# EXPERIMENTAL SYSTEM FOR INVESTIGATION OF VISUAL SENSORY INPUT IN POSTURAL FEEDBACK CONTROL

*Jozef PUCIK[1], Marian SALING[2], Stanislav LOVAS[1], Martin KUCHARIK[2], Oldrich ONDRACEK[1], Elena COCHEROVA[1]*

[1]Institute of Electronics and Photonics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Ilkovicova 3, 812 19 Bratislava, Slovak Republic
[2]II Neurologic Department, Medical Faculty of Commenius University, Derer University Hospital, Limbova 5, 833 05 Bratislava, Slovak Republic

jozef.pucik@stuba.sk, marian.saling@kr.unb.sk, st.lovas@gmail.com, martin.kucharik@kr.unb.sk, oldrich.ondracek@stuba.sk, elena.cocherova@stuba.sk

***Abstract.*** *The human postural control system represents a biological feedback system responsible for maintenance of upright stance. Vestibular, proprioceptive and visual sensory inputs provide the most important information into the control system, which controls body centre of mass (COM) in order to stabilize the human body resembling an inverted pendulum. The COM can be measured indirectly by means of a force plate as the centre of pressure (COP). Clinically used measurement method is referred to as posturography. In this paper, the conventional static posturography is extended by visual stimulation, which provides insight into a role of visual information in balance control. Visual stimuli have been designed to induce body sway in four specific directions – forward, backward, left and right. Stabilograms were measured using proposed single-PC based system and processed to calculate velocity waveforms and posturographic parameters. The parameters extracted from pre-stimulus and on-stimulus periods exhibit statistically significant differences.*

## Keywords

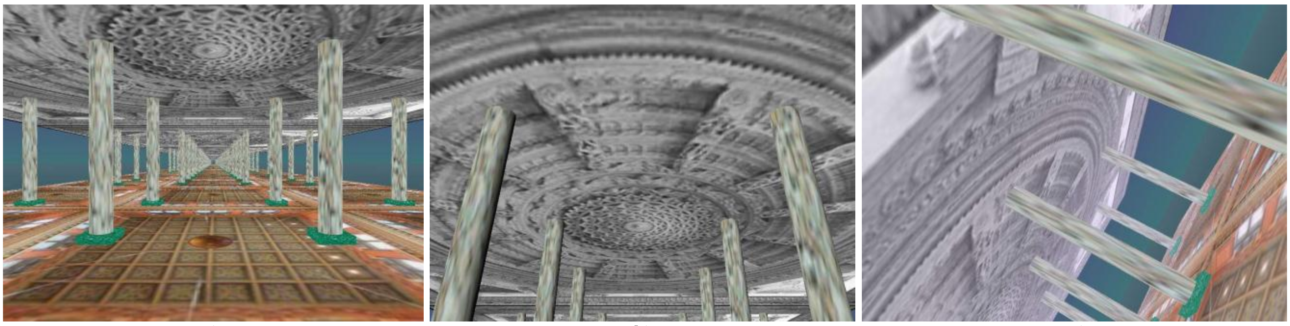
***Postural control, balance, force platform, posturography, stabilometry, centre of pressure, visual stimulation, virtual reality.***

## 1. Introduction

A human body in upright standing can be modeled as an inverted pendulum: the centre of mass of the body is located above the base point represented by the ankle joints. Equilibrium state of the inverted pendulum is, by its nature, an unstable constitution. Therefore, maintenance of upright standing must be ensured by an ingenious control mechanism. Postural control is thus a complex process, which includes proprioceptive, vestibular and visual sensory systems. All of these sensory inputs are „integrated“ by the central nervous system to provide a control signal continually correcting action of the mechanical effectors. If some sensory system is altered by disease, injury or aging, or if central controller output is inappropriate, a person exhibits postural instability or even it can fall. Falls can significantly affect the quality of life, especially in elderly peoples.

