Human Movement Science 32 (2013) 48–64

Contents lists available at SciVerse ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Correlation dimension estimates of human postural sway

Senih Gurses [a,b,*], Huseyin Celik [a]

[a] Department of Engineering Sciences, Middle East Technical University, 06800 Ankara, Turkey
[b] BIOMATEN Center of Excellence in Biomaterials and Tissue Engineering, Middle East Technical University, 06800 Ankara, Turkey

ARTICLE INFO

Article history:
Available online 26 January 2013

PsycINFO classification:
2221
2240
2320
2330
2540

Keywords:
Postural sway
Center-of-pressure
Ergodicity
Correlation dimension
Optimum time delay
Aging

ABSTRACT

Human postural sway during quiet standing demonstrates a complex structured dynamics, which has been studied by applying numerous methods, such as linear system identification methods, stochastic analysis, and nonlinear system dynamics tools. Although each of the methods applied revealed some particular features of the sway data none of them have succeeded to present a global picture of the quiet stance dynamics, which probably has both stochastic and deterministic properties. In this study we have started applying ergodic theory of dynamical systems to explore statistical characteristic of the sway dynamics observed in successive trials of a subject, different subjects in an age group, and finally different age groups constituted by children, adults, and elderly subjects. Five successive 180-s long trials were performed by each of 28 subjects in four age groups at quiet stance with eyes open. Stationary and ergodic signal characteristics of five successive center of pressure time series collected from a subject in antero-posterior direction (CoP_x) were examined. 97% of the trials were found to be stationary by applying *Run Test* while children and elderly groups demonstrated significant nonstationary behavior. On the other hand 13 out of 24 subjects were found to be nonergodic. We expected to observe differences in complexity of CoP_x dynamics due to aging (Farmer, Ott, & Yorke, 1983). However linear metrics such as standard deviation and Fourier spectra of CoP_x signals did not show differences due to the age groups. Correlation dimension (D_k) estimates of stationary CoP_x signals being an invariant measure of nonlinear system dynamics were computed by using the average displacement method (Eckmann & Ruelle,

* Corresponding author at: Department of Engineering Sciences, Middle East Technical University, 06800 Ankara, Turkey. Tel.: +90 312 210 44 61; fax: +90 312 210 44 62.
E-mail address: senih@metu.edu.tr (S. Gurses).

0167-9457/$ - see front matter
http://dx.doi.org/10.1016/j.humov.2012.07.007

1985). Postural dynamics was expanded in m-dimensional space through CoP_x signal by introducing optimum time delays, $\tau_{critical}$. 112 out of 136 stationary CoP_x signals for 24 stationary subjects converged to D_k estimates. Average of D_k estimates for children and adult groups was 3.67 ± 0.28, whereas mean of D_k estimates for elderly subjects was 4.12 ± 0.59. Nonlinear metrics of postural sway ($\tau_{critical}$, $m_{saturated}$, and D_k estimates) showed significant differences with respect to the age groups. D_k estimates computed from ergodic subjects' CoP_x sway trajectories revealed that human quiet standing demonstrates multiple degree of freedom dynamics having a fractal structure with a considerable level of noise embedded in the signal whose characteristics is determined individually for each subject. Furthermore by using ergodic theory of complex systems, we have been able to show that the ability to independently control multiple degrees of freedom has been affected by aging.

1. Introduction

The human upright posture exhibits erratic motion of a complex nature described as postural sway (generally measured by recording the Center of Pressure signal; CoP) (Badii & Politi, 1997). Characteristics of the complex nature of human postural sway have been extensively investigated using linear system identification methods, stochastic processes, and nonlinear dynamical tools. Linear system approaches through inverted pendulum models with sensory feedback have been widely used in order to identify the physiological mechanisms that control and stabilize the human erect posture (Gurfinkel, Ivanenko, Levik, & Babakova, 1995; Ishida, Imai, & Fukuoka, 1997; Johansson, Magnusson, & Akesson, 1998; Massion, 1998; Mergner, 2002; Peterka, 2002). However, postural behavior is not a linear input/output system but demonstrates nonlinear response features due to multisensory fusion which manifests itself when amplitude and composition of the postural perturbation has changed (Jeka, Oie, & Kiemel, 2000; Mergner & Rosemeier, 1998; Oie, Kiemel, & Jeka, 2001, 2002).

CoP is known to be complex in the sense that it is a summary signal of the dynamics of the hierarchically structured neuro-musculo-skeletal system which can be scaled in time and space with well-known sources of nonlinearities such as redundant number of kinematic degrees-of-freedom of motion to be controlled through senses having different thresholds, latencies, and frequency responses as well as sensory-motor redundancies to control motion in a given single axis (Gurses, Dhaher, Hain, & Keshner, 2005; Mergner, 2010; Oie et al., 2002). By revealing inherent nonlinearities in the human postural control system, the inevitably complex sway pattern becomes an integral part of the postural dynamics, where a 'signature' of the individual can be searched for (Collins & De Luca, 1993; Doyle, Dugan, Humphries, & Newton, 2004; Gurses, 2002; Riccio, 1993). For example, the presence of structured, i.e., deterministic dynamics next to the random, i.e., stochastic fluctuations in CoP profiles has been shown to exist in the temporal evolution of the displacement of CoP during prolonged unconstrained standing (Duarte & Zatsiorsky, 1993, 2000, 2001). Diffusion plots generated from CoP time series indicated a fractional stochastic process with (at least) two scaling regions: a short term region (<1 s) where the time series behaved as a positively correlated random walk and a long term region (>1 and <10 s) where the time series behaved as a negatively correlated random walk (Collins & De Luca, 1993, 1994). Furthermore, depending on the decomposition of the postural control action into a slow and a fast component (rambling and trembling), Bottaro and colleagues argued the plausibility of a nonlinear control mechanism which maintains a weaker stability than asymptotic stability through intermittent stabilization (Bottaro, Casadio, Morasso, & Sanguineti, 2005; Gurses, 2002; Zatsiorsky & Duarte, 1999, 2000).

The purpose of this study was to explore the individuality of postural sway through its nonlinear metrics (Collins & De Luca, 1993; Farmer et al., 1983; Riccio, 1993). The main question that we ask is not whether human postural sway can be assumed to be a linear process even when in the vicinity of