A THREE-DIMENSIONAL BALANCE CONTROL MODEL OF QUIET UPRIGHT STANCE BASED ON AN OPTIMAL CONTROL STRATEGY

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INTRODUCTION

Many existing balance control models have adopted a single-segment inverted pendulum to model the human body, and have focused on investigating postural sway only in the sagittal plane (e.g. Maurer et al., 2005). However, evidence indicates that postural sway in the frontal plane is important, and able to account for different balance control mechanisms as well (e.g. McClenaghan et al., 1996). Thus, a simple two-dimensional balance control model that cannot simulate medial-lateral (M/L) postural sway is not able to sufficiently reflect how humans control upright posture. The purpose of this study was to develop a balance control model that can accurately simulate postural sway in three-dimensional space.

METHODS

In the model, the human body was represented as a two-segment inverted pendulum, in which there are two joints representing the ankle and hip. In order to linearize body dynamics, several assumptions were made, for example that there was no axial rotation during quiet upright stance. Sensory systems were assumed to provide accurate ankle and hip sway angles to the neural controller, but with an inherent time delay. The neural controller was assumed to be an optimal controller that generates ankle and hip control torques to minimize a performance index defined by physical quantities relevant to sway in both the anterior-posterior (A/P) and M/L directions. An optimization procedure using heuristic search approaches was performed to determine unspecified model parameters such as sensory delay times at the ankle and hip joints. The cost function in this optimization procedure was defined by a scalar error between the simulated and actual center of pressure (COP) based measures.

Experimental data were required to specify model parameters, and were obtained from 16 young participants (eight males and eight females). During data collection, participants stood barefoot on a force platform, and triaxial ground reaction forces and moments were sampled at 100Hz, and subsequently low-pass filtered (5Hz cut-off) to derive COP time series. Simulated COP-based measures were normalized by their experimental references, and 95% confidence intervals of these normalized measures were calculated and used to evaluate the proposed model in terms of its ability to simulate postural sway. The dependent COP-based measures include root mean square displacement (RMS), mean velocity (MV), centroidal frequency (CFREQ), frequency dispersion (FREQD), transition time (TT), transition amplitude (TA), short term scaling exponent (H_S), and long term scaling exponent (H_L).

RESULTS AND DISCUSSION

For all dependent COP-based measures, 95% confidence intervals of the normalized simulated values included unity (Figure 1), indicating that there were no significant differences between experimental and simulated COP-based measures. Thus, the proposed model appears able to accurately simulate postural sway behaviors.

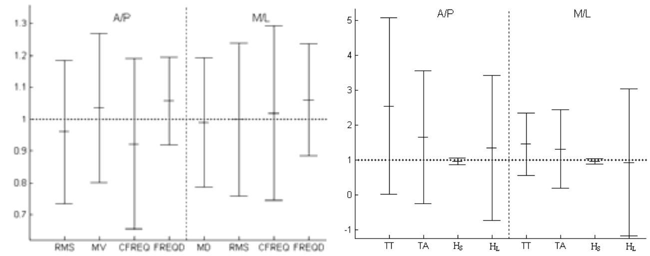

Figure 1: Mean and 95% confidence intervals of the normalized simulated COP-based measures. Experimental references used for normalization are given in Table 1.

Several assumptions were made in the model, but appear reasonable. For example, we assumed that the lower and upper segments only rotate in the sagittal and frontal planes, respectively, based on earlier evidence for the use of ankle and hip strategies to control postural sway in these planes (e.g. Winter et al., 1996). In addition, axial rotation should be minimal during quiet upright stance. According to the above arguments, we may conclude that the proposed model is valid to some extent in terms of simulating COP-based measures, and thus can be used to further investigate balance control mechanisms, for example how individual differences and task conditions (e.g. aging and localized muscle fatigue) affect balance control.

REFERENCES

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Table 1. Experimental COP-based measures

		RMS	MV	CFREQ	FREQD	TT	TA	H_S	H_L
A/P	Mean	6.68	10.52	0.549	0.903	0.579	26.33	0.817	0.198
	SD	2.95	3.55	0.139	0.061	0.297	26.23	0.041	0.100
M/L	Mean	6.31	13.08	0.582	0.844	0.477	34.35	0.829	0.148
	SD	2.19	4.95	0.153	0.079	0.122	31.50	0.030	0.109