Model-Based Investigation of the Roles of Efferent and Afferent Noise in Balance Control in the Postural Control System

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Abstract— **The objectives of this study were to evaluate the performance of two 2D balance control model structures and to make model-based inferences regarding balance control mechanisms, specifically the degree to which afferent vs. efferent noise is involved in generating sway. The balance control model structures were based on an optimal control strategy, and differed in the sources of noise in postural control (efferent vs. afferent). Results showed that all 95% confidence intervals of traditional measures resulting from both model structures included unity, indicating that there were no significant differences between the simulated and experimental measures. The model structure with efferent noise input generated a smaller cost function and smaller scalar errors compared with that with afferent noise input. Smaller cost function and smaller scalar errors are associated with better performance in terms of simulating postural sway. Thus, it might be concluded that efferent noise in the postural control system plays a relatively important role in driving postural sway. These findings may be useful for the development of intervention strategies for the improvement of balance and reduction of fall risks.**

Keywords— **Balance control, efferent/afferent noise, model simulation, center of pressure.**

I. INTRODUCTION

Falls are a major cause of injuries in occupational settings and daily life, and substantial number of falls events result from loss-of-balance. Thus, a better understanding balance control may aid in reducing fall risks. Balance control is commonly assessed by studying quiet upright stance. Quiet upright stance is not perfectly quiet, given the existence of internal perturbations such as heart rate, respiration, and muscle tremor. Internal perturbations can be considered as noise in the postural control system, and internal control must be generated by the neural controller to counteract such noise and to maintain upright posture. Different sources of noise in postural control have been assumed and/or adopted in the development of balance control models. Some studies have modeled this noise as existing in the efferent pathways, typically as random disturbance torques acting on joints [1, 2], whereas others have indicated that such noise exists in the afferent pathways, specifically at sensory organs [3].

The objectives of this study were to evaluate the performance of two 2D balance control model structures and to make model-based inferences regarding balance control mechanisms, specifically the degree to which afferent vs. efferent noise is involved in generating sway. These balance control models are all based on an optimal control strategy, and model development and implementation followed an approach described earlier [4].

II. METHOD

A. Alternative Model Structures

In the balance control models presented here, the neural controller is assumed to be an optimal controller that can minimize a performance index defined by physical quantities relevant to sway. Human body dynamics are represented by a single-segment inverted pendulum model, and sensory systems are assumed to be able to provide accurate body orientation information to the neural controller but with a certain time delay. Experimental data are needed to specify model parameters, such as sensory delay time, and this specification is accomplished using an optimization procedure that adopted heuristic search approaches. Details regarding the model development are given in [4].

Two alternative model structures were developed (Fig 1). In the figure, TN and SN indicate joint torque noise and sensory noise, respectively. Only one noise source (either joint torque noise or sensory noise) was chosen in each model structure, and the noise was modeled as white noise.

Several anthropometric measures were required: moment of inertia of the body about the ankle (I), body mass (M), height of whole-body COM (h), mass of the feet (m_F), height of the ankle (h_F), and anterior-posterior (A/P) distance between the ankle and the COM of the feet (d_F). Several measures were obtained directly from each participant

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prior to the experimental trials: M, stature (l) and foot length (l_F). The remaining measures were estimated from existing equations which were presented earlier [5-7].

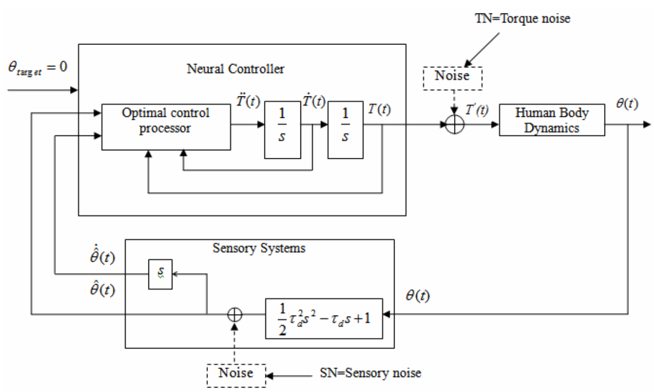

Fig. 1 Alternative model structures. (1) TN model structure; (2) SN model structure. θ = sway angular displacement; $\hat{\theta}$ = delayed sway angular displacement; T' = ankle torque; T = active control torque generated by the neural controller; θ_{target} = target sway angle; τ_d = sensory delay time

