Analyzing Balance Model

Group 20
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ABSTRACT

The focus of our study was to examine the degree of body sway induced in subjects by platform perturbations under two conditions: eyes-open (EO) and eyes-closed (EC). With this data we were able to estimate the contributions of the three sensory systems critical to human postural control, specifically, the proprioceptive, vestibular, and visual systems. Each of the 16 college-aged participants experienced pseudo-randomized platform perturbations with a peak-to-peak amplitude of 2 degrees under both EO and EC conditions. Center of pressure data in relation to platform perturbation was recorded by the Equitest platform system which was then filtered to determine degree of body sway. By eliminating visual sensory information in the eyes-closed test, we were able to determine the contribution of the proprioceptive system under these conditions. After comparing this value to the one calculated in the eyes-open trial, we found that the proprioceptive system does in fact play an increased role in balance control when the visual system is removed. Further investigation with a range of subject ages is necessary to fully elucidate the relationship between the availability of sensory information and how balance is maintained.

I. INTRODUCTION

The human body is subject to gravitational forces that generate torque which drives the body away from the upright vertical position. Human posture is an unstable system, and these gravitational forces must be counteracted through stabilizing torques generated by active and passive physiological mechanisms.

Neurally mediated postural control, also known as the active mechanisms, consists of three sub systems: vestibular, visual, and proprioceptive [1]. The vestibular and visual systems are responsible for controlling head orientation and motion in space. The proprioceptive system controls orientation and motion of each body segment with respect to each other. These three systems are fully integrated with each other to resist gravitational forces. Each system provides a different percentage contribution to stabilization such that the sum of their contributions equals 100%. Contributions of each of these three systems in maintaining balance can change in response to the amplitude and frequency of external perturbations on the body [2].

In comparison to the active mechanisms of postural control, the passive systems make only minor contributions to maintaining upright position, and therefore were not considered during calculations in this experiment. Passive controllers include the visco-elasticity of muscles and the stiffness of tendons [2].

The main goal of this experiment was to quantify the contribution of the proprioceptive system through a weighting factor in a model of human balance control. Specifically, we sought to measure this factor in human subjects standing on an oscillating platform. The perturbations were introduced on the anterior-posterior axis between the medial malleoli, causing anterior-posterior sway. Measuring the induced sway was then used to determine the degree of body motion in response to stimuli [2]. To explore the contributions of each system of the active mechanisms, we established a suitable human balance model. For practicality, several simplifications to the human model were made to more easily replicate balance conditions while maintaining accuracy.

First, the body can be represented as a single-link inverted pendulum with a pivot point at the ankle [1]. This simplification was made because the equations of motion for an inverted pendulum are relatively simple, yet still represent the body at its most basic form (i.e. arms held across chest, knees and hips not bending).

Second, each of the three systems of the active mechanisms were isolated to analyze their contributions to overall balance. Because the visual system is easy to manipulate by imposing EC or EO conditions, the first simplification to the body system was the removal of the visual system [1]. Under EC conditions, the contribution of the visual system to balance was eliminated, allowing for a greater understanding of contributions made by the vestibular and proprioceptive systems to balance, as compared to their contributions under EO conditions. Not only does manipulating the visual system help isolate the vestibular and proprioceptive systems in an attempt to quantify their contributions to balance, but it also assists in determining the difference in balance between EC and EO conditions as suggested in literature [1].

By testing balance in college-aged subjects using a simplified model of the human body and random platform perturbations, we hoped to better understand the contributions of the vestibular, proprioceptive, and visual systems in maintaining balance. We also sought to determine any differences in body sway under EO and EC conditions. This data can be beneficial in quantifying the relationship between the availability of sensory information and postural control, which could be used to study several other age ranges and conditions.

