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From stochasticism to determinism in evaluation of human postural responses

Boris Barbolyas, Cyril Belavý
Ján Vachálek, Ladislav Dedík
Institute of Automation, Measurement and Applied Informatics, Faculty of Mechanical Engineering
Slovak University of Technology in Bratislava
boris.barbolyas@stuba.sk

Diana Bzdúšková
Institute of Normal and Pathological Physiology
Slovak Academy of Sciences
Bratislava, Slovakia

Abstract — **The Center of Pressure (COP) signal is a kind of human postural response and it is an established indicator of human ability to maintain balanced posture. Its form of the statokinesigram has complicated profile, which suggests stochastic or chaotic nature of COP movement. Here is presented developed statokinesigram trajectory (DST) as a basis of method for human postural response analysis. Since DST does not show signs of stochastic behavior it is suitable for modeling with help of linear system theory. In this study, volunteer's postural responses were affected by bilateral vibration stimuli of Achilles tendons. This vibration stimulus causes nonlinear response in anterior-posterior direction. DST allows to analyze this phenomenon through mathematical model in form of a transfer function. Its estimated parameters are useful in evaluation of human posture control.**

Keywords — COP; chaos; posture; vibrations

I. INTRODUCTION

Research groups from different fields of interest are dealing with human postural control. Most significant contributions to this research area are obviously from researchers with neurophysiological background [1], [2]. Recently, new findings have been produced with collaboration of neurophysiologists, clinicians and engineers with background of system theory, systems identification [3], [4], humanoid robotics [5], [6], [7] and rehabilitation robotics [8], [9], [10]. It is known that human balance is controlled in biological feedback from central nervous system (CNS). Feature of feedback mechanism is important indication of every cybernetic system [12]. Sensory information about actual position of center of body mass and position of body segment in space is provided to central nervous system with somatosensory, visual and vestibular sensory channels. Skeleton muscles are working as position actuators of human body. CNS, sensory systems, skeleton and its muscles are basic elements of human postural system, which main role is to maintain balance utilizing synergy of mentioned sensory channels. Defects of any sensory channel or neurological disease may affect ability to maintain upright stance posture. Two main external indicators of balance control are widely used, the center of mass (COM) and the center of pressure (COP) signals. COP is defined as point of ground reaction forces on support surface [3]. Modifying of COP position, may one control the position of COM too [13]. Raw COP signal in form of statokinesigram shows complicated trajectory, even in quiet stance. This indicates that maintaining bipedal upright stance posture is a complex motor task, since COP is continuously moving. Naturally, complexity of postural response depends on postural conditions including quality of support surface [13].

Very basic analytical steps like to determine the COP amplitudes from statokinesigram decomposed into anterior-posterior (AP) and medio-lateral (ML) directions, or the area of full statokinesigram, provide brief notion about subject´s ability to maintain balance. However, more sophisticated methods of postural response analysis provide insight into the mechanisms of human postural control. In late eighties, method for analysis of human postural dynamics based on mechanisms of single inverted pendulum was presented [15]. This mechanism embodies ankle strategy of COM stabilization. Postural control is quantified through physiological interpretable parameters of designed transfer function, which provides estimation of ankle torque necessary for stabilization of the COM in dynamic equilibrium. Model of postural system dynamics based on dynamics of single inverted pendulum was used in design of the Independent channels model too [16]. Sensory information weighting concept was included in this model. Since this model resembled dynamical behavior of human postural response in frequency domain, it was a successful application of system theory in research area of human postural control. Latest important achievements in modeling of the human postural control are presented by Disturbance Estimation and Compensation model (DEC) [5] and its modification [17], [18]. Since, DEC model is an integrated part of humanoid control system, humanoid mimic's dynamic behavior of real human subject providing solutions applicable in designing of assistive devices or exoskeletons [9], [11]. Pierce et al. [7] provide another example of robotics dealing with posture control. Alongside the modeling of postural control dedicated on simulations and control of humanoids, numerical methods for analysis of postural response is designed to analyze human dynamic behavior. Measured signals analysis allows to evaluate and describe quality of postural control in humans. In addition, it serves as a tool to reveal hidden pathological states in humans without postural disorder, to quantify degree of pathological state in rehabilitation, as well as to predict pathology in humans with postural disorder. Since,

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statokinesigram is similar to Brownian motion and it appears like stochastic process, there was an effort to analyze it through the fractional Brownian motion [19]. The goal was to determine dynamic features of COP behavior, and the level of randomness in statokinesigram, which may reflect instability of postural system. The heading change parameter deals with two directional natures (AP, ML) of COP motion and follows directional changes in meaning of their rate [20]. Horak and Macpherson [1], Engelhart et al. [3], Hettich et al. [17], Abrahamová et al. [21], Dzurková and Hlavačka [22] provide with a good overview of available methods for postural response analysis in time and frequency domain.

