Proceedings of the ASME 2009 Summer Bioengineering Conference (SBC2009)
June 17-21, Resort at Squaw Creek, Lake Tahoe, CA, USA

SBC2009-203989

EXAMINING QUIET STANDING CENTER OF PRESSURE DATA USING INVARIANT DENSITY ANALYSIS

Pilwon Hur, K. Alex Shorter, Elizabeth T. Hsiao-Wecksler

Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign, Urbana, IL
Email: ethw@illinois.edu Web: http://mechse.illinois.edu/research/hsiao-wecksler

INTRODUCTION

Posturographic data collected during quiet stance using force plates is widely used to assess postural stability [1]. Center of pressure (COP) is a commonly used experimental variable for several types of analyses. Traditionally, COP data have been analyzed using measures that describe the shape or speed of the trajectory [1]. Unfortunately, these parameters do not provide insight into the physiological system as a whole and have been shown to have questionable reliability [2].

Collins and DeLuca observed that fluctuations in the COP behave mainly like a stochastic process but with underlying deterministic behavior [3]. Quiet standing can be compared to balancing an inverted pendulum where the unstable system is prevented from falling using a control system. Using Stabilogram Diffusion Analysis (SDA), they identified regions of short term (open loop) and long term (closed loop) postural control strategies used to maintain upright stance. Even though SDA parameters can detect deterministic behavior in a stochastic random walk, it is still hard to extract physical insights of how the COP actually moves and where the transition between deterministic and stochastic behavior arises.

Markov chain models are used as reduced order models of stochastic systems. In this paper, COP data were used to create a Markov model of the system. The invariant density of the model corresponds to the steady state distribution of the system and is used in this paper to characterize long term quiet standing behavior and to capture the effect of age on postural sway. Specifically, we developed a stochastic Markov chain model of quiet stance using COP data. The Markov model was used to create a novel analysis technique termed Invariant Density Analysis (IDA). IDA was then used to compare quiet standing data from young, middle-aged, and older adults.

METHODS

Mathematical Background (*Modeling Stochastic Systems):* Dynamical systems are approximated using mathematical models to describe the states of the system and evolution of those states. The evolution of the system can be a deterministic or stochastic process. Deterministic models have only one possible future state that evolves from the current state (e.g., differential equations that describe the motion of a pendulum). Stochastic models have several potential states, and the likelihood that the stochastic system evolves to a particular state is described using a probability distribution. A stochastic process is called Markov if future states are independent of all past states given the present state [4]. In other words, the description of the present state fully captures all the information that could influence the future evolution of the process.

At each step, the probability distribution describes how likely the system is to remain in the current state or change from the current state to another state. The changes to a state are called transitions, and the probabilities associated with various state changes are called transition probabilities. If there are finite states, the transition probabilities can be expressed in the form of a matrix known as the transition matrix, P. The evolution of the probability distribution is expressed as, $\lambda_{n+1}= \lambda_n P$, where λ_n is the distribution of the state at the n-th iteration. If the Markov chain is irreducible, it will converge to a steady state distribution with an equilibrium equation, $\pi= \pi P$, where π is known as the invariant density. π is determined from the transition matrix P and is defined as the left eigenvector of P with an eigenvalue of 1.

IDA Analysis: This section will present the methods for calculating the invariant density and the parameters that make up Invariant Density Analysis. The Markov model of the quiet standing system and the invariant density were calculated in the following manner. First, the average location of the planar COP was used to locate the centroid of the data. The data points were then zero adjusted using the average, and system states where defined as concentric rings emanating from the centroid. The width of the rings, 0.2 mm, was determined by the level of noise of the force platform. Second, the transition matrix was constructed using transition probabilities that were solved by counting the number of COP data points that remained in the current state or moved to a new state at each time step. Third, the invariant density was computed by solving for the left eigenvector of the transition matrix with an eigenvalue of one.

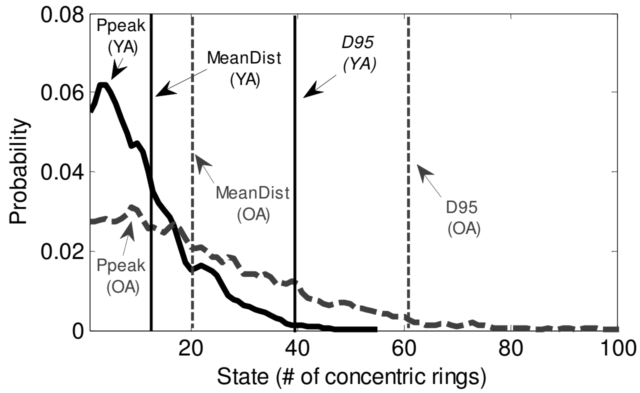

Figure 1. A plot of the invariant densities of both a young (YA, solid) and old (OA, dashed) subject showing the probability that the COP will be found in a particular state. Total probability under each curve is equal to 1.