B. Participants and Experimental Procedures

Experimental data were required to specify model parameters, and were obtained from a prior experiment. Sixteen young participants (eight males and eight females) without injuries, illness, and musculoskeletal disorders were included in the study (age: 21±1.7 years; height: 171.4±7.0cm; weight: 66.4±11.3kg). Trials consisted of brief periods of quiet upright stance. During these, the participants stood barefoot on a force platform (AMTI OR6-7-1000, Watertown, Massachusetts, USA) as still as possible with their eyes closed. To ensure the same feet placement across trials, the feet were outlined on poster board placed on top of the force platform. Each trial was 75 seconds in duration, and the initial 10 seconds and last five seconds were removed. Three trials were performed by each participant, with at least one minute of rest between each. Triaxial ground reaction forces and moments were sampled at 100Hz, and subsequently low-pass filtered (5Hz cut-off). These forces and moments were used to derive center of pressure (COP) time series, which are commonly used to characterize sway behaviors [8].

C. COP-Based Measures

The set of measures used to define the cost function are traditional measures. During model simulation, values of these traditional measures must be specified in advance, from experimental data, in order to calculate the cost function. Traditional measures are all summary statistics and cannot account for inherent dynamics characteristics of COP time series [9]. In order to compensate for this limitation of traditional measures, several measures derived from statistical mechanics approaches have been proposed (e.g. [10, 11]). These approaches are all based on the stabilogram diffusion analysis (SDA) developed by Collins and DeLuca [10]. Four statistical mechanics measures (i.e. TT, TA, H_S, and H_L) derived from the fractional Brownian motion model [12] were chosen for analysis. Descriptions and units of COP-based measures are given in Table 1.

Table 1 Glossary of COP-based dependent measures

Acronym	Description	Unit
MD	Mean distance	
RMS	Root mean square distance	mm
MAXD	Maximum distance	mm
MV	Mean velocity	mm/s
MFREQ	Mean frequency	Hz
P50	50% power frequency	Hz
CFREQ	Centroidal frequency	Hz
P95	95% power frequency	Hz
FREQD	Frequency dispersion	--
TT	Transition time	S
TA	Transition amplitude	mm^2
H_S	Short-term scaling exponent	--
H_L	Long-term scaling exponent	--

D. Model Simulation and Analysis

The proposed model structures were separately used to simulate selected experimental trials of quiet upright stance. Each simulation trial was 75 second in duration with the initial 10 seconds and last five seconds removed. Separate comparisons of traditional COP-based measures were made between experimental data and simulated values generated by each model structure. To account for individual variability, simulated measures were normalized by their corresponding experimental measures (i.e. a perfect prediction would yield a value of unity). Subsequently, 95% confidence intervals of the normalized measures were determined, and used to evaluate the simulated data generated by each model structure. These confidence intervals are equivalent to two-tailed *t*-tests with α=0.05.

Values of the cost function were compared to evaluate the ability of different model structures to simulate traditional COP-based measures. These comparisons were done by using a paired *t*-test. To evaluate predictions yielded by the different model structures, scalar errors between predicted statistical mechanics measures and their corresponding experimental measures were calculated. The definition of the scalar error is given by

$$e = \left| \frac{m_{pre} - m_{ref}}{m_{ref}} \right| \tag{1}$$

where m_{pre} is a predicted statistical mechanics measure for a given simulation trial, and m_{ref} is the corresponding experimental measure. Separate comparison of scalar errors across different model structures was performed for each statistical mechanics measures using paired *t*-tests.

III. RESULTS

All 95% confidence intervals of traditional measures resulting from the TN and SN model structures included unity (Fig. 2), indicating there were no significant differences between the simulated and experimental measures.

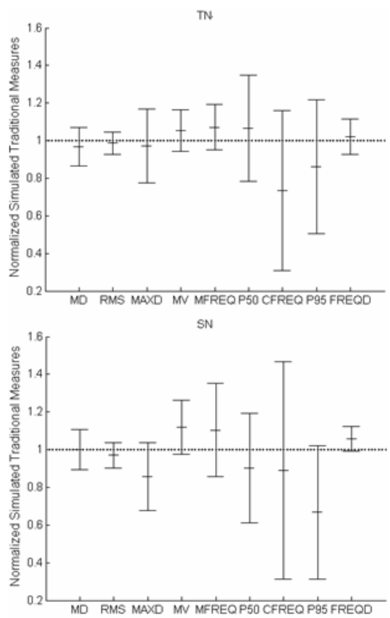

Fig 2 Mean and 95% confidence intervals of the normalized simulated traditional measures resulting from different model structures

The cost functions obtained from the TN model structure (Mean (SD) = 0.441 (0.159)) were significantly ($p<0.01$) smaller than those that resulted from simulating the SN model structure (Mean (SD) = 0.572 (0.141)).

