillatory trials with the movement pattern displayed on the virtual reality screen. A trend was found for the faller group to have higher coherence than the two healthy groups, however, this was not significant. A main effect across the amplitudes was found, F (4, 660) = 3.14, $p < 0.05$. Coherence increased with the magnitude of the virtual motion.

Participants oscillated in-phase with the moving room as indicated by phase lags approximately near zero across all trials. The coupling phase lags did not exhibit any main effects or interactions across the amplitude conditions or groups. A near main effect for amplitude was found ($p = 0.061$), however, with each group anticipating the virtual motion with postural transitions during the 1 cm condition.

2.4. Time-to-stability

Fig. 2 displays the mean amount of time each group required to return to stability during the DA and DP conditions. A group effect was found [F (2, 1320) = 7.42, $p < 0.05$] with the young adults requiring the least amount of time-to-stability (ps < 0.05). The faller group took on average an additional 3 s to return to stability than the young adults, while the healthy elderly adults only required an additional 1.5 s. The young adults required more time to return to stability following the discrete posterior condition than the discrete anterior condition ($p < 0.05$), requiring on average an additional 1 s to return to stability. There was no effect for the direction of room movement, anterior versus posterior, for either of the two elderly groups.

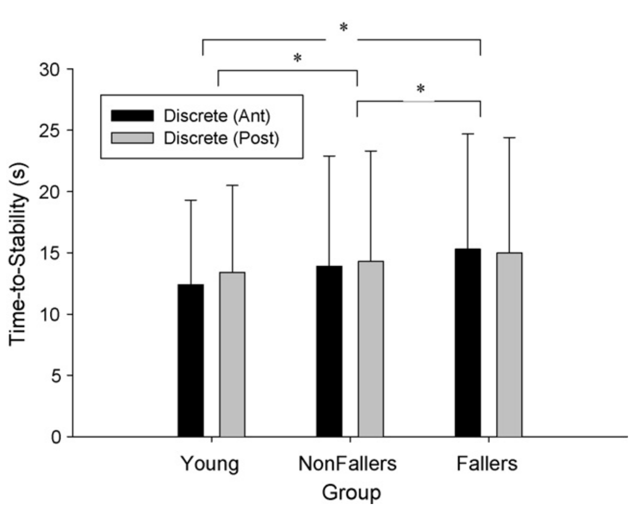

Fig. 2. Time-to-stability following discrete anterior and discrete posterior visual perturbations for all three groups; $^{*}p < 0.05$.

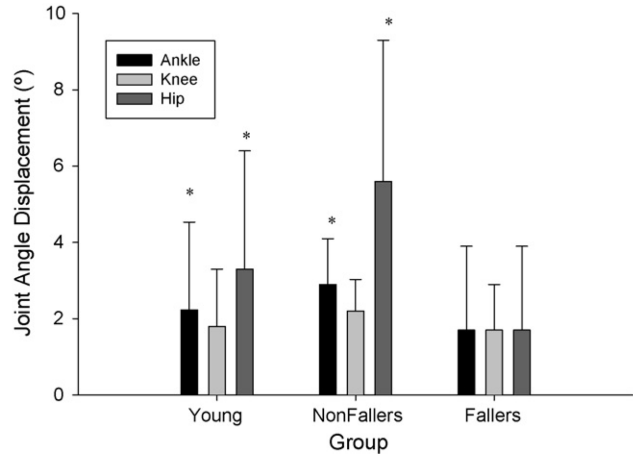

Fig. 3. Joint angle displacements for the ankle, knee and hip across the groups. No significant differences across the joints were found for the group of elderly fallers; $^{*}p < 0.05$.

