CHARACTERISTIC PHASE PLANE PATTERN OF HUMAN POSTURAL SWAY

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Abstract: Reasons for the everlasting complex oscillatory behavior of human postural sway have been explored by constructing the phase-plane representation of the Center of Pressure data recorded experimentally. For this purpose, 275-seconds time records are received from a healthy subject while standing still in an upright posture. A Sensorial threshold has been proposed as being one of the nonlinear sources governing postural dynamics. Ethyl alcohol has also been introduced to the subject for provocation of the nonlinear behavior associated with the sensorial dynamics.

Keywords: Postural Sway, Nonlinear Dynamics, Sensorial Threshold, Phase Plane, Motor Control, Chaotic Behavior

1. INTRODUCTION

The human upright posture exhibits an everlasting oscillatory behavior of complex nature, called as the postural sway. Maintaining balance during quiet stance is a complex task accomplished by various mechanisms depending on different senses relying on the passive properties of the musculo-skeletal machinery controlled by applying different strategies. Mechanisms responsible for these oscillations are recruited by the information coming from a variety of sensory events, which include proprioceptive, vestibular, visual, and cutaneous receptors. These sensory modalities were experimentally shown to have different frequency bands (Ishida, *et al*., 1997; Mergner, 2002). The characteristic frequencies of the human postural sway have recently been reported (Gurses, *et al*., 2001).

Attempts to reveal the dynamics behind the complex nature of the oscillatory behavior of human postural sway are numerous. Johansson, *et al*. (1988) made use of the parametric identification of a transfer function representing a PID-stabilized inverted pendulum model through a set of experimental results. The application of various stochastic models (Collins and De Luca, 1994; Chow and Collins, 1995; Newell, *et al*., 1997; Chiari, *et al*., 2000) either to show the existence of long-range correlations causing fractal properties of the natural human standing (Duarte and Zatsiorsky, 2000) or to diagnose the chaotic attractor of the human postural sway during a quiet bipedal stance by calculating the largest Lyapunov exponent of the system (Yamada Norimasa, 1995) is available in the literature.

It has always been a difficult task to describe the posture and to differentiate it from the movement, per se (Massion, 1998). An ecological approach treats the postural adjustments stabilizing every kind of motor behavior acting as an interface between the organism and its environment. The approach presents an analytical perspective whose functional topological characteristics are the dynamics of the system (Riccio, 1993; Slobounov, 1997; Yamada, 1995).

The present research aims to explore the reasons behind everlasting oscillations of human upright posture. A non-linear mathematical model is developed and tuned, in the frequency domain, using the experimental data collected. The existence and the physical characteristics of chaotic attractors related to the postural oscillations are investigated. The diagnostic tools, used to reveal the non-linear properties of the postural dynamics, are based upon the calculation of the largest Lyapunov exponent at the Poincaré sections of the phase-plane diagrams constructed from the time series recorded experimentally. Here we report some preliminary results indicating the existence of a characteristic pattern observed on the phase-plane constructed from the experimentally recorded signals of human postural oscillations.

2. METHODS

2.1 Subjects, Apparatus, and Procedures

During a biped stance, the feet of a subject apply distributed forces on the ground in three directions. The ground reaction equilibrating this distributed force system can be measured by means of a force platform while the subject is standing on it. The ground reaction actually consists of three force components and three moment components but we will limit our study to the motion in the sagittal plane. The vertical axis passes through the *Center of Pressure* (CoP). In this study, three components of the ground reaction force (F_x, F_y, F_z) and the moment causing rotation in the sagittal plane (M_y) are measured with a Bertec® force plate in the Biomechanics Laboratory of the Department of Mechanical Engineering at the Middle East Technical University (METU). Force plate signals are first pre-amplified internally and then sent to an external amplifier in which a filter with a pre-set cut-off frequency of 500 Hz is employed. Filtered analog signals are fed to the computer after being digitized by an A/D converter (DAS 1202 Keithley MetraByte®). Force-Plus ALPHA Version 1.00 software (Bertec Corp.) is used to manipulate the signals to obtain the ground reaction forces and the moment at a sampling frequency of 50 Hz.

The analysis is confined to the sagittal plane. Accordingly, variations in the magnitude of the horizontal frictional force (F_x) and in the position of the center-of-pressure (CoP_x) are used to identify the postural sway. It should be noted that the problem considered is planar in xz-plane with the two force components F_x and F_z, and the moment M_y. CoP_x is obtained from F_z and M_y as $CoP_x = - M_y / F_z$.

Table1. Data Acquisition Protocol

Time (Minutes)	Record (i^{th})
Just before alcohol intake	1^{st}
0^{th}	85 gr. alcohol intake
10^{th}	2^{nd}
25^{th}	3^{rd}
40^{th}	4^{th}
70^{th}	5^{th}
100^{th}	6^{th}
160^{th}	7^{th}

Seven sets of 275-second time records of CoP_x are collected from a healthy adult due to a protocol presented below while the subject is instructed to stand still in upright posture. Sensorial non-linearities associated with the upright posture are provoked by the introduction of alcohol intake to the subject. 85 grams of 60% diluted ethyl alcohol are consumed by the subjects at the 0^{th} minute of recording where as, the 1^{st} time-record is received just before alcohol intake (see Table 1).

2.2 Analyses

Phase-plane representation; In order to construct the phase plane representation of the CoP_x signal, the velocities corresponding to the related CoP_x positions are also needed. As the only measured variable related to the center-of-pressure is the time variation of the position of the center-of-pressure, the unknown corresponding velocities are obtained by numerical differentiation. Forward finite difference formula is used for the numerical differentiation from the time series of the CoP_x signal; i.e.,

$$\frac{d}{dt} CoP_x(t_n) = \frac{CoP_x(t_{n+1}) - CoP_x(t_n)}{t_{n+1} - t_n} \qquad (1)$$

where, $CoP_x(t_n)$ is the n^{th} data recorded at the time series of the signal CoP_x and the time interval between two successive data points was 20 milliseconds.

Mathematical modeling; The whole body posture is modeled as an inverted pendulum (Peterka, 2001; Mergner and Becker, 2003). The system presented in Fig. 1 is a damped, driven, inverted pendulum which can be assumed to behave in a linear fashion for