Balance is clinically assessed by posturography [1] The most commonly available posturographic apparatus is a static force platform. The force platform measures coordinate of the centre of pressure (COP) that is related to the centre of mass (COM) projected on the ground plane. Changing experimental conditions, effects of individual sensory cues can be studied. Among sensory branches of the postural control feedback system mentioned above, this work is concentrated on visual cues. The simplest way to document the importance of vision in the postural control is a comparison of posturographic parameters measured when eyes are open and closed. More valuable information can be obtained by means of studying postural responses to specifically designed visual stimuli.

Researchers use various technologies to elicit a visual stimulus, such as analog mechano-optical systems, controlled mechanically driven moving patterns [2], or apparatuses based on digital technology, such as virtual reality environments [3], [4], with images projected on screens, HMD (head mounted displays), or expensive special purpose projection systems, such as those known under recursive acronyms CAVE [5], NAVE [6], BNAVE [7]. Proposed experimental system exploits, except the force platform, only general purpose, commercially available components, comprising of a single PC with dual graphic output, projector and rear projection screen.



a) b) c)

**Fig. 1:** Design of visual stimuli: a) insight into scene, b) effect of camera elevation in AP scene, α = 31 ° , c) ML scene snapshot corresponding to angle φ = 60 °.

The measuring system is PC-based, where PC provides measurement control, communicates with DAQ hardware, controls presentation of sequences of visual stimuli and provides videosignal for projector. Visual stimuli were created by moving the virtual camera over the static scene defined in VRML format (Virtual Reality Modeling Language). Measured stabilograms were processed to extract selected posturographic parameters.

Outline of the paper is as follows. Section 2 explains concepts of visual stimuli composition. In Section 3, components of the proposed measurement system and experimental procedure are described, including sample measured stabilograms and velocity waveforms. Section 4 presents group-averaged waveforms and provides statistical comparison of selected posturographic parameters evaluated before and during stimulation.

## 2. Stimulus Composition

Visual scenes used for moving stimuli were composed from 3D objects defined in VRML format (VRML97 standard), displayed by means of Virtual Reality Toolbox (Matlab). The scene consists of floor and ceil separated by 6,1 m distance and pillars placed at regular distance 6 m. Objects are filled by color textures. Insight into the scene is shown in Fig. 1a).

Moving scenes were created by translational and rotational movement of a camera over static scene described above. Camera position, look direction and orientation are defined by three vectors in Virtual Reality Toolbox notation. VRML uses Cartesian coordinate system, where Z-axis comes out of screen, X-axis is horizontal and Y-axis is vertical; standard spatial unit in VRML is meter. These three vectors are: *CameraPosition* $\boldsymbol{c}_{\mathrm{pos}}$ (specifies the position of point from which the scene is viewed), *CameraDirection* $\boldsymbol{c}_{\mathrm{dir}}$ (pan and tilt the camera) and *CameraUpVector* $\boldsymbol{c}_{\mathrm{up}}$ (roll the camera, this vector projected on the imaging plane corresponds to the vertical direction oriented up).

Two types of movement scene were considered for our experiments, which are expected to induce body sway in the anterior-posterior direction (AP scene) and medial-lateral direction (ML scene). Special attention was given, in contrast to similar research works in the topic of this paper, to avoid the possibility of fixation, i.e. no stationary point can be found in a visible area of the moving scene. Therefore, simple translation and roll of the camera in the scene does not meet this requirement and proper camera direction adjustment must be involved.

AP scene stimulus was created by linear motion of the elevated camera along Z-axis direction at constant velocity $v_z$ [m·s$^{-1}$] of the camera in the virtual scene

$$\boldsymbol{c}_{pos}(t) = [x_0, y_0, z_0 \pm v_z t]. \tag{1}$$

It can be found by projective geometry and pinhole camera model, that the vertical component of the velocity in the central part of the projection screen $v_{y0}$ [m·s$^{-1}$] is

$$v_{y0} = \frac{v_z}{d}\sin(\alpha)^2 \tfrac{3}{4} W_{screen} \frac{1}{2\tan(FOV_V/2)}, \tag{2}$$

where $d$ is the vertical distance of the camera from ceiling, $W_{\mathrm{screen}}$ is screen width, 3:4 is image height-to-width ratio, $FOV_{\mathrm{v}}$ [rad] denotes vertical field of view angle, and $\alpha$ is camera elevation angle specified indirectly by *CameraDirection* vector