We were interested in finding the order in statokinesigram as total COP response. While COP has apparent stochastic nature hereby it is meaningful for overall posture control. We use the approach of experimental identification of developed statokinesigram trajectory (DST) and evaluate COP control through its fundamental features like COP position and velocity. In our previous studies, we showed that DST may provide useful information for quantification and classification of subjects [23], [24]. Presented study is aimed on structural sequential modeling of DST of subject bilaterally stimulated by vibration on Achilles tendons during upright stance, and estimation of model parameters. It is known that vibration stimulation causes kinesiology illusion of movement and subject compensates this illusion with body leaning around ankle joint [25]. The AP component of statokinesigram exerts nonlinear time profile, and full statokinesigram has complex profile too. On the other hand, statokinesigram in form of DST shows any complicated parts and it is suitable for modeling. In addition, DST takes into account AP and ML direction of COP together, so the information about postural response dynamic is not reduced. According to DST we can clearly distinguish between three main phases of postural system response as a pre-vibration, vibration and post-vibration response. Interestingly, individual phases have quasi linear time profile. This suggests constant velocity of COP motion in individual phases (due to linear development of COP trajectory in time dependence). According to this finding, the model of constant velocities in form of a transfer function was designed. In real world conditions, COM velocity has a critical meaning for posture stabilization. This feature is also transferred on COP. In our study, COP velocity is considered as a controlled quantity of postural system. From this point we are able to distinguish steady states of posture equilibrium, where COP has constant velocity (Fig. 1).

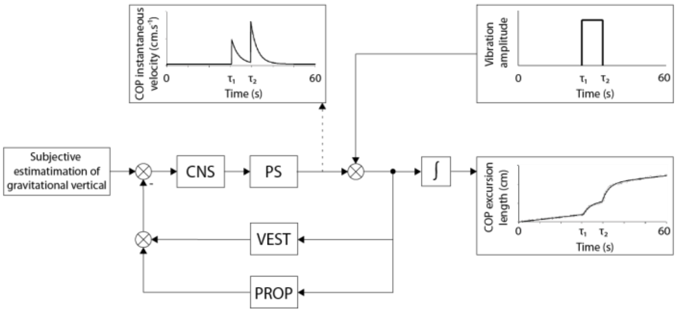

Fig. 1. Block diagram of COP velocity control (CNS - central nervous system, PS - postural system, VEST - vestibular input, PROP - proprioceptive input).

II. MATERIALS AND METHODS

A. Participants

Nine young (aged 25.5±2.1 years) and 9 older (aged 64.5±7.8 years) healthy adults participated in this study. The participants did not reported any musculoskeletal or neurological disorders related to postural balance. All participants consented to record their COP signal and to process the output signals for academic purposes. The procedures of this study were performed in accordance with ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments, or with comparable ethical standards. Trials with human participants were approved by Ethical committee in Institute of Normal and Pathological Physiology, Slovak Academy of Sciences (Ethical Committee INPP SAS).

B. Procedures

Participants were instructed to maintain bipedal quiet upright stance, with heels aligned with hips, on firm and foam support surface. Recording of postural responses in each trial lasted 60 s. Postural responses were registered in form of COP signal by the force platform with sampling frequency of 60 Hz. Subjects stood with eyes closed, so sensory information was limited to somatosensory and vestibular inputs. Somatosensory information was affected by bilateral vibration of Achilles tendons. Vibration was produced with two DC motors with eccentricity. Exciting vibration frequency was set on 60 Hz. Vibration stimuli lasted 10 s and it started 30 s after the onset of trial. Participant repeated each trial three times in random order.