Five parameters were used to characterize the invariant density (Figure 1) and offer insight into the physiology of the system.

1. *Ppeak*: Identifies the largest probability of the invariant density.
2. *MeanDist* ($\sum_{i\in I} i\pi(i)$): Weighted average state (or average location) of the COP. *I* is the set of all states.
3. *D95*: 95% of the COP data are contained within and below this state.
4. *EV2*: The second largest eigenvalue of the transition matrix. This corresponds to the rate of convergence of the invariant density.
5. *Entropy* ($-\sum_{i\in I} \pi(i)\log_2\pi(i)$): Describes the randomness of the system; i.e., low entropy corresponds to a more deterministic system and high entropy refers to a more stochastic system.

Experimental protocol: Fifteen subjects from three different age groups (young (20-30yrs), middle-aged (40-60yrs), and old adults (62-80yrs)) were analyzed. Each subject was asked to stand quietly on a force platform (AMTI BP600900) using a self-selected stance with arms crossed at the chest and eyes open. Ten 30s trials were conducted for each subject. Foot tracings were used to maintain consistent stance between trials. Data were recorded with at a frequency of 1000 Hz.

Statistical analysis: One-way analysis of variance (ANOVA) was used to test for differences between the groups (SPSS Inc., Chicago, IL; v15). Tukey's Honestly Significant Differences (HSD) tests were used for post-hoc comparisons. The level of significance was set to $\alpha = 0.05$.

RESULTS

Significant age-related differences for all 5 parameters were found, Table 1. Post-hoc tests revealed statistically significant differences between young and old adults for all IDA parameters, and between young and middle-aged adults for two parameters. There were no significant differences between middle-aged and old adults.

Table 1. IDA parameters for each age group. Mean±SE

	Young n=15	Middle n=15	Old n=15	p
Ppeak	.052±.003	.040±.002‡	.034±.002†	<.001
MeanDist	3.19±0.18	3.70±.18	5.20±.80†	.015
D95	7.99±0.47	9.20±.47	13.62±2.33†	.017
EV2	.995±.002	.999±.0001	.9995±.0001†	.034
Entropy	5.19±.09	5.53±0.07‡	5.82±.10†	<.001

† Young and old adults are significantly different
‡ Young and middle-aged adults are significantly different

DISCUSSION

In this study, we introduced a novel technique for analyzing steady-state quiet standing behavior, termed Invariant Density Analysis (IDA). IDA was applied to data from young, middle-age, and old adults, and showed significant differences in IDA parameters between the groups. The differences between the young and old populations were the most apparent. For the young adults, *Ppeak* was significantly larger, while both *MeanDist* and *D*95 were significantly smaller than the older population. Larger *Ppeak* and smaller *MeanDist* values in the young data result from invariant densities with noticeable peaks in the probability distributions located close to the centroid. Data from older subjects had smaller peaks and more uniform distributions. Additionally, the larger *MeanDist* and the smaller *Ppeak* values in the older population illustrate that the data points wander further from the centroid and are less likely to be found in any particular state for this group. Both of these trends are illustrated in Figure 1.

The larger *Entropy* value for the older population indicates that the COP follows a more stochastic path, while a smaller *Entropy* value for the young adults indicates more deterministic information in the data. This can be interpreted as young adults using a greater degree of 'active control' to keep the COP trajectory closer to the centroid. Finally, the second eigenvalue, *EV2*, is significantly smaller for the younger subjects showing that they converge more quickly to their steady-state behavior. This result suggests that younger subjects have a faster response time than older subjects. The middle-aged subjects also have significantly smaller *Ppeak* and larger *Entropy* values than the younger subjects. Again, this indicates that the postural sway behavior for middle-aged adults is less likely to be found in a particular state and is more stochastic. Invariant Density Analysis is a novel stochastic COP analysis technique which can be used to provide physiological insight into the mechanisms used to maintain quiet stance.

REFERENCES

[1] Prieto, T.E. et. al., IEEE Trans Biomed Eng, Vol 43, 1996
[2] Doyle, T.L., Newton, R.U., Burnett, A.F., Arch Phys Med Rehabil, Vol 86, October 2005.
[3] Collins J.J, De Luca, C.J., Exp Brain Res, Vol 95, 1993.
[4] Norris J.R, Markov Chains, Cambridge, 1998

ACKNOWLEDGEMENT

Authors thank Prof. Prashant Mehta for guidance and comments