$$\boldsymbol{c}_{dir} = [0, \tan(\alpha), -1]. \tag{3}$$

ML scene requires concurrent manipulation of *CameraDirection* as well as *CameraUpVector* to keep stationary point out of the visible area:

$$\boldsymbol{c}_{dir}(t) = [\tan(\alpha)\sin(\varphi), \tan(\alpha)\cos(\varphi), -1], \tag{4}$$

$$\boldsymbol{c}_{up}(t) = [\sin(\varphi), \cos(\varphi), 0], \tag{5}$$

$$\varphi = \pm\omega t, \tag{6}$$

where $\omega$ denotes angular velocity [rad·s$^{-1}$] of scene rotation. Linear velocity in the central point of the screen is

$$v_{x0} = \omega \sin(\alpha) \tfrac{3}{4} W_{screen} \frac{1}{2\tan(FOV_V/2)}. \tag{7}$$

Effects of described camera manipulations on camera image can be seen in Fig. 1b), c).

# 3. Experimental Methods

## 3.1. Measurement System

The measurement system is constituted by force platform, data acquisition card, PC, projector and back projection screen (Fig. 2). A force platform is a rigid platform supported in 3 or 4 points in which load cells are located that produce signals used for calculation of COP coordinates. The force platform used in our system was developed by the Institute of Normal and Pathological Physiology, Slovak Academy of Sciences, and produces two analog signals proportional to deviations of COP in medial-lateral (ML, x) and anterior-posterior (AP, y) directions. Signals are digitized at a sampling rate 100 Hz by means of NI USB-6008, 12-bit data acquisition device. Whole measurement is controlled from Matlab environment, by means of the program that displays graphic user interface on the primary monitor. The secondary monitor is used for playing videostimulus, projected on the translucent screen. The projector is standard DLP type, with a refresh rate of at least 60 Hz for smooth playing fast moving scenes at 60 fps, with a native resolution 1024×768 points and throw ratio 1,8. Measured subjects were standing close to the projection screen (at a distance of about 50 cm) to maximize field of view, because peripheral vision plays an important role in postural control [4].

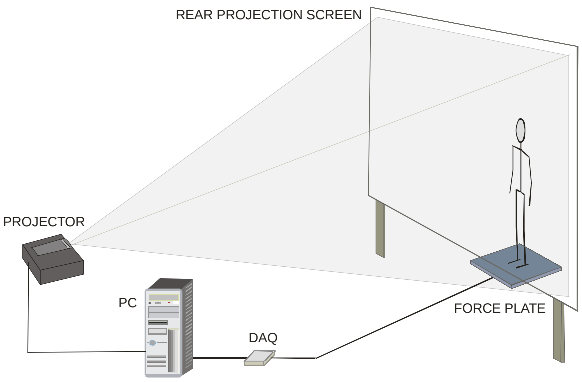



**Fig. 2:** Components of the proposed measurement system.

## 3.2. Experimental Procedure

Each of participant undergone a measurement protocol, that consists of presentation 4 scenes (AP forward and backward directions, ML left and right directions). Direction of movement was controlled by sign in equations (1) and (6).

For AP scene, values used for its design in the virtual world were $v_z$ = 10 m·s$^{-1}$, $d$ = 5,1 m, elevation angle 31 °, $FOV_v$ = 45 °, that yields central velocity 0,89 m·s$^{-1}$ on 1,9 m-wide projection screen. Velocity increases linearly with respect to $x$ (horizontal) and quadratically with respect to $y$ (vertical) coordinate of the projection screen, giving average vertical velocity component 1,04 m·s$^{-1}$ and average vector magnitude velocity 1,14 m·s$^{-1}$. In the case of ML scenes we used angular velocity 72 °·s$^{-1}$ that produces velocity 1,11 m·s$^{-1}$ measured at central area of the screen.