C. Data analysis

All measured postural responses had profile similar to which is shown in Fig. 2A. Time series of measured data were reduced using a data-number reduction algorithm applied in custom-made software CTDB (Clinical Trials Data Base) [26]. Data reduction is helpful for acceleration of estimation algorithm as well as reduction of noisy data samples from measured data and for imaging and interpretation. The reduced statokinesigram acquired the profile shown in Fig. 2B. Subsequently, this was used for construction of DST according to,

$$S(t_k) = \sum_{k=1}^{n} \sqrt{\begin{matrix} \left(COPX(t_k) - COPX(t_{k-1})\right)^2 \\ +(COPY(t_k) - COPY(t_{k-1}))^2 \end{matrix}} \qquad (1)$$

where $COPX(t_k)$ and $COPY(t_k)$ are coordinates of COP in medio-lateral (ML) and anterior-posterior (AP) direction on statokinesigram in time t_k, respectively.

Instantaneous velocities of COP $V_k(t)$ were calculated as follows

$$V(t_k) = \sqrt{(V_{CoPX}^2(t_k) + V_{CoPY}^2(t_k))^2} \qquad (2)$$

Relation between vibration input applied on Achilles tendon of postural system and postural response, may be mathematically described from recorded subjects postural responses, as follows

$$H_{DST}(\mathrm{s}) = \frac{\frac{S_{max}}{s^2}(\alpha.e^{-t_1 s}+\beta.e^{-t_2 s})\cdot\frac{1}{Ts+1}}{A\cdot\frac{e^{-t_1 s}-e^{-t_2 s}}{s}} \tag{3}$$

where S_{max} is maximal length of COP trajectory, A is a vibration amplitude (equal 1), T is a time constant, α and β are gain factors of DST at pre- and post- vibration phases, t_1 and t_2 is time of vibration onset and offset, respectively, s is Laplace operator [24].

A mathematical model in form of transfer function was fit on DST (Fig. 3).

$$H_F(s) = \frac{G_i}{T_i s+1} e^{-\tau_i s} \tag{4}$$

where G is gain of COP trajectory, T is time constant, τ is a time delay, respectively, i is phase of experiment, $i = 1$ refers to vibration onset and $i = 2$ refers to vibration offset, s is Laplace operator.

Used model has a structure of simple linear system with a time delay τ [27], [28]. DST was fitted in a sequential fashion. Numerical parameters of transfer function were estimated by optimization and simulation of the Monte Carlo method. As a criterion of a fit quality was used the minimal value of Akaike's information criterion [29]. Optimized model of DST was used for estimation of optimal COP velocity over time of measurement. In order to follow the traditional evaluation of measurement, length of COP trajectory in individual trials was determined. Velocity of COP movement was analyzed according to its actual time profile.

III. RESULTS

Preliminary results suggest that there are some basic types of postural reactions in situation of bipedal quiet upright stance with Achilles tendon vibration in healthy adults, in the meaning of DST model i.e.:

- model with time constants T_1 and T_2 is a most typical variant of postural response in form of DST, Fig. 3;
- model with time constant T_1 and time delay τ_1 at a vibration onset, Fig. 5;
- model without time constant T_1 at a vibration onset, Fig. 7. This variant occurred only during stance on foam support surface.

Further, DST allowed to estimate a time profile of actual velocity as a regulated quantity of human postural control in a time dependence (Fig. 8). Fig. 8A, 8B, 8C are derived from Fig. 3, Fig. 5 and Fig. 7, respectively.

Transient response induced by vibration onset and offset are shown as a rapid increase of COP instantaneous velocity at time of τ_1 and τ_2. Slope of DST model kept a constant value in an individual part, with exceptions of transients at τ_1 and τ_2. COP trajectory is longer during stance on foam support surface compared to standing on firm support surface (Fig. 5, Fig. 7). Paired t-test showed statistical significant difference between postural reactions during standing on foam and firm support surface, with a level of significance at 0.05.