Fig. 3 shows the distributions of the scalar errors between predicted and experimental statistical mechanics measures. Results revealed that the TN model structures provided significantly smaller scalar errors of TT, TA, and H_S than did the SN model structure.

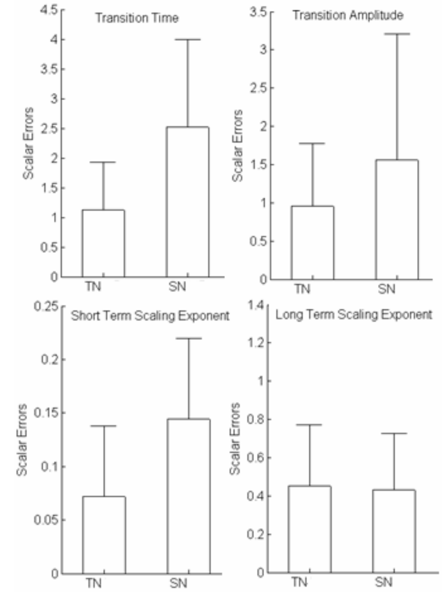

Fig. 3 Scalar errors. Error bars indicate one standard error

IV. DISCUSSION

Two balance control model structures were developed and evaluated in this study. These model structures differed in the source of noise in postural control. By evaluating the performances of different balance control model structures, it is possible to examine the validity of alternative balance control theories. Performance of these model structures were evaluated in terms of their ability to accurately simulate COP-based measures.

When analyzing the 95% confidence intervals of the normalized traditional measures, we found that all the confidence intervals resulting from the TN and SN model structures included unity. This finding indicates that any simulated traditional measure from both model structures was not significantly different from its corresponding experimental measure. In addition, simulation performance was evaluated by the values of the cost function in the optimization procedure. The objective of the optimization procedure was to minimize the cost function so that the simulated traditional measures could best duplicate their corresponding experimental measures. Hence, a smaller cost function indicates better model performance. The cost functions resulting from the TN model structure were found to be significantly smaller than those from the SN model structure, indicating that the TN model structures could simulate traditional measures more accurately. Thus, from the perspective of simulating traditional measures, the TN model structure performed better than did the SN model structure.

When evaluating the performance of different model structures in predicting statistical mechanics measures, we found that the scalar errors of these measures from the TN model structure were typically smaller than those from the SN model structure (Fig. 3). This indicates that the predicted statistical mechanics measures from the TN model structures could better account for their experimental references. Thus, it might be further concluded that the TN model structure could simulate postural sway more accurately than did the SN model structure.

In the TN model structure, noise in postural control was modeled as a random disturbance torque acting on the ankle joint. In contrast, the SN model structure introduced noise to sensory signals. The fact that the TN model structures performed better does not deny the existence of sensory noise; however, it does at least suggest that, compared with joint torque noise, sensory noise might play a less important role in driving body sway. Both sensory noise and joint torque noise were modeled as white noise in this study. However, in reality, noise acting on the human body may not be perfect enough to be white noise. Thus, another possible explanation for why the TN model structure performed better might be that joint torque noise has more common properties with white noise than does sensory noise.

Some other limitations in this study should be noted. First, several anthropometric measures were estimated, and thereby served as a source of errors in the model simulation. Second, both sensory noise and joint torque noise should exist at the same time; however, in this study, in order to compare the roles of these noise sources in balance control, they were introduced to the model separately. Third, limitations within the presented balance control model based on an optimal control strategy also apply in this study [4]. For example, this model is only applicable for small amplitudes of planar sway motion given that only ankle torques were considered to contribute to maintaining balance [13]. In addition, since only two-dimensional balance control model structures were studied, the results can only account for the attributes of balance control in the sagittal plane. Thus, in future research, different three-dimensional balance control model structures should be investigated.

In summary, this study investigated afferent/efferent noise in postural control during quiet upright stance by simulating alternative balance control model structures, and further supported that mathematical models are a useful tool to examine validity of different balance control theories. The results from this study suggest that efferent noise plays a relatively important role in driving body sway.

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