Each measurement scene was presented 5 times, with randomly changed direction of movement to suppress subject adaptation to the scene. A single measurement starts with 10 s pre-stimulus period (static scene), continued with 10 s stimulation (moving scene) and 30 s post-stimulation period (static scene). Baseline of each measured stabilogram was corrected by subtraction the time-averaged value computed from pre-stimulus period. Sample postural responses can be observed in Fig. 3. Stimulation period is delineated by gray lines. Backward scene in the figure caption refers to patterns moving outwards screen (towards the subject), the scene forms a contracting pattern, and vice versa in the case of forward scene. Scenes denoted as right and left are characterized by x-component of velocity pointing to right and left directions, respectively. Positive deflections in x and y component of a stabilogram correspond to subject deviation in right and forward direction, respectively.

Whereas stabilogram waveforms are useful for body sway evaluation, absolute values of sway velocities characterize an effort to maintain stability. Sway velocities can be evaluated separately for ML and AP directions:

$$v_x[n] = \frac{1}{D\,T}\left|x[n] - x[n-D]\right|, \tag{8}$$

$$v_y[n] = \frac{1}{DT}\left|y[n] - y[n-D]\right|, \tag{9}$$

where $T$ denotes sampling period, $x[n]$ and $y[n]$ are ML and AP components of stabilograms, respectively, and $D$ represents time step used to derivative estimation. The quantities computed by (8), (9) are smoothed to reduce contributions of intrinsic variability of stabilogram

$$\bar{v}_x[n] = v_x[n] * h[n], \tag{10}$$

$$v_y[n] = v_y[n] * h[n], \tag{11}$$

where $h[n]$ denotes a smoothing convolution kernel.

Sample postural responses in terms of smoothed sway velocities are shown in Fig. 4. Velocities computed according to (8), (9) were processed by rectangular moving average window of 1 s duration in (10), (11), applied in order to suppress large random variations observed in instantaneous velocities.