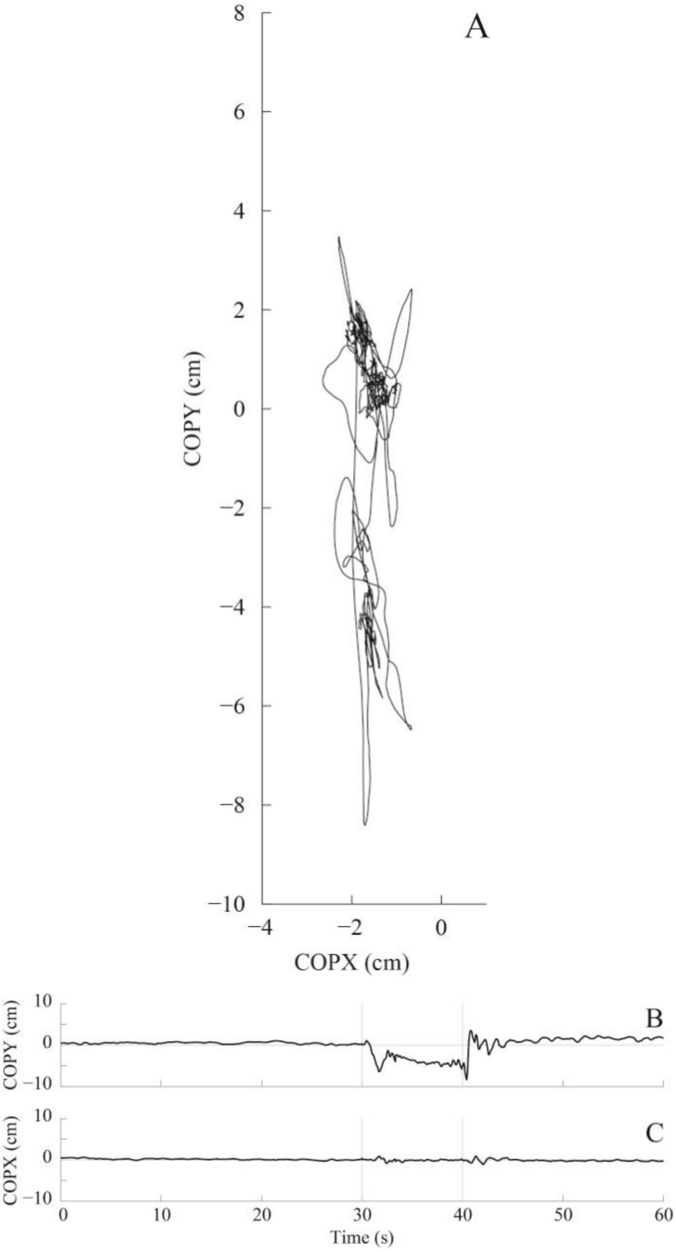

Fig. 2. Postural response of a typical young subject standing on firm support surface. A - statokinesigram; B, C - amplitudes of COP in anterior-posterior and medio-lateral direction, respectively.

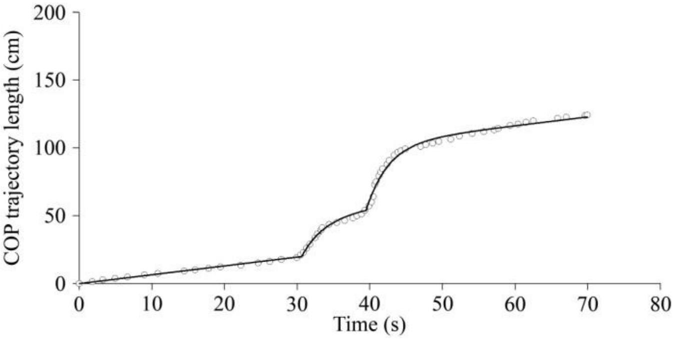

Fig. 3. Developed statokinesigram trajectory (circles) fitted by system's model (full line), constructed from Fig. 2A.

