# CHAOS LEVEL INVESTIGATION OF CENTRE-OF-PRESSURE SINGLE-STEP DISPLACEMENT IN STATIC AND DYNAMIC VISUAL CONDITIONS

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Abstract: As a convenient and feasible measure of postural control, centre-of-pressure (CoP) trajectories are investigated in most of postural research. The characteristics extracted from CoP trajectories provide valuable evidences in nature explorations of postural control. In this research, Shannon entropy is introduced into CoP trajectories analysis to reveal random characteristics of human upright postural control. In our Shannon entropy analysis, chaos level of CoP single-step displacement is inspected in static and dynamic visual conditions. Experimental results from twenty-one subjects under four visual conditions indicate that human postural control in upright stance appears more regulated in direction control than in amplitude control. This conclusion has specific significance in postural experiment design and postural control improvement.

## 1 INTRODUCTION

Postural control is widely investigated in posture-related realms, such as balance assessment, motion analysis, disease rehabilitation and elderly or disabled assistance. Numerous researchers performed their explorations of postural control through signal analysis (Rougier, 1999), model simulation (Hidenori & Jiang, 2006) and sense-influence investigation (Rougier, 2004). Although these researchers have made many achievements, current investigation into postural control is still far from completion.

Sense-influence investigators care about visual, vestibular, and proprioceptive influence on postural control. These researchers inspect subjects' postural responses by manipulating postural environments. Bronstein (1986) studied visually evoked postural response by positioning subjects on an earth-fixed force platform inside a movable room. Mergner (2005) and his cooperators placed subjects on a rotational force platform inside a rotational cabin to explore the visual induced postural saturation.

Other investigators focus their efforts on postural data analysis and model simulation. As a measure of posture, displacements of centre-of-pressure (CoP) are largely analyzed in postural control research. The CoP is the point location at which the vertical ground reaction force is applied. Collins and De Luca (1993) analyzed CoP trajectories of upright stance and presented a stabilogram-diffusion plot. Based on the plot, the researchers suggested that open-loop and closed-loop control schemes were utilized by the postural control system over different time intervals. Peterka (2000) demonstrated similar plots through simulation with a purely closed-looped control model. Therefore, Peterka (2000) hypothesized that a nonlinear open-loop operation might be unnecessary for upright stance maintenance.

In our research, Shannon entropy is introduced into the analysis of CoP trajectories in order to reveal random characteristics of human upright postural control. With the entropy analysis, CoP single-step displacements are investigated both in amplitude and deflection angle. Furthermore, static and dynamic visual conditions are designed to confirm the validity of our findings.

## 2 METHODS

Upright stance in two static (S1 and S2) and two dynamic (D1 and D2) visual conditions is examined


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in this study. As Figure 1-a shows, the first visual scene (in S1) displays a stationary black background; as Figure 1-b indicates, in the second scene (in S2), a stationary white spot is added in the centre of the aforementioned background; as Figure 1-c pointed out, in the third scene (in D1), the white spot moves with its position controlled by preset signals; and as Figure 1-d exhibits, in the last scene (in D2), the motion of the white spot follows the changes of CoP of each subject, and a stationary blue circle is additionally displayed in the centre of the background.

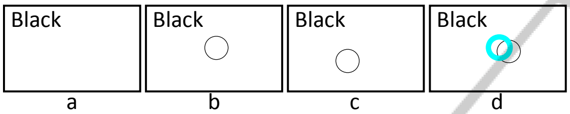


Figure 1: Schematic representation of static and dynamic visual scenes.

## 2.1 Subjects

Twenty-one healthy adult volunteers (seven females and fourteen males) aging from twenty-two to thirty-two years (mean ± standard deviation: age 25.7 ± 1.6 years; weight 61.4 ± 7.9 kg; height 169.1 ± 5.5 cm) were included in this study. Every subject participated in all 40 trials of the four visual conditions. None of the subjects had evidence or known history of any gait, postural, or musculoskeletal disorder. All of the subjects had normal or corrected-to-normal vision. Informed consents were obtained from all subjects prior to their participations.

## 2.2 Apparatus

The experiment was conducted in a closed area (2.5m×4.0m) that was isolated with a shade curtain and two walls, as shown in Figure 2.

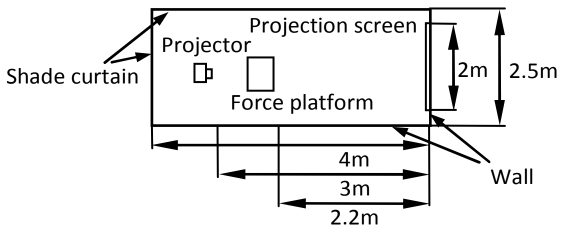


Figure 2: Schematic experimental environment.

In the closed area, a projection screen (1.5m ×2m) was hung on the front wall, a projector (Toshiba TDP-T355) was fixed on the ceiling, and a force platform (Kistler 9286BA) was settled horizontally 2.2m from the projection screen. Connected with the projector and the force platform, a desk-top computer generated visual scenes, controlled the CoP data acquisition, and performed other necessary work, for example, data saving and processing.