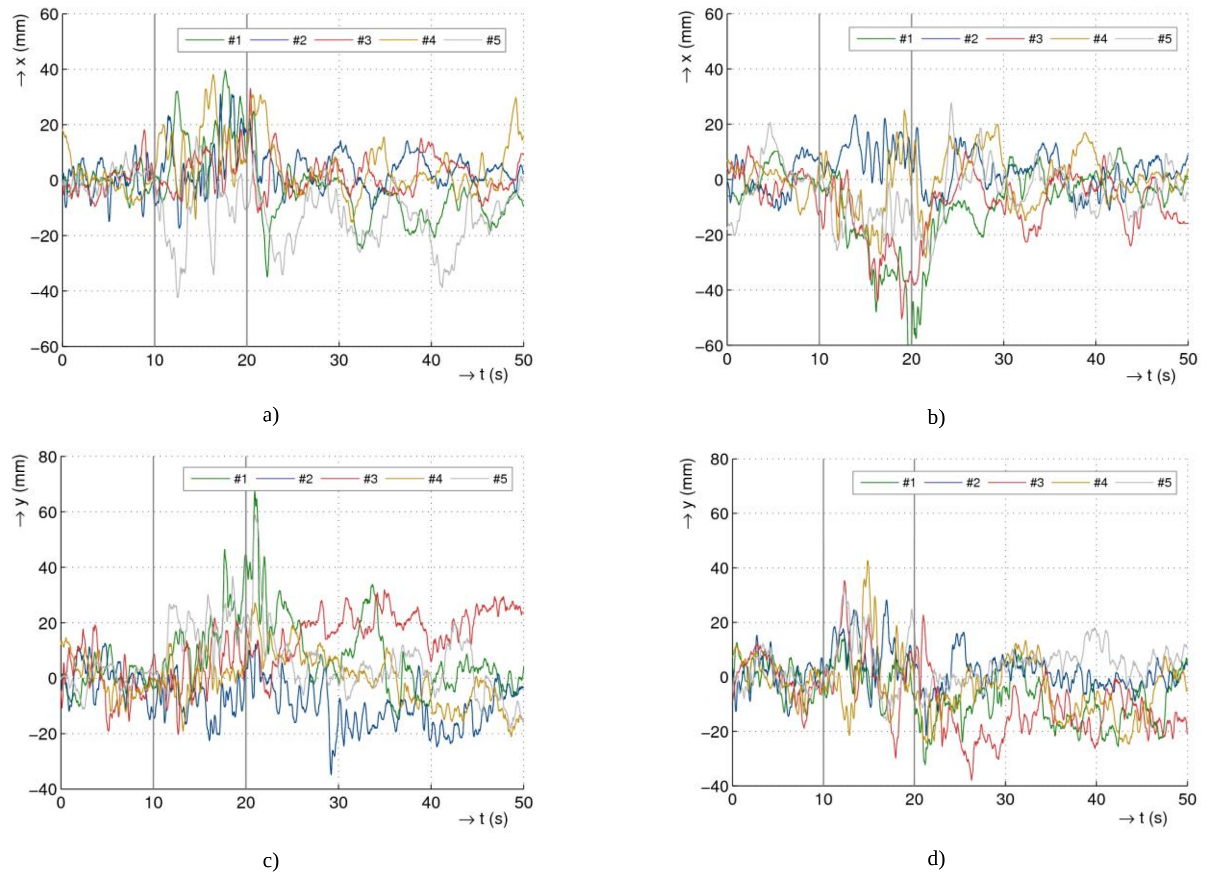



**Fig. 3:** Sample sway responses for specific scenes: a) ML-Right, b) ML-Left, c) AP-forward, d) AP-backward; 5 measurements.

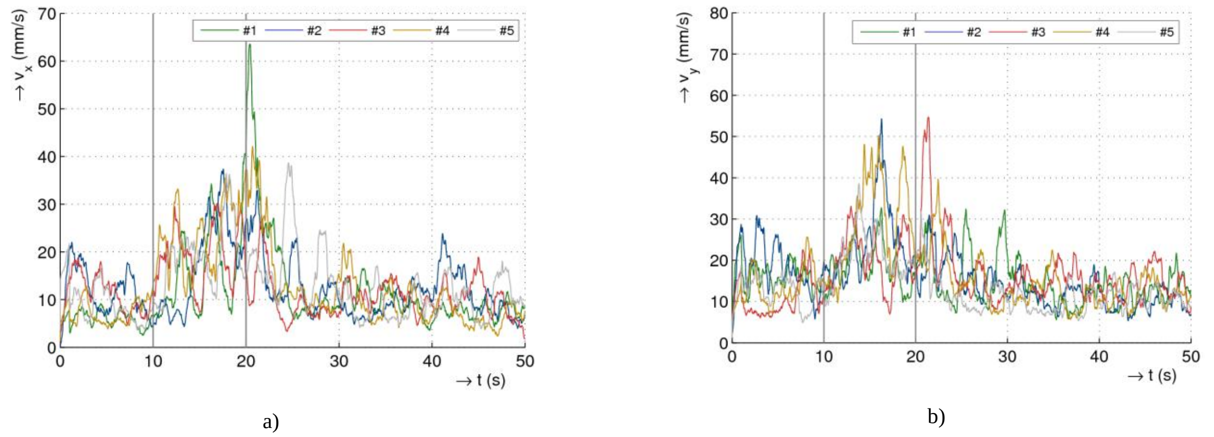
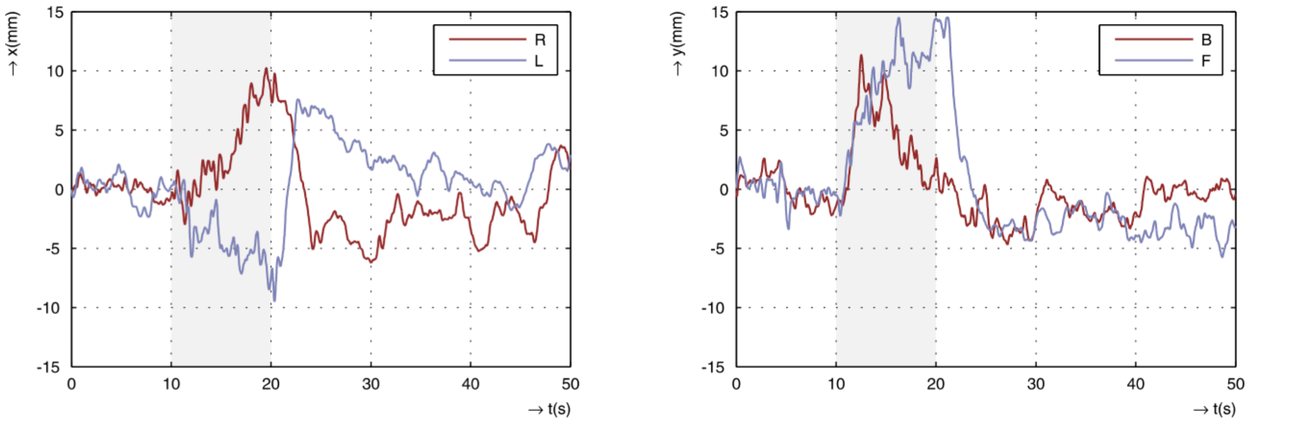



