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Open- and closed-loop responses of joint mechanisms in perturbed stance under visual and cognitive interference

Mohammed N. Ashtiani, Mahmood-reza Azghani*

Faculty of Biomedical Engineering, Sahand University of Technology, Tabriz, Iran

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ABSTRACT

Balance control requires sensory information to properly adjust the posture against the applied perturbation in which the early responses may not use the sensory feedback. Stabilogram-diffusion analysis (SDA) was developed to distinguish the open- and closed-loop modes of postural control based on routine standing indices. This study was aimed at evaluating the roles of visual and cognitive interference on regulations of the joint strategies. Sixteen healthy young males were stood on a rotating support with open and closed eyes and with and without cognitive interference (total four sensory conditions). Motion analysis was employed to obtain kinematic changes in the body. In addition to calculating some classical metrics (path length, range of joint motion, etc), the SDA was applied to the kinematics of the center of mass and lower limb joints to determine how they use sensory information during perturbed stance. Effects of vision were merely observed in the classical stance parameters, but the cognitive loads influenced the SDA ones. The joint mechanisms revealed totally different behaviors during the short- and long-term regions ($p < 0.016$) and the time interval and squared angles while starting to acquire sensory information ($p < 0.030$). Cognitive loads reduced the stability of standing by increasing the short-term diffusion coefficients ($p = 0.015$). Application of the SDA could present some details about the sensory-dependent behaviors of the joint strategies.

1. Introduction

Stable standing requires simultaneous activation of lower limb muscles which may cause kinematic changes in the joints called standing strategies. Depending on the conditions imposed on the body, the central nervous system (CNS) recruits the joint supporting muscles to contract and limit motions of the body center of mass (CoM) [1]. Upright standing under the activation of joint strategies needs information about the body and the environment by vision, vestibular and somatosensory [2] to continuously [3]; 2002) or intermittently [4–6] maintain the balance by a closed-loop control mode of the posture. It was comprehensively stated that the visual and cognitive interference alter the strategies in human standing from quiet upright to perturbed stance [7,8]. The CNS, however, may employ an open-loop control mode which does not require sensory information. To distinguish these different modes of balance control, [9] introduced the concept of stabilogram-diffusion analysis (SDA) using statistical mechanics. The SDA first plots the squared-mean value of the parameters of interest (majorly the center of foot pressure) against the time intervals. In the stochastic processes, these parameters maybe linearly related together by a diffusion factor as

$$\langle \Delta x^2 \rangle = 2D\Delta t$$

where D is the diffusion coefficient and represents the average stochastic activity of the parameter of interest which behaves as a random walk movement [10]. By applying this technique to the standing parameters the overall behavior of the body has been divided into two distinct regions. The linear regression on each region characterizes the control modes. The intersection between the lines segregates the CNS responses into short-term open-loop control and long-term closed-loop control mode of balance. The reliability of the SDA metrics was assessed as good to excellent [10].

Effects of different visual conditions in unperturbed stance have been investigated using the SDA which indicates that loss of vision increases the postural instability [9,11–15]. Cognitive tasks also gained several attentions to be analyzed by the SDA with controversial outcomes which were ranged from destabilizing to modifying effects [16–18]. Other studies also performed to investigate the dif-

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* Corresponding author at: Faculty of Biomedical Engineering, Sahand University of Technology, P.O. Box: 51335-1996, Tabriz, Iran.
E-mail address: azghani@sut.ac.ir (M.-r. Azghani).

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ferences in posturographic data of the aged population [19–22,14], patients with Parkinson's disease [23], loss of the foot somatosensory [24], phobic postural vertigo [25], muscular fatigue [13,26], patients with diabetes [27], etc. which majority of them found that the interventions or disorders were detectable by the SDA metrics.

The majority of the above-mentioned studies used the posturographic data of the center of pressure as an index of the whole body's efforts to control the balance. But this standing index, which is partly regulated by the CNS, may not properly disclose the joint mechanisms [28,29]. Therefore, it is noteworthy to generalize the SDA to other biomechanical indices like the lower limb joint angular rotations while keeping the balance. More importantly, the above works majorly analyzed the unperturbed stance data using the SDA and the studies on perturbed or non-quiet standing were limited. [30] compared the sway between the tiptoe and quiet stance using the SDA and found that further contractions of the muscles acting on the ankle provide the stability during tiptoe standing. [26] also used the SDA on excursions of the center of pressure and indicated that standing on a foam with muscle fatigue significantly reduces the stability. The effects of using an artificial feedback delivery of the body sway on the patients with vestibular deficits was analyzed using the SDA metrics which confirmed an increase in the stability [31,32] also calculated the SDA parameters in the subjects stood on an unstable plate after doing a mountain ultra-marathon and found that the metrics in closed eyes conditions were of less sensitivity.

