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Controlling balance during quiet standing: Proportional and derivative controller generates preceding motor command to body sway position observed in experiments

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Abstract

To compensate for significant time delays in the control of human bipedal stance, it was suggested that a feed-forward control mechanism is needed to generate a preceding motor command to the body sway position observed in quiet standing. In this article, we present evidence that a feedback proportional-derivative (PD) controller can effectively generate a desired preceding motor command. We also discuss the following characteristics of the proposed PD controller: (1) the level of robustness of the controller with respect to neurological time delays and (2) how well the controller replicates the system's dynamics observed in experiments with able bodied subjects, i.e. how well the controller generates the observed preceding motor command. Human quiet stance was simulated using an inverted pendulum model regulated by a PD controller. The simulations were used to calculate the center of mass (COM) position and velocity data, and the motor command (ankle joint torque) data as a function of time. These data and the data obtained in the experiments were compared using cross-correlation functions (CCFs). The results presented herein imply that a PD feedback controller is capable of ensuring balance during human bipedal quiet stance, even if the neurological time delays are considerable. The proposed feedback controller can generate the preceding motor command that was observed in the experiments. Therefore, we conclude that a feed-forward mechanism is not necessary to compensate for the long closed-loop time delay in human bipedal stance as suggested in recent literature, and that the PD controller is a good approximation of the control strategy applied by able bodied subjects during quiet stance.

Keywords: Equilibrium control; Posturography; Cross-correlation analysis; Simulation; Feedback control; PD control

1. Introduction

Human bipedal stance is inherently unstable since it requires that a large body consisting of multiple flexible segments is kept in an erect posture with its center of mass (COM) located high above a relatively small base of support. The complexity of this system and its ability to maintain stable stance, despite various perturbations, have attracted the attention of many researchers in the field and have inspired various theories that try to explain the control mechanism of bipedal quiet stance. However, the true nature of this control mechanism is still an object of discussion and controversy.

The ankle joint torque needed to control the body during quiet stance can be evoked actively and passively. *Passive torque* components are the result of the intrinsic mechanical property, i.e. stiffness and/or viscosity, produced by muscle and surrounding tissue, such as ligaments and tendons. We can refer to the additional torque as *active torque*, which is generated by active muscle contraction. Since the COM is located in front of the ankle joint, plantar flexing torque is continuously required to prevent the body from falling forward [1]. However, the passive torque by itself is not

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sufficient to ensure this required plantar flexing torque [2–4]. Therefore, an additional active torque, regulated by the central nervous system (CNS) and produced by the plantar flexors, is needed [2–8].

Gatev et al. [5] reported that there is a significant statistical correlation between lateral gastrocnemius muscle activity and the position of spontaneous body sway, which was measured as the COM position. This finding supports the notion that the active torque is provided by lateral gastrocnemius muscle contractions in response to body sway. They also discovered that the muscle contractions preceded changes in the COM position by approximately 200 ms. Since the motor command appears to be generated in anticipation of future positions of the COM, these findings were later used to suggest that a feed-forward control mechanism is responsible for ensuring stable balance during quiet standing. Morasso and Schieppati [2] supported the feed-forward control theory and suggested that, in order to compensate for the long neurotransmission delay, this control mechanism is required to generate the preceding motor command.

Similar to the study by Gatev et al. [5], Masani et al. [8] also found preceding muscle activities in plantar flexors during standing. However, they demonstrated that this preceding motor command could be accomplished by applying an appropriate feedback control system. In this context, a high gain PD (proportional-derivative) controller that uses the position and the velocity information of the COM was shown to be an effective method to regulate balance during standing even when long neurotransmission delays are present [8]. In their study two PD controllers were compared: one with a high derivative gain and one with a low derivative gain. Although both controllers could stabilize the body during quiet standing with a closed-loop time delay of 100 ms, only the PD controller with the high derivative gain was able to generate a long preceding motor command (121 ms) similar to the one obtained in experiments with able bodied subjects (155 ms). In addition to the preceding time, they discovered that the shape of the cross-correlation function (CCF) between the COM position and the muscle activity was similar to the CCF between the COM position and the joint torque obtained in simulations using the high derivative gain controller. These findings suggested that the control mechanism, which is responsible for the active torque generation, adopts a control strategy that relies notably on velocity information. However, to explain the experimental results in their study, only two PD controllers with arbitrarily selected gains were compared. Since the results were favorable, we realized that a systematic investigation was needed to determine the true capability of a PD controller that regulates balance during quiet stance with a preceding motor command observed in the experiments.

The purpose of the present study was to carefully examine various proportional and derivative gain pairs in simulations and provide answers to the following questions: (1) Is the PD controller capable of facilitating robust balance during quiet standing, despite long neurological time delays? and (2) Can the PD controller generate the system behavior observed in the experiments, including the long preceding motor command? By answering these questions, we have provided strong evidence that the feedback mechanism is capable of effectively regulating balance during quiet stance in the manner observed in experiments with able bodied subjects.

A preliminary report pertaining to this study was published as an abstract in Ref. [9].

2. Materials and Methods

2.1. Experiments

To identify appropriate PD controller gains, we compared the CCFs between the body kinematics (COM position and velocity) and the motor command of the modeled system with the body kinematics and muscle activity obtained experimentally. As a criterion of comparison, we determined whether the lag times of the model's CCFs were in the range of the lag times of the physiological CCFs obtained in the previous study [8]. Here, we briefly present the results of the previous study [8] which was used to evaluate the PD controller in this article.

Sixteen healthy men (mean $\pm$ S.D. age, 23.8 ± 3.9 years; mean $\pm$ S.D. height, 169 ± 6.6 cm) participated in the study. Each subject was requested to keep a quiet stance posture for 30 s in five trials, standing barefoot with eyes closed. The horizontal position of the waist point was measured as an approximation for the COM position in the antero-posterior direction using a laser displacement sensor. We adopted this approach since it was confirmed that the dynamics of quiet standing can be approximated by an inverted pendulum rotating around the ankle joint [5,10]. However, we should note that this approximation might result in an relatively small error in the measurement. Electromyograms were recorded from the right plantar flexors. In this study, we examined the behavior of the medial gastrocnemius muscle, which showed the highest correlation with the body sway compared to other plantar flexors. The rectified and smoothed (4th-ordered, zero-phase-lag Butterworth low-pass filter with cutoff frequency of 4 Hz) electromyogram (EMG) was considered to represent the level of muscle activity.

Next, using the experimental results, we calculated two CCFs: (1) CCF between COM position and EMG, and (2) CCF between COM velocity and EMG. This allowed us to determine two objective time shift ranges for the CCF comparison. The time shift from COM position to EMG is defined as the lag time of the peak of the CCF between COM position and EMG. The time shift for each subject was calculated as the average of five trials, and the group average value $\pm$ S.D. of the time shift was -155 ± 46 ms. It should