II. METHODS

A. Experimental Setup

Experiments were performed with young adults of both genders (N = 16). Subject height and weight were recorded. For each subject, the height of the center of mass (h) was estimated using the approximation 0.6 * height, and the moment of inertia (J) was estimated using the formula $J = mh^2$. Each subject stood on a dynamic posturography platform (NeuroTest, Neurocom International, Inc., Clackamas, OR) that rotated along the antero-posterior (AP) axis in a pseudorandom manner with a maximum displacement of 2 degrees peak-to-peak. The platform's pressure plates recorded subjects' center of pressure. Subjects stood with arms crossed to better emulate an inverted pendulum. Each subject went through 2-4 trials split evenly between the eyes-closed and eyes-open conditions. There were 28 trials in total, 14 for each condition. Each trial involved 3.5 cycles of pseudorandom platform motion, 48.4 seconds long each. Subjects had a one-minute rest period between each trial. The order in which the two conditions (eyes-open and eyes-closed) were presented was randomized. During each trial, the platform oscillated while recording the pressure distributions of each participant as a function of time. All data points were recorded at 100 Hz.

B. Data Analysis

Data for platform angle and subject center of pressure was resampled to 10 Hz to focus on frequencies relevant to human response. The resulting center of pressure was used to calculate the body sway angle data using a computer-implemented algorithm. The first half cycle of each trial was discarded to minimize the effect of the transient response, leaving three full 48.4 second cycles. The mean body sway angle was removed from each cycle. Then, these detrended body sway angles for each cycle were ensemble averaged into a single response. The root mean square (RMS) body sway angle and platform angle were calculated and the ratio between them found. Next, we calculated the frequency response using Laplace domain transformations. These frequency responses were smoothed before being used in subsequent analysis.

To determine the model parameters that best fit each trial, a curve fitting routine was used. This routine fit each transfer function estimate to the human inverted pendulum model:

$$\frac{BS}{SS} = \frac{W_p(K_D s^2 + K_P s + K_I)e^{-st_d}}{Js^3 - mghs + (K_D s^2 + K_P s + K_I)e^{-st_d}} \quad (Eq. 1)$$

Where BS/SS is the ratio of body sway to platform angle, W_p is the contribution of the proprioception system to balance, and t_d is the overall system time delay. The K values represent neural controllers: K_P is active stiffness, K_D is active damping, K_I is an integration factor. The curve fit routine determined the values of these parameters that minimized the error between the transfer function estimates and the modeled frequency response.

After calculating the platform / body sway angle RMS ratio and inverted pendulum model parameters for each trial, results were averaged across the eyes-open and eyes-closed conditions. A pairwise T-test was used to determine the significance of differences between the two conditions.

III. RESULTS

As discussed, we first examined body sway angle relative to platform angle. In Figure 1 it is evident that the RMS angle ratio shows a slight increase in body sway during EC trials as compared to EO. This difference is statistically significant ($P < 0.01$).

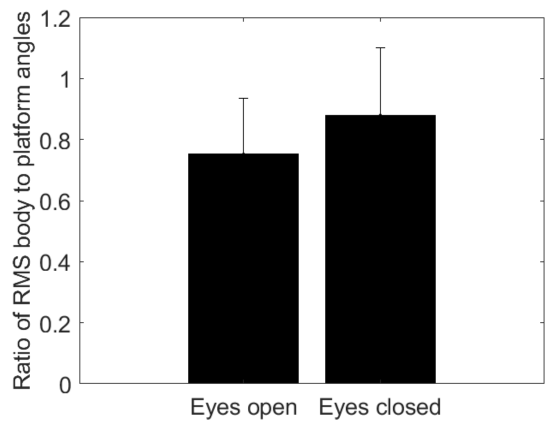

Figure 1: The ratio of the RMS subject body sway to RMS platform angle, with standard deviation. This ratio is significantly higher for the EC condition ($P < 0.01$). The data used was an average across all trials of EC and EO respectively.