**Fig. 4:** Sample velocity responses (rectified and time smoothed): a) ML scene; b) AP scene; 5 measurements.

# 4. Results and Discussion

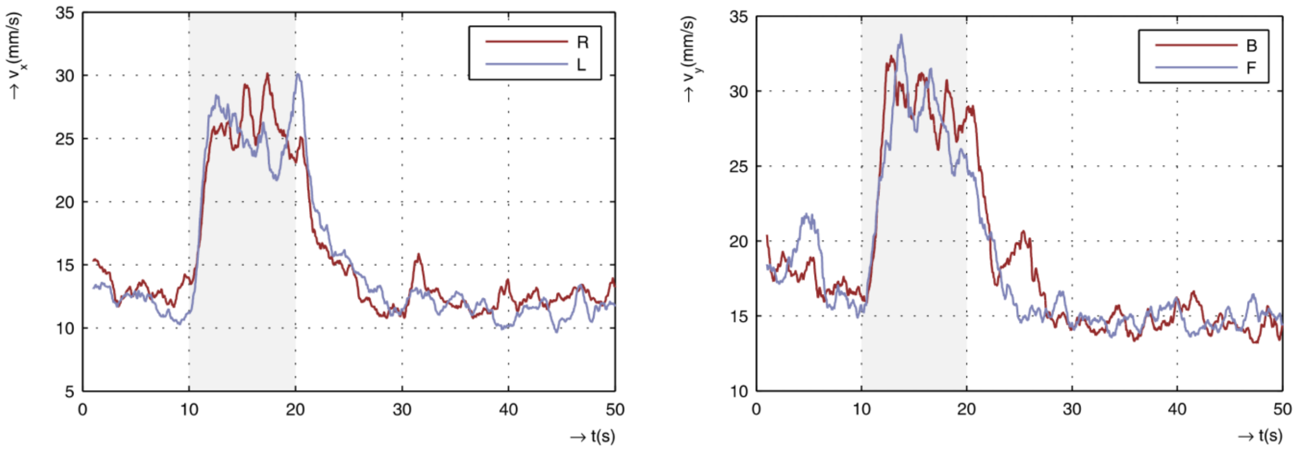
Postural responses to the designed stimuli were measured in a group of healthy persons. All repeated measurements for a particular scene were averaged. Individual responses corresponding to a particular scene type and orientation were then group-averaged, that allowed to observe general behavior of the human postural control system. Fig. 5 depicts averaged responses for 7 subjects. Stimulation period is highlighted by gray filled areas. The body vector deviation is related to the direction of visual stimuli. It is interesting to note initial positive deflection of the stabilograms both for forward and backward moving scenes. Such a phenomenon was observed also in [3]. After this transient, the body sway is directed concordantly with scene direction.

The velocity waveforms shown in Fig. 6 can be related to increased effort to maintain stable stance during stimulation. The increased sway velocity during visual stimulation reflects central postural controller ability to cope with "false visual information".




a) b)

**Fig. 5:** Group-averaged and time-smoothed stabilogram for ML (R-right, L-left) scenes a); AP (B-backward, F-forward) scenes b).




a) b)

**Fig. 6:** Group-averaged and time-smoothed velocity for ML (R-right, L-left) scenes a); AP (B-backward, F-forward) scenes b).