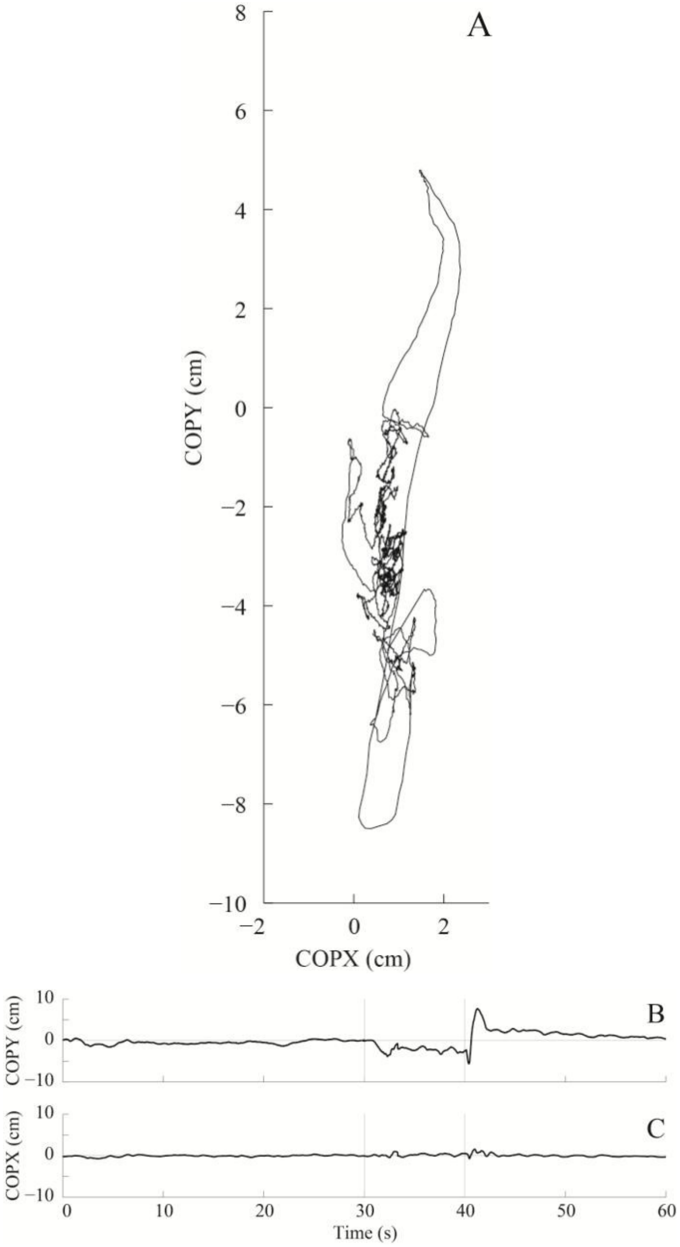

Fig. 4. Postural response of a typical old subject standing on firm support surface. A - measured statokinesigram; B, C - amplitudes of COP in anterior-posterior and medio-lateral direction, respectively.

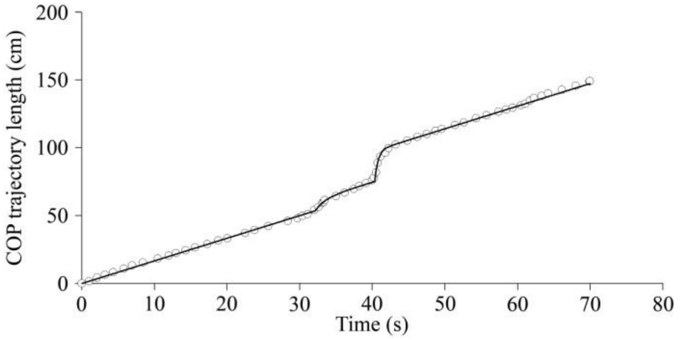

Fig. 5. Developed statokinesigram trajectory (circles) fitted by system's model (full line), constructed from Fig. 4A.