Using our data for body sway and platform movement, we estimated the frequency response of the system. To quantify the effects of physiological parameters on human balance, we used Equation 1 in order to see how the different weighting of the senses influence balance as a whole. Table 1 shows the average parameter values and standard deviations generated by the nonlinear curve fitting model we used. P-values for a paired T-test between the two conditions are also shown. These parameters fit into Equation 1 to model the response to a perturbation. By graphing our experimental data in Matlab relative to the data generated by our parameters and Equation 1 we could see that the model is qualitatively similar to the estimated transfer function for each trial. Example model fits for one subject are shown in Figure S1.

To further validate the inverted-pendulum model parameters obtained with our approach, we examined the first-order optimality of the fitted models. This value was below 0.02 for all trials.

Parameter	EO	EC	P-value
K_D	290.85 ± 73.53	310.57 ± 96.85	0.139
K_P	871.19 ± 166.02	906.90 ± 179.24	0.149
K_I	21.42 ± 15.49	23.22 ± 19.01	0.359
W_p	0.22 ± 0.05	0.28 ± 0.05	0.0048
t_D	0.20 ± 0.03	0.22 ± 0.03	0.192

Table 1: Experimentally determined parameters for the inverted pendulum model of human balance (Eq. 1) across EO and EC conditions. Only W_p is significantly different between conditions.

By taking a closer look at W_p, we were able of evaluate how proprioception contributes to overall balance. As seen in Figure 3 below, while the difference between EC and EO for W_p was relatively small, it was still statistically significant. The P-value from the T-test gave us a 99% confidence interval, indicating that the discrepancy was not due to random chance.

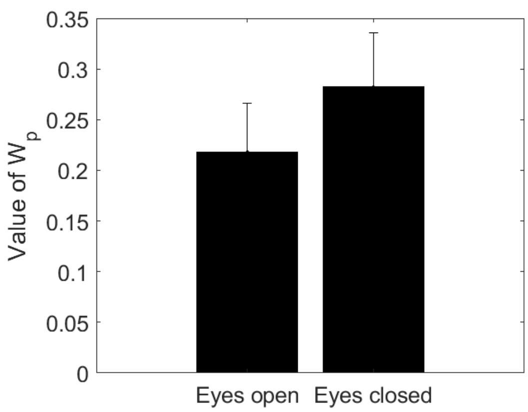

Figure 3: W_p values for EO and EC conditions, plotted with standard deviation. The EC condition results in a significantly higher value (P < 0.01).

IV. DISCUSSION

Ishida *et. al.* showed that vision is a crucial component of human balance [3]. Our results suggest a slight increase in body sway during EC trials and we were able to confirm that removing visual sensory information causes a statistically significant increase in sway. Cenciarini *et. al.* showed that young healthy adults respond much more effectively to perturbations than older adults [3]. Had we collected data from elderly subjects, we might have seen an even larger discrepancy between EO and EC trials.

Our subjects showed a fairly even frequency response to platform perturbations between 0.05Hz and 0.7Hz. These results were comparable to a previous study [2] which included a similar experiment. However, our analysis showed a significant drop off in frequency response above 0.7Hz, while the same prior study did not show a similar drop off until approximately 2Hz. The discrepancy might be explained by differences in experimental procedures such as the amplitude of platform oscillation or subject stance width.

Peterka discussed the use of an equation that relates the contributions of postural sensory systems to overall balance [1]. In this model, $W_v + W_p + W_g = 1$, where W_p represents the contribution of the proprioceptive system, W_v represents that of the visual system and W_g represents that of the vestibular system. This relationship could be considered to be a coefficient in front of the neural controller terms in the denominator of Equation 1. In EC trials, contributions from the visual sensory system are eliminated. Mathematically, this is shown by setting W_v equal to 0. To maintain the relationship in which the sensory weights sum to 1, $(W_p + W_g)$ must increase to offset the loss of W_v. With only two variables in the relationship, we can use the value for W_p determined from our balance model to solve for W_g. The same methodology cannot be applied to EO trials because W_v is present and we still have two unknowns remaining after solving for W_p. This has been a long-standing issue in human balance modeling. Several previous studies have examined the effect of visual sensory information by eliminating W_g instead. One prior study avoided this problem by using subjects with absent vestibular function, therefore eliminating W_g from the relationship [1]. Another study used electrical stimulation to temporarily disrupt vestibular function and was consequently able to remove W_g as well [2].