## 2.3 Procedure

Subjects were instructed to stand barefoot on the force platform in a comfortable stance, in front of the projection screen, with their arms hanging naturally beside their body.

In S1 and S2, subjects were required to keep their body as immovable as possible, with their eyes looking straight at the black background (for S1) or focusing on the stationary white spot (for S2).

For D1, the spot rested at the centre of the background in the first five seconds, and moved with preset signals during the left time of a trial. In vertical direction, the preset signal was the summation of a sinusoidal curve and a white noise, but in the horizontal, just a white noise. In D1, subjects were asked to keep their body as still as possible, with their eyes fixed on the spot whether it held still or moved.

In the first five seconds of D2, the spot was located at the centre of the background. In this stage, subjects were asked to keep their body immovable as much as possible, with their eyes focused on the spot. At the end of this stage, the mean position $CoP_{mean}$ of CoP was calculated, and the spot began to move. During the left time of D2, the spot was controlled by CoP of subjects and the displacement of the spot was linear to the difference between the current CoP and $CoP_{mean}$. In coordinates, motions of the spot from top to bottom and from left to right on the background respectively denoted movements of the CoP in anterior-posterior and media-lateral direction. In this stage, subjects were instructed to control their upright posture to make the spot to be overlapped by the stationary circle, but relative movements between the body components were not allowed except between the feet and the else body parts.

Several practice runs were performed prior to the test to ensure that subjects had mastered the relationship between the spot motion and their body sway, and could act as the instructions asked them to do.

In our research, subjects needed to finish ten 40s-lasting trials for each condition. Between every two of these ten repeated trials, subjects had one minute of rest time, and after all of these ten trials, at least ten minutes. Although only the data of the last 30s were valid in the signal processing, CoP data were recorded all through every trial, with a 1 KHz sampling frequency.

### 2.4 Signal Processing

According to Shannon entropy theory, the entropy of a random variable is related to the information that the observation of the variable gives. The more unpredictable and unstructured the variable is, the larger its entropy (Hyvarinen, Karhunen, & Oja, 2001). In our investigation, the CoP single-step displacement is regarded as a random variable. Entropy of this variable reflects the adjustment effects of the postural control system. The larger the entropy is, the less the variable is controlled.

Defined by Shannon entropy theory, the entropy $E$ of a random variable $Y$ with probability mass function $p_Y(y_k)$ is:

$$E(Y) = -\sum_{k=-\infty}^{+\infty} p_Y(y_k) \log p_Y(y_k) \tag{1}$$

To get the entropy, the probability mass function of CoP single-step displacements needs to be estimated. Postulate the modulus $R$ and the deflection angle $\Theta$ of CoP single-step displacements are random variables. Their observations, $r_k>0$ and $\theta_k \in [0, \pi)$, are calculated from CoP trajectories as demonstrated in Figure 3 by the following equations:

$$r_k = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} \tag{2}$$

$$\theta_k = \arccos \frac{\vec{r}_k \cdot \vec{r}_{k-1}}{|\vec{r}_k| \cdot |\vec{r}_{k-1}|} \tag{3}$$

where

$$\begin{aligned} \vec{r}_k \cdot \vec{r}_{k-1} = {} & (x_k - x_{k-1})(x_{k-1} - x_{k-2}) \\ & + (y_k - y_{k-1})(y_{k-1} - y_{k-2}) \end{aligned} \tag{4}$$

$$|\vec{r}_k| = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} \tag{5}$$

$$|\vec{r}_{k-1}| = \sqrt{(x_{k-1} - x_{k-2})^2 + (y_{k-1} - y_{k-2})^2} \tag{6}$$

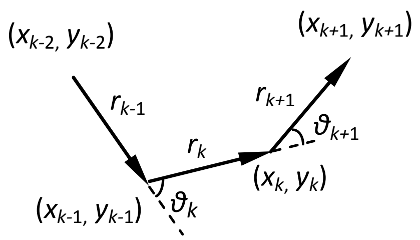


Figure 3: Schematic representation of calculation of $r_k$ and $\theta_k$. $(x_{k-2}, y_{k-2})$, $(x_{k-1}, y_{k-1})$ , $(x_k, y_k)$ and $(x_{k+1}, y_{k+1})$ are sequential points on a CoP trajectory.

Then, the finite value ranges $[\min(r_k), \max(r_k)]$ and $[\min(\theta_k), \max(\theta_k)]$ of $r_k$ and $\theta_k$ are divided into $n$ equal-lengthed subintervals individually:

$$[\min(r_k), \max(r_k)] = \bigcup_{i=0}^{n-1} R_i \tag{7}$$

$$[\min(\theta_k), \max(\theta_k)] = \bigcup_{j=0}^{n-1} \Theta_j \tag{8}$$

where $\forall p, q \in [0, n\text{-}1]$, $p \neq q$, $R_p \cap R_q = \emptyset$, and $\Theta_p \cap \Theta_q = \emptyset$. Suppose $m(\cdot)$ represent Lebesgue measure in $\mathbf{R}^1$. The following equations are satisfied:

