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Evaluation of Human Postural System Dynamical Behavior via Developed Statokinesigram Trajectory

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Abstract: Presented study deals with the formulation of a model of the postural system behavior in the form of transfer function derived from Development Statokinesigram Trajectory (DST). As compared with statokinesigram, a DST shows a minimal signs of chaotic behavior while it takes anteroposterior and mediolateral postural sway direction into account together. Proposed method provides an alternative approach to established methodology based on the Center of Pressure (CoP) in evaluating the autoregulation control process in humans. For demonstration of DST application, CoP signals of young and healthy participants without and with bilateral vibration stimulus located on Achilles tendons were registered. Data analysis involves DST construction and numerical parameter estimation of the proposed model. Quadratic criterion showed that there is a disproportion between actual and mean DST time profile that was proposed as a sensitive parameter of posture control quality in all tested subjects in quiet stance condition.

Keywords: Biomedical system, Model formulation, Bio-signals analysis and interpretation, Postural system, Center of pressure

1. INTRODUCTION

Human posture is controlled by the musculoskeletal system through biological feedback over the central nervous system (Engelhart et al. 2014; Torrence & Ting 2008). Feedback mechanism is an important feature of cybernetic system (Ashby 1956). Maintaining balance is a complex task of human postural control. However, it is practically autonomous for healthy adult human, without urgent concentration on balancing task (Kandel 1991). This study will refer to it also as postural systems autoregulation. The capability of the human body to maintain balance is influenced by postural disorders (Horak & Hlavacka 2001), by age (Tanaka & Uetake 2005) or body weight (Buckova et al. 2014), which could possibly affect the sensitivity of sensory channels (mainly proprioceptive, vestibular and visual). Published studies dealing with human motor control often aim on the analysis of human posture responses in meaning of the Center of Mass (CoM) (Assländer et al. 2015) and the Center of Pressure (CoP) (Ito et al. 2003). Signal processing techniques originating in from system engineering (Mahalanabis 1982; Singh 1987) allow to analyze the human postural response signal in time or frequency domain (van der Kooij et al. 2005). This study is dealing with CoP analysis with application of system theory and system identification (Corradini et al. 1990; Dedik & Durisova 1999; Gurses et al. 2006; Ljung & Yuan 1985). Any postural change leads to the displacement of the CoP, and consequently to the change instantaneous position of CoP and its instantaneous velocity continuously during postural reaction measurements; this is also referred to as sway response. Continuous modification of CoP position which leads to dynamically stable upright bipedal stance posture indicated a continuous control of human posture (Masani et al. 2003), analogically to the inverted pendulum simplification (Peterka 2002). Raw CoP response recorded in form of statokinesigram (CoP location in Cartesian coordinate system) shows signs of chaotic behavior, due to its complexity. The CoP based method for detecting the stability of the human postural system, usually operates using statokinesigram decomposition into anteroposterior (AP) and mediolateral (ML) components. This representation shows the direction of human body tilt tendency (Lin et al. 2008; Prieto et al. 1996) or direction specified postural tilt reaction (Abrahamova et al. 2009), in situation of quiet stance posture or properly excited postural system, respectively. Parameters

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like magnitude of CoP displacement, postural sway deviation, mean velocity of CoP, maximum ground reaction forces are derived from time characteristic of human body tilt (Du Pasquier et al. 2003; Raymakers et al. 2005). Whole statokinesigram can be used to derived the instant equilibrium point, sway area, rate heading change (Rhea et al. 2014). We hypothesize that, numerical parameters derived from decomposed statokinesigram and from complex trajectory of overall statokinesigram do not provide objective information for the evaluation of postural stability or quality of postural control. Our study introduces a Developed Statokinesigram Trajectory (DST) as additional tool to the established methods for human postural response signal analysis. Presented approach for postural response analysis, involves construction of a fully developed length of statokinesigram trajectory in time dependence. Consequently, this representation of human postural response shows a minimal effect of chaotic behavior, in contrast to measured statokinesigram; and it takes into account AP and ML postural sway directions, together. These features are helpful in system identification and provide two essential advantages: 1) Postural response can be evaluated by indicative numerical parameters sensitive for hidden marks of postural system disorders. 2) Postural response can be described by the model of postural system behavior derived from DST in form of a transfer function. Proposed model is characterized by gains and time constant parameters. It is shown, how DST the looks like for situation of unperturbed bipedal quiet stance posture and for situation of bipedal stance posture perturbed by bilateral vibration of Achilles tendons. In previous study, DST was used for description of correlation between measured statokinesigram with kinematics data measured by retroreflective markers (Barbolyas et al. 2016). The aim of this study is to demonstrate alternative system approach to the assessment of human postural system properties by easily interpretable parameters derived from DST and to describe the human postural system autoregulation capability.

