Examining quiet standing center of pressure data using invariant density analysis

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INTRODUCTION

Center of pressure (COP) has been frequently collected to assess postural stability.

Traditionally, COP has been analyzed by its shape or speed of the trajectory [1]. However, those techniques lack physiological insights and have questionable reliability [2].

Some other stochastic approaches do not provide easy interpretation [3]

In this study, we developed and proposed a novel method to analyze COP using Markov chains, which address these previous weaknesses.

METHODS

Mathematical background:

Stochastic models of dynamical systems have several potential states, and the likelihood that the stochastic system evolves to a particular state can be described with probability distributions.

A stochastic process is called "Markov" if future states are independent of all past states given the present state.

At each time step, the probability distribution describes how likely the system is to remain in the current state or change from the current state to another (called transition).

If there are finite states, the transition probabilities can be expressed in the form of transition matrix, $\boldsymbol{P}$.

The evolution of the probability distribution is expressed as

$$\lambda_{n+1} = \lambda_n \boldsymbol{P}$$

where λ_n is the distribution of the state at the n-th iteration.

If the Markov chain which is stochastic process with Markov property is irreducible, the probability distribution converges to a stationary distribution, which is expressed as

$$\boldsymbol{\pi} = \boldsymbol{\pi P}$$

where $\boldsymbol{\pi}$ is known as the ***invariant density***.

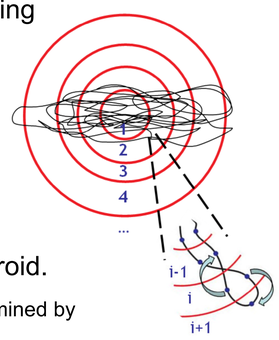
$\boldsymbol{\pi}$ is determined from the transition matrix $\boldsymbol{P}$, as the left eigenvector of $\boldsymbol{P}$ with the eigenvalue of 1.

In this analysis, $\boldsymbol{P}$ represents the dynamics of COP in probability and $\boldsymbol{\pi}$ represents the long term behavior of COP.

References:
[1] Prieto, T.E. et al. *IEEE Trans Biomed Eng,* Vol43, 1996.
[2] Doyle, T.L. et al. *Arch Phys Med Rehabil,* Vol86, 2005.
[3] Collins J.J., De Luca, C.J., *Exp Brain Res,* Vol95, 1993.

Invariant Density Analysis (IDA) and the algorithm:

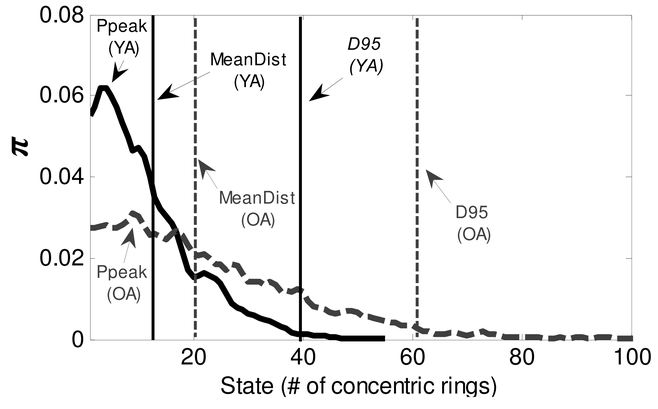
Invariant Density Analysis involves determining the invariant density probability distribution and examining several key parameters associated with this distribution.



Algorithm to find invariant density

1) Zero adjust the COP to centroid .
2) Define each state as the enumeration of concentric rings emanating from the centroid.
   The width of each ring was 0.2 mm (determined by the level of noise of force platform).
3) Construct transition matrix.
4) Solve for the transition matrix $\boldsymbol{P}$ from the equation

$$\boldsymbol{\pi} = \boldsymbol{\pi P}$$



In order to have meaningful interpretation of π, we have defined five IDA parameters.

1) ***Ppeak***: Peak value of the invariant density probability.
2) ***MeanDist*** [$\sum i\,\pi(i)$]: Average location of the COP.
3) ***D95***: 95% of the COP distribution is contained within and below this state.
4) ***EV2***: The second largest eigenvalue of $\boldsymbol{P}$. This corresponds to the rate of convergence to the invariant density.
5) ***Entropy*** [$-\sum \pi(i)\,log_2\,\pi(i)$]: 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 to collect COP during quiet stance:

45 subjects from 3 age groups (young (20-30yrs), middle-aged (40-60yrs), and old adults (62-80yrs)).

Each subject stood 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 with sampling frequency of 1000 Hz.

Statistical analysis:

One-way ANOVA was used to test for differences in IDA parameters between the groups. Tukey's Honestly Significant Differences (HSD) tests were used for post-hoc comparisons. The level of significance was set to α=0.05 (SPSS v15).

RESULTS

Table 1. *Mean (SE) model parameters.*

Parameter	Young	Middle	Old	*p*-value
Ppeak	0.052 (0.003)	0.040 (0.002)	0.034 (0.002)†	<0.001
MeanDist (mm)	3.19 (0.18)	3.70 (0.18)	5.20 (0.80)†	.015
D95 (mm)	7.99 (0.47)	9.20 (0.47)	13.62 (2.33)†	.017
EV2	0.995 (0.002)	0.999 (0.0001)‡	0.9995 (0.0001)†	.034
Entropy	5.19 (0.09)	5.53 (0.07)	5.82 (0.10)†	<0.001

† Significantly different from young and middle-aged adults.

‡ Significantly different from young adults.

IDA parameters found significant age differences.

It was found that COPs of older population wander farther (***MeanDist, D95***) from the centroid, are less likely to be found in any particular state (***Ppeak***) in slower (***EV2***) and more stochastic ways (***Entropy***) suggesting that older adults are less robust and are using a less degree of active control to keep the COP closer to centroid.

SUMMARY

In this study, we proposed a novel method to examine postural stability and characterize the behavior of the center of pressure (COP) using Invariant Density Analysis (IDA).

IDA significant identified age differences. IDA can be used to provide physiological insight into the mechanisms used to maintain quiet stance.

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