Beside visual inspection of stabilograms (i.e. COP coordinate signals), effect of visual stimulation on postural changes can be documented and quantified by means of posturographic parameters derived from measured data. Posturographic parameters are evaluated from segments of duration of 10 s selected in pre-stimulus period and in the period with stimulus present. Velocity components can be combined into vector magnitude velocity, which integrated over a specified time period, yields so called line integral posturographic parameter. The line integral (LI [mm]) express length of COP trajectory excursed during the specified time period, consisting of $N$ samples of the stabilogram

$$LI = \sum_{n=1}^{N-1} \sqrt{(x[n]-x[n-1])^2 + (y[n]-y[n-1])^2} \ . \quad (12)$$

Overall time variability of a stabilogram segment is characterized by $RMS$ parameter defined as

$$RMS = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}(x[n]-x_0)^2 + (y[n]-y_0)^2} \ , \quad (13)$$

where $x_0$ and $y_0$ are time averages over analyzed segment.

Results of group-averaged parameters are summarized in Tab. 1, Tab. 2. LI as well as RMS evaluated during stimulation period significantly increased when compared to pre-stimulus values of the parameter. Paired t-test was used to evaluate parameter changes due to stimulation.

**Tab.1:** Effect of visual stimulation on line integral parameter.

| Scene | $LI_0$ [mm] | $LI_1$ [mm] | $LI_d$ [mm] | *P*-value |
|---|---|---|---|---|
| B | 247 | 373 | 127 | $8{,}5 \cdot 10^{-4}$ |
| F | 250 | 367 | 117 | $2{,}0 \cdot 10^{-3}$ |
| L | 232 | 397 | 165 | $2{,}4 \cdot 10^{-3}$ |
| R | 261 | 416 | 155 | $5{,}6 \cdot 10^{-4}$ |

$LI_0$ – pre-stimulus line integral, group average; $LI_1$ – intra-stimulus line integral, group average; $LI_d$ – difference $LI_1 - LI_0$; P-value evaluated by means of two-tailed paired t-test

**Tab.2:** Effect of visual stimulation on RMS parameter.

| Scene | $RMS_0$ [mm] | $RMS_1$ [mm] | $RMS_d$ [mm] | *P*-value |
|---|---|---|---|---|
| B | 7,7 | 11,6 | 3,9 | 0,005 |
| F | 7,9 | 11,8 | 3,9 | $2{,}0 \cdot 10^{-4}$ |
| L | 8,1 | 12,3 | 4,2 | 0,011 |
| R | 8,7 | 11,9 | 3,2 | 0,010 |
| $RMS_0$ – pre-stimulus RMS, group average; $RMS_1$ – intra-stimulus RMS, group average; $RMS_d$ – difference $RMS_1 - RMS_0$; P-value evaluated by means of two-tailed paired t-test | | | | |

## 5. Conclusion

In this paper, we have proposed measurement system and experimental procedure for measurement of postural responses to visual stimuli. Presented measurements document that developed system and designed visual stimuli are effective in inducing postural responses and allow their quantification in terms of posturographic parameters. Experimental data indicate that a person is, after stimulus onset, directed to sway in the same direction as it is the direction of scene movement. This finding is consistent with negative feedback concept, i.e. postural response tends to reduce retinal optic flow. Maintenance of balance during stimulation requires increased effort when compared to a stationary scene condition that is manifested by elevated posturographic parameters.

Proposed methods give insight into control mechanism involved in maintaining human body balance, which is of active clinical importance with regard to assessing a risk of falls.

## Acknowledgements

This work was supported by the Ministry of Health of the Slovak Republic under the grant MZ 2007/67-FNsPBA-05 and by the Ministry of Education of Slovak Republic under the grant VEGA No. 1/0987/12.

## References

[1] DUARTE, Marcos and Sandra M.S.F FREITAS. Revision of Posturography Based on Force Plate for Balance Evaluation. *Revista Brasileira de Fisioterapia*. 2010, vol. 14, no. 3, pp. 183–192. ISSN 1413-3555.