2.5. Joint angles

Group differences were found for the joint angle displacements, ankle, F (2, 1980) = 65.13, $p < 0.05$; knee, F (2, 1980) = 37.40, $p < 0.05$ and hip, F (2, 1980) = 277.29, $p < 0.05$, with the healthy elderly and young adults producing more compensatory motion than the faller group (Fig. 3). The healthy elderly adults compensated the most of the three groups (ps < 0.05). Post hoc analysis revealed differences between each group for the ankle and hip displacement ($p < 0.05$). Both the young adults and the faller group differed from the healthy elderly in the knee joint displacement (ps < 0.05); however, no differences were found between these two groups. No amplitude effects were found for any of the joint angles.

There were no differences found for the type of room motion (ps > 0.05). However, further analysis of the discrete conditions revealed that the majority of the postural compensation occurred following the virtual motion. This compensation occurred during a brief period of time, however, resulted in a range of motion that was comparable to that of the continuous oscillatory condition.

3. Discussion

The present experiment examined postural stability in a clinical application of the moving room paradigm to compare elderly adults with and without a history of falls. Two main assessments were conducted to examine the applicability of the virtual moving room as a predictor of falls. During the continuously oscillatory condition, fall risk was assessed by egomotion as indexed by COP and coherence analysis. Even though much research has exhibited visual decline in older adulthood [4–6], this decline has not been shown to affect postural compensation during purely visual manipulations [13,23]. Not only did the visual motion induce a postural response in both elderly groups, the older adults responded to the virtual motion more strongly than the young adults. This effect was further pronounced in the group of fallers. These results indicate that visual feedback is very important in older adulthood in the integration of postural control and motion.

The group of fallers exhibited a trend towards more correlated postural motion with the virtual motion than the healthy elderly adults. Although the cause of previous falls in the faller group was variable, it appears that a common feature amongst the group was enhanced postural instability and frequency coupling over healthy age-matched controls. The analyses showed that this pattern of findings on postural control was not correlated to visual deficits on standard vision tests. Perhaps evaluations of contrast sensitivity and depth perception [24] could have provided additional pertinent information relevant to the postural instabilities associated with the examined tasks.

The joint angle analyses provided further evidence that the fallers adapted their performance to a greater extent than healthy adults. The fallers did not produce a significant change in joint angle displacement in any of the joints of the lower limbs. Although not quantitatively assessed, it was observed that the faller group used much more arm motion to control balance which induced more postural motion in this group. The healthy elderly adults showed greater joint angle motion at all joints than the other groups, while still standing with increased postural motion over that of the young adults. This may be partly explained by a reduced sensitivity to proprioceptive feedback in elderly adults [13].

Time-to-stability has been used as a measure of postural instability in a stepping task and indicated that older adults require a greater amount of time to return to stability [8]. The present experiment indicated that this effect also holds for visual perturbations. Aging effects were found with both older age groups requiring a greater amount of time to return to stability. Optimally, the system would return to a stable posture in the least amount of time, limiting the amount of time in an unstable posture. If sensory information is altered or an additional perturbation occurs while the body is in an unstable posture, a fall may occur [25]. The elderly adults with a history of falls required an additional 3 s to regain postural stability over healthy elderly adults. This value is not taking into account the fact that older adults have a reduced stability boundary [26] and reach this boundary in significantly less time [27] than young adults. Furthermore, elderly adults require a greater displacement of postural sway before they were able to detect a postural instability [28].

In conclusion, the moving room paradigm may be a useful assessment tool for fall risk. In the current study, elderly fallers exhibited greater compensatory postural motion with virtual motion in the form of frequency coupling and center of pressure motion and required considerable time to return to stability. Further assessments should include a longitudinal study on elderly adults who have not incurred a fall at the onset of the study and adding measures of stability boundaries to provide a more functional measure of fall risk.

Conflict of interest

There is no conflict of interest in the submission of the manuscript.

References

[1] Bloem BR, Steijns J, Smits-Engelsman B. An update on falls. Curr Opin Neurol 2002;16:15–26.

[2] Tinetti ME, Doucette J, Claus E, Marotolli R. Risk factors for serious injury during falls by older persons in the community. J Am Ger Soc 1995;43:1214–21.