2. MATERIALS AND METHODS

2.1 Participants

Thirty six healthy volunteers (aged 20 to 40 years) participated in the study. The participants did not report any musculoskeletal or neurological disorders related to postural balance. According to Body Mass Index (BMI), two groups of subjects were examined in the first measurement season, in this study. The first group was comprised of fifteen lean (L) volunteers (eight female and seven males) with a $BMI = 18.5 - 25\,kg.m^{-2}$. The second group was comprised of fifteen obese (O) volunteers (seven females and eight males) with a $BMI = 25 - 40\,kg.m^{-2}$. Third group of six volunteers were examined in regard to vibration stimuli application on Achilles tendons, in the second measurement season. All the participants consented to recording their CoP signal and processing of the outputs 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.

2.2 Design of study

All postural response signals was registered by same custom made force platform in both measurement seasons. In the first measurement season, the postural stability of lean and obese subjects was tested with a stabilometric force platform under four postural conditions: 1) bipedal quiet stance on firm support surface with eyes open (EO), 2) bipedal quiet stance on firm support surface with eyes closed (EC), 3) bipedal quiet stance on foam support surface with eyes open (EOF), 4) bipedal quiet stance on foam support surface with eyes closed (ECF). Subjects were instructed to maintained stability by bipedal quiet upright stance during the tests. The tests procedures were performed under the same laboratory conditions, *i.e.* closed room without any sound or mechanical stimuli. Tested session lasted 50 s at first measurement season and sampling frequency of the CoP position was 100 Hz. In the second measurement season was tested the postural stability of a group composed of six lean volunteers in disturbed upright stance posture. Disturbance of postural control was applied by vibrators (two DC motors with eccentricity) located bilaterally on Achilles tendons. Frequency of vibration stimuli was 20, 60 and 80 Hz. Measurement lasted 60 s in the second measurement season and sampling frequency of the CoP position was 100 Hz. For comparison, it was registered postural response without stimulation before and after stimuli on set, in the second measurement season.

2.3 Data analysis

The registered CoP signals measured by force platform have a similar shape like the particular statokinesigram of lean subject shown in Fig. 1A for unperturbed stance posture; and a similar shape like the particular statokinesigram of subject shown in Fig. 4A for perturbed stance posture. The quantity of registered data was reduced using a data-number reduction algorithm applied in custom-made software CTDB (Clinical Trials Data Base) (Dedik & Durisova 1999). Data reduction was useful in improving estimation algorithm efficiency as well as the extraction of the information from a large noisy measurement data set (Dedik & Durisova 2004) and for imaging purposes. The reduced statokinesigram acquired the shape shown in Fig. 1B. A fully developed statokinesigram trajectory (DST) was constructed from a reduced statokinesigram in time dependence (Fig. 2). DST was used for determination numerical parameters quantifying measured postural response in case of bipedal quiet stance posture and for design a mathematical model in form of transfer function.

2.4 Parameters derived from DST for quiet stance posture

The time profile of the trajectory length $S(t)$ can be determined by the instantaneous velocity $V_i(t)$ of CoP displacement as follows

$$S(t) = \int_0^t V_i(t)d\tau \qquad (1)$$

The unknown instantaneous velocity $V_i(t)$ can be calculated from the measured CoP coordinates - $CoPX(t_i)$ and $CoPY(t_i)$ in the time interval t. The actual length of the