[2] ADAMCOVA, Nada and Frantisek HLAVACKA. Modification of Human Postural Responses to Soleus Muscle Vibration by Rotation of Visual Scene. *Gait & Posture*. 2007, vol. 25, iss. 1, pp. 99–105. ISSN 0966-6362.

[3] TOSSAVAINEN, Timo, Esko TOPPILA, Ilmari PYYKKO, Pia M. FORSMAN, Martti JUHOLA and Jukka STARCK. Virtual Reality in Posturography. *IEEE Transactions on Information Technology in Biomedicine*. 2006, vol. 10, no. 2, pp. 282-292. ISSN 1089-7771.

[4] STREEPEY, Jefferson W., Robert V. KENYON and Emily A. KESHNER. Field of View and Base of Support Width Influence Postural Responses to Visual Stimuli During Quiet Stance. *Gait & Posture*. 2007, vol. 25, iss. 1, pp. 49–55. ISSN 0966-6362.

[5] CRUZ-NEIRA, Carolina, Daniel J. SANDIN, Thomas A. de FANTI, Robert V. KENYON and John C. HART. The CAVE: Audio Visual Experience Automatic Virtual Environment. *Communications of the ACM*. 1992, vol. 35, iss. 6, pp. 64–72. ISSN 0001-0782. DOI:10.1145/129888.129892.

[6] PAIR, Jarrell, Carlos JENSEN, Julian FLORES, Jeff WILSON, Larry HODGES and Dave GOTZ. The NAVE: Design and Implementation of a Non-Expensive Immersive Virtual Environment. In: *Siggraph 2000 Sketches and Applications*. New York, NY, USA: ACM Press/Addison-Wesley Publishing Co., 2000, pp. 238. ISBN 1-58113-208-5.

[7] JACOBSON, Jeffrey, Mark S. REDFERN, Joseph M. FURMAN, Susan L. WHITNEY, Patrick J. SPARTO, Jeffrey B. WILSON and Larry F. HODGES. The Balance NAVE: A Virtual Reality Facility for Research and Rehabilitation of Balance Disorders. In: *Proceedings of the ACM Symposium on Virtual Reality Software and Technology 2001*. New York, NY, USA: ACM, 2001, pp. 103-109. ISBN 1-58113-427-4.

## About Authors

**Jozef PUCIK** was born in Bratislava, Slovakia, in 1972. He obtained the M.Sc. degree in 1996 and the Ph.D. degree in 2000 in electrical engineering from the Slovak University of Technology in Bratislava. Currently, he is a lecturer at the Institute of Electronics and Photonics, Faculty of Electrical Engineering and Information Technology of the Slovak University of Technology in Bratislava. His main field of interest covers digital signal processing, especially biomedical signal processing.

**Marian SALING** was born in 1948. He received his M.D. in 1972 and the Ph.D. in Normal and Pathological physiology in 1986 from Slovak Academy of Sciences. He is chief of clinical neurophysiological laboratory. His research interests include motor and posture control, also movement disorders.

**Stanislav LOVAS** was born in Nitra in 1982. He graduated from Slovak University of Technology specializing in bioelectronics in 2006. Since then he is working on several projects relating to postural control research. He co-worked with specialized teams on II. Neurologic clinic, Faculty of Medicine, Comenius University in Bratislava and Laboratory of Motor Control, Institute of Normal and Pathological Physiology in Slovak Academy of Sciences.

**Martin KUCHARIK** was born in 1981. He received his M.D. from Charles University in Prague, 1st faculty of medicine in 2006. His research activities include posturography and movement disorders.

**Oldrich ONDRACEK** was born in Prague, Czech

Republic, in 1950. He received his M.Sc. from FEI SUT Bratislava in 1974; Ph.D. in 1983 and Assoc. Prof. in 1991. His research interests include analog and digital signal processing.

**Elena COCHEROVA** was born in Trencin in 1970. She received her M.Sc. degree in radioelectronics in 1993 and Ph.D. degree in electronics (2002) from the Faculty of Electrical Engineering and Information Technology (FEI), the Slovak University of Technology (SUT) in Bratislava. Her research interests include biosignal processing, simulation of electrical activities of the cells and health aspects of non-ionizing radiation.