[3] Fortinsky RH, Iannuzzi-Sucich M, Baker DI, et al. Fall-risk assessment and management in clinical practice: views from healthcare providers. J Am Geriatr Soc 2004;52:1522–6.

[4] Bron AJ. The aging eye. In: Evans JG, Williams TF, editors. Oxford textbook of geriatric medicine. Oxford: Oxford University Press; 1992

[5] Sekuler R, Sekuler AB. Visual perception and cognition. In: Evans JG, Williams TF, editors. Oxford textbook of geriatric medicine. Oxford: Oxford University Press; 1992.

[6] Verillo RT, Verillo V. Sensory and perceptual performance. In: Charness, editor. Aging and human performance. New York: Wiley; 1985.

[7] Haegerstrom-Portnoy G. Seeing into old age: vision function beyond acuity. Optom Vis Sci 1999;76:141.

[8] Johnson C, Mihalko S, Newell K. Aging and the time needed to reacquire postural stability. J Aging Phys Act 2003;11:419–29.

[9] Lee DN, Aronson E. Visual proprioceptive control of standing in human infants. Percept Psychophys 1974;15:529–32.

[10] Lee DN, Lishman JR. Visual proprioceptive control of stance. J Hum Mov Study 1975;1:87–95.

[11] Sheldon JH. The effect of age on the control of sway. Gerontologia Clinica 1963;5:129–38.

[12] Nakamura S, Shimojo S. Critical role of foreground stimuli in perceiving visually induced self-motion (vection). Perception 1999;28:893–902.

[13] Wade MG, Lindquist R, Taylor JR, Treat-Jacobson D. Optical flow, spatial orientation and the control of posture in the elderly. J Gerontol: Psych Sci 1995;50B:P51–8.

[14] Tossavainen T, Juhola M, Aalto H, et al. Postural control as assessed with virtual reality. Acta Otolaryngol 2001;545:53–6.

[15] Keshner E, Kenyon RV. Using immersive technology for postural research and rehabilitation. Assist Tech 2004;16:54–62.

[16] Keshner E, Kenyon RV, Dhaher YY, Streepey JW. Employing a virtual environment in postural research and rehabilitation to reveal the impact of visual information. In: International conference on disability, virtual reality and associated technologies; 2004.

[17] Smart JL, Stoffregen TA, Bardy BG. Visually induced motion sickness predicted by postural instability. Hum Factors 2002;44:451–65.

[18] Damato BE. Oculokinetic perimetry: a simple visual field test for use in the community. Brit J Opthalam 1985;69:927–31.

[19] Chatfield C. The analysis of time series: an introduction, 3rd ed., London: Chapman and Hall; 1984.

[20] Janacek G. Practical time series. London: Arnold; 2001.

[21] Kay S. Modern spectral estimation: theory and application. Upper Saddle River, NJ: Prentice-Hall; 1988.

[22] Stoica P, Moses R. Introduction to spectral analysis. Upper Saddle River, NJ: Prentice-Hall; 1997, 61–64.

[23] Prioli AC, Freitas Júnior PB, Barela JA. Postural control in active and sedentary elderlies. Gerontology 2005;51:145–8.

[24] Chandler JM, Duncan PW. Balance and falls in the elderly; issues in evaluation in treatment. In: Cuccione AA, editor. Geriatric physical therapy. St. Louis, MO: Mosby; 1993.
[25] Maki BE, McIlroy WE. Postural control in the older adult. Gait Bal Dis 1996;12. 635.
[26] Lee WA, Deming L. Correlation between age and the size of the normalized static support base while standing. In: Goodman D, Reid G, McAuley E, editors. Psychology of motor behaviour and sport. Vancouver: University of British Columbia; 1987.
[27] Slobounov SM, Moss SA, Slobounova ES, Newell KM. Aging and time to instability in posture. J Gerontol 1998;53A:B71–8.
[28] Stelmach GE, Worringham CJ. Sensorimotor deficits related to postural stability: implications for falling in the elderly. Clin Ger Med 1985;1:679–94.