$$m(R_0)=m(R_1)=\ldots=m(R_{n-1}) \tag{9}$$

$$m(\Theta_0)=m(\Theta_1)=\ldots=m(\Theta_{n-1}) \tag{10}$$

Let $f_R(i)$ and $f_\Theta(j)$ respectively represent the ratios of the numbers of $r_k$ and $\theta_k$ in arbitrary subintervals $i$ and $j$ and the total numbers of $r_k$ and $\theta_k$. The estimation of the probability mass functions $f_R(r_k)$ and $f_\Theta(\theta_k)$ of $R$ and $\Theta$ can be obtained as follows:

$$\hat{f}_R(r_k) = f_R(i) = \frac{\mu(\{r_k : r_k \in R_i\})}{\mu(\{r_k\})} \tag{11}$$

$$\hat{f}_\Theta(\theta_k) = f_\Theta(j) = \frac{\mu(\{\theta_k : \theta_k \in \Theta_j\})}{\mu(\{\theta_k\})} \tag{12}$$

where $i, j \in [0, n\text{-}1]$ and $\mu(\cdot)$ denoting the amount of the elements in the set. Thus, the entropy of $R$ and of $\Theta$ are obtained by the following expressions:

$$E(R) = -\sum_{i=0}^{n-1} f_R(i) \log_{10} f_R(i) \tag{13}$$

$$E(\Theta) = -\sum_{j=0}^{n-1} f_\Theta(j) \log_{10} f_\Theta(j) \tag{14}$$

## 3 RESULTS

In a total of 840 trials in our investigation, for all subjects and all visual conditions, the resultant entropy of $R$ of CoP single-step displacement remains larger than entropy of $\Theta$, without exception. Figure 4 demonstrates an example of our experiment results for an individual subject, and Table 1 shows the entropy results for the whole population of subjects in different visual conditions.

Figure 4 and Table 1 explicitly indicate a regulation that the entropy of $R$ is always larger than entropy of $\Theta$, no matter in which visual environment. This regulation reveals that the chaos level of CoP single-step displacement is higher in amplitude than in angular. Since CoP trajectories reflect performance of postural control, speculation can be deduced from this result that human upright posture may be regulated more in direction control than in amplitude control under the four specific visual conditions.

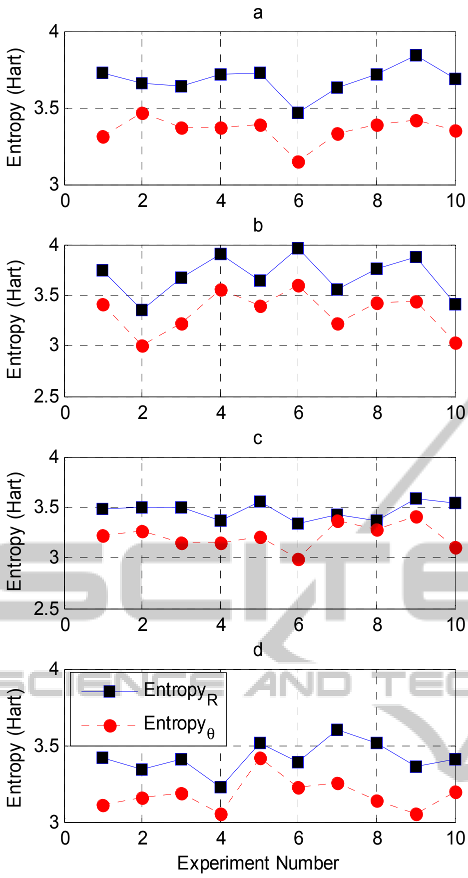


Figure 4: Entropy of *R* and Θ of ten trials from one subject in both the static and dynamic visual conditions: a. for S1; b. for S2; c. for D1; d. for D2.

Table 1: General entropy of *R* and Θ from the population of subjects under different visual conditions.

| | Entropy of *R* (Hart) (mean$\pm$SD) | Entropy of Θ (Hart) (mean$\pm$SD) |
|---|---|---|
| S1 | 3.5808$\pm$0.0215 | 3.2421$\pm$0.0171 |
| S2 | 3.6156$\pm$0.0196 | 3.2869$\pm$0.0173 |
| D1 | 3.3803$\pm$0.0153 | 3.1407$\pm$0.0149 |
| D2 | 3.3988$\pm$0.0135 | 3.1561$\pm$0.0143 |

## 4 DISCUSSION

In this study, the entropy of CoP single-step displacement in human upright postural control under specific visual conditions is investigated. This investigation presents a result of larger amplitude entropy and smaller angular entropy of CoP single-step displacement. This result suggests that the angular control is more regulated than the amplitude control in human upright stance maintenance.

However, these findings may be related to our experimental settings, for example, the visual scenes provided. In our future research, alternation of visual scenes will be made to further confirm our suggestion that upright stance is more regulated in direction control than in amplitude control. If this suggestion can be confirmed, displaying more detectable visual information will provide a feasible way to improve the control ability of human upright stance. To this extent, the chaos level investigation of CoP single-step displacement through entropy analysis in this presentation has directive significance for postural experiment design and meaningful implications to postural control improvement.

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