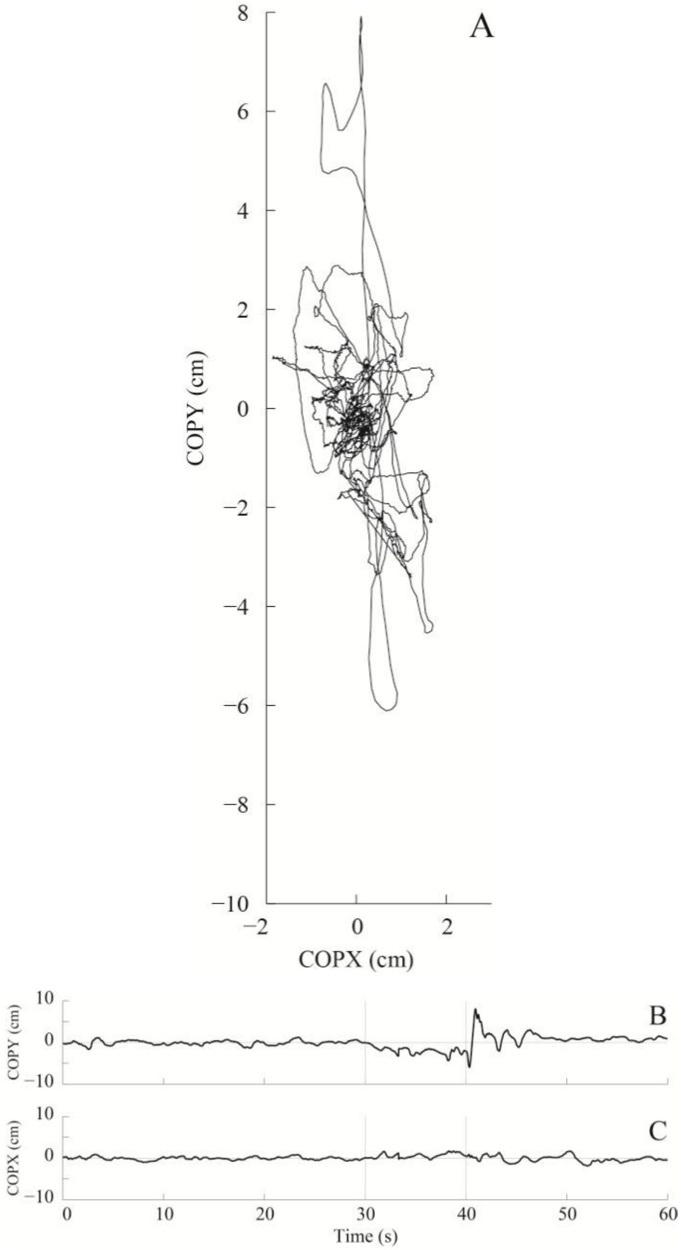

Fig. 6. Postural response of a typical young subject standing on foam support surface. A - measured statokinesigram; B, C - amplitudes of COP in anterior-posterior and medio-lateral direction, respectively.

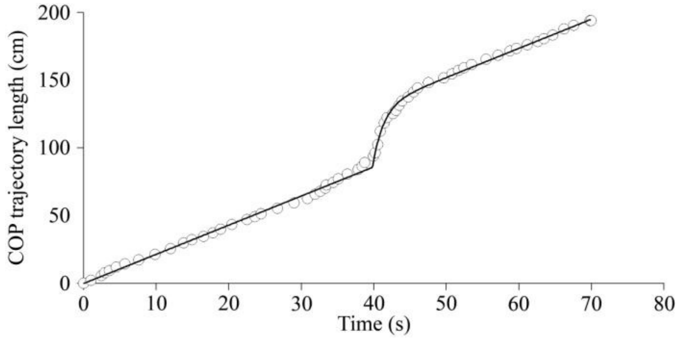

Fig. 7. Developed statokinesigram trajectory (circles) fitted by system's model (full line), constructed from Fig. 6A.

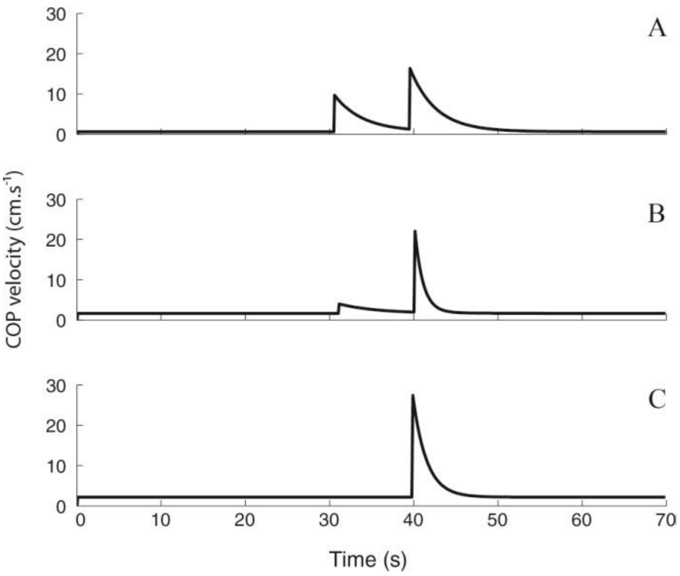

Fig. 8. Velocities of COP derived from DST models. A - COP velocity of typical young subject; B - COP velocity peak with a time delay $\tau_1 + 2$ s; C - single COP velocity peak at τ_2 .

Postural reactions differ in the values of an estimated parameter of DST model and in the actual velocity time profile, in the meaning of different type of support surface.