In Figure 3 we saw that there was a significant difference between the W_p for EO and EC trials. This difference confirms that our initial assumption was true, and that sensory weighting is in fact rebalanced based on external stimuli. However, because we were unable to separate W_v and W_g during EO trials, we could not measure the exact change in W_g between the two experimental conditions.

V. CONCLUSIONS

Our study measured body sway induced in young adult subjects standing on a platform oscillating between 2 degrees peak-to-peak along the anterior/posterior axis. We tested two separate conditions, one with eyes-open and one with eyes-closed. To examine the effect of visual sensory information on balance control, we compared the body sway angle against the platform movement angle. As intuition would suggest, analysis indicated an increase in body sway in the eyes-closed trials. This trend was confirmed to be statistically significant. The contribution of W_p to the balance control model also increased slightly for the eyes-closed condition and was also shown to be significant. These results suggest that, for young adults subjected to moderate perturbations, the loss of visual system sensory information can be compensated for by increased weighting of the vestibular and proprioceptive systems. Further work should seek to establish a better understanding of the relationship between the postural sensory systems, particularly when W_v is present.

REFERENCES

[1]: Peterka, R.J. (2003). "Simplifying the Complexities of Maintaining Balance: Insights Provided by Simple Closed-Loop Models of Human Postural Control." *IEEE Engineering in Medicine and Biology Magazine.*

[2]: Cenciarini, M., Louglin, P.J., Sparto, J., & Redfern, M.S. (2010). “Stiffness and Damping in Postural Control Increase with Age.” *IEEE Transactions on Biomedical Engineering, 57:2.*

[3]: A. Ishida, T. Masuda, H. Inaoka, and Y. Fukuoka (2008). “Stability of the human upright stance depending on the frequency of external disturbances,” *Med. Biol. Eng. Comput., vol. 46, pp. 213–221*.

APPENDIX

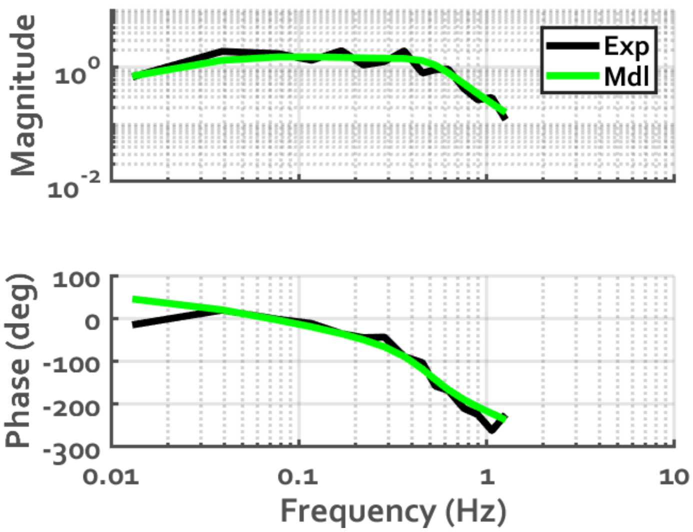

Figure S1: Example fits of the inverted pendulum model to the estimated transfer function of one subject over EC (left) and EO (right) conditions. The fitted results are close to the experimental transfer functions with first-order optimality < 0.2.

RESPONSE TO REVIEWER

We respectfully disagree with the reviewer that this figure does not add to the report. The figure helps validate that it is reasonable to model the human balance system as an inverted pendulum, and that the balance parameters we obtain do help explain the system. However, we do agree that the figure isn’t nearly as important as our table of obtained parameters. Therefore, we propose including this figure as supplementary and including it in the appendix instead of in the main report.