Although the quiet standing is inherently disturbed by some physiological activities [33,34], it could be inspirable that applying a larger mechanical perturbation like the support surface rotation may better elucidate the response of the CNS in terms of the joint mechanisms in both open- and closed-loop control modes. Therefore, the aim of the present study was to investigate the roles of the joint mechanisms in keeping balance by focusing on the changes in transition from the steady-state behavior to the functional interaction of the CNS after application of the sensory and physical perturbations. This study is about to elucidate how the visual and cognitive interference affect the closed-loop control of the standing strategies. It was hypothesized that the joint mechanisms are not similarly behaved in use of the sensory feedback and the body maintains the balance in perturbed standing by delayed collaboration of its strategies. To further investigate the roles of physical and sensory disturbances on postural control, some classical parameters in the study of postural control like path lengths of the displacement- and velocity-time diagrams (l_x and l_v), three-joint space path length (l_{3j}), range of motions (w) and peak velocity (v_{max}) were calculated to compare between the significance of them and the SDA parameters.

2. Methods

2.1. Subjects

Sixteen healthy young males from the university students (aged 27.1 ± 2.9 years; height 176 ± 5 cm; weight 74.3 ± 9.4 kg) were participated in the test. They have had no nervous, muscular or joint-related disease at once or during their lifetimes. The Institutional Review Board of the Medical Experiments approved the test

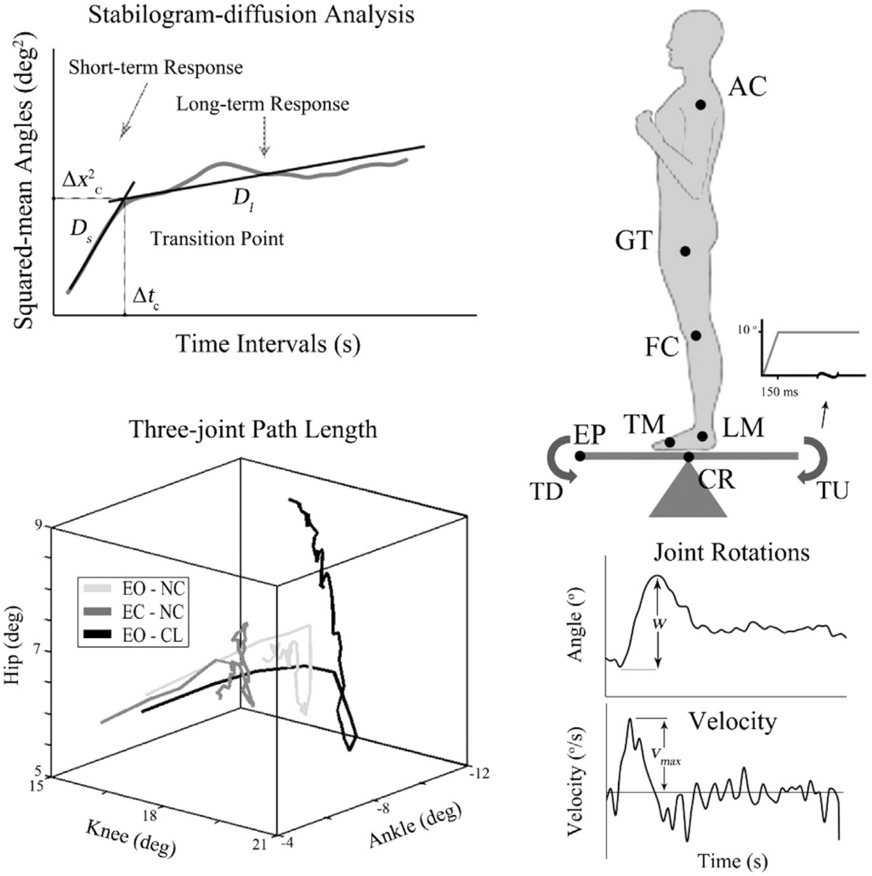

Fig. 1. Schematic view of the experimental set-up and kinematics of the applied perturbation with marker locations (top right panel), a typical representation of the time-varying kinematic parameters of standing like those of the knee joint for defining the range and maximum velocity (bottom right panel), stabilogram-diffusion diagram which introduces the short- and long-term responses (top left panel), and, a real three-joint space paths for normal (EO – NC), closed eyes without cognitive load (EC – NC) and eyes open with cognitive loads (EO – CL) conditions in average between the subjects in TD perturbations (bottom left panel). Abbreviations: AC = acromion, GT = greater trochanter, FC = femoral condyle, LM = lateral malleolus, MT = fifth metatarsal, CR = center of rotation, EP = end-plate, TD = toes-down, TU = toes-up.