For young participants standing on firm support surface, the average velocity of COP 1.89±0.69 cm.s^{-1} and 1.99±0.74 cm.s^{-1}, before vibration onset and after vibration offset, respectively, was found. During standing on foam support surface, the average velocity of COP was 3.11±1.15 cm.s^{-1} and 3.03±1.19 cm.s^{-1}, before vibration onset and after vibration offset, respectively. For old participants standing on firm support surface, the average velocity of COP 1.45±0.63 cm.s^{-1} and 2.01±1.20 cm.s^{-1}, before vibration onset and after vibration offset, respectively, was found. During standing on foam support surface, the average velocity of COP was 4.81±0.73 cm.s^{-1} and 4.55±0.52 cm.s^{-1}, before vibration onset and after vibration offset, respectively.

Paired t-test showed, that there is no statistical difference in the velocity of COP movement before and after vibration onset and offset in young participants during standing on firm and foam support surface. We also found the same in old participants.

IV. DISCUSSION

With help of DST, it is possible to analyze human postural responses from a formerly chaotic statokinesigram without decomposition into anterior-posterior and medio-lateral components of postural response. This implies two main advantages - DST form of postural response does not reduce information about postural dynamics; DST application allows to analyze postural response with help of a linear systems theory [27], [28].

In present study, we suggest basic typology of DST model variants for bipedal quiet upright stance with bilateral vibration of Achilles tendons. This variation reflects sensitivity of DST model parameters. Exceptions from presented typology suggest that postural reactions include some kind of artifacts caused by different source of energy as an applied external stimulus or by a postural disorder.

We consider time constant T as an important parameter, since it reflects a dynamics of postural response to vibration onset and offset in process of upright posture stabilization. Fig. 7 represents a case, where DST could be fitted by a model with neglected (or minimal) time constant T_1. This occurred only during stance on foam surface. However, DST model of all subjects had noticeable time constant T_2, which corresponds to vibration offset. For stimulus offset, higher velocity of COP is characteristic (Fig. 8). We suggest that model with high value of T_1 indicates a slow response to stimulus due the subject's caution or sensitivity to applied external stimulus. In opposite, low value of T_1 may indicate only latent effect of vibration stimulus. Implicitly, noisy somatosensory information caused by standing on foam support surface causes higher velocity of COP and higher amplitudes of COP excursions [2]. According to T_2, postural system is sensitive to applied vibration stimulus. Kinesiology illusion disappears after vibration offset and in effort to get back into stable upright position, central nervous system controls desired position of COM. In order to fulfill this task as soon as possible, velocity of COM and COP is controlled as an impulse function (Fig. 8).

Designed DST model is useful for estimation of COP instantaneous velocity and so the actual velocity time profile as a regulated quantity of human postural control. Except the rapid increase of velocity in times τ_1 and τ_2 like impulses functions, COP has constant velocity of low level amplitude. In DST, this is shown as linear increase of COP trajectory length. Finally this led us to idea, that COP has a constant velocity in steady state.

For evaluation of this feature, slope of DST is considered in its linear parts, i.e. except transients. Previously, vibration stimulus lasting 20 s was used [23]. During this time interval of actuation, postural system reached his steady state with similar slopes and both time constants were significant. This may imply that postural system of healthy adult is in state of continuous caution checking the COM and COP positions, respectively, and it is most sensitive to onset and offset of external actuation. This is in order with a constant slope of DST in moments when external conditions are static. This suggests that for steady state of postural system during quiet upright stance, a state of dynamic equilibrium with a low amplitude velocity of COP is characteristic.

Despite that average velocity of COP before and after vibration onset and offset was not equal, there was not significant statistical difference. This suggests that COP velocity has a tendency to converge into its base value after external actuation setpoints (Fig. 8).

Even though COP is continuously moving and changing its direction [19], [20]. COP velocity control is as important as COP position control. This idea is in agreement with neurophysiological research, where muscle spindles as somatosensory receptors are sensitive to changes in position and velocity [30].

Constant velocity of COP movement during static external conditions implies an autoregulation ability of postural system and DST is proposed as tool for evaluation of this complex process. DST is easy to understand and interpret the measured data set. Since transfer function is an universal mathematical model, we chose this form as a tool for construction of the DST model to describe a dynamic behavior of postural system. DST model parameters allow to determine a basic static and dynamic parameters of an individual postural system.

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