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Metastable postural coordination dynamics

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HIGHLIGHTS

- Metastable center-of-mass and head coordination was found in the majority of trials.
- A bifurcation from bi-metastability to mono-metastability occurred.
- Task difficulty appeared to act as a control parameter.

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ABSTRACT

The present study examined the coordination dynamics of the head and center of mass (COM) using accelerometry in quiet 1 and 2 leg stance with and without vision. The root mean square jerk of effectors was greater in 1 leg stance and without vision, and was greater for the head in 2 leg stance and greater at the COM for 1 leg stance. The coordination of the COM and head was more variable in 1 leg stance with vision than in the other stance and vision combinations. Both grouped and individual participant data showed metastable coordination dynamics with the presence of ghost attractors on both axes of motion that varied with the task. The findings indicated that stance and visual information conditions acted as control parameters, with increments in task difficulty increasing relative phase variability until a bifurcation in the metastable dynamics occurred in 1 leg stance without vision.

1. Introduction

The dynamics of hip–ankle coordination have previously been investigated in a protocol involving voluntary postural sway about the anteroposterior axis of motion. In these dynamics phase transitions occur from in-phase to antiphase as movement frequency is scaled-up and from antiphase to in-phase as movement frequency is scaled down [2,8]. In hip–ankle coordination the attractor for the in-phase coordination mode is located approximately between 30° and 60° and the antiphase mode approximately between 170° and 200° [2,7]. The in-phase and antiphase hip–ankle coordination modes [1,2,6,7] found in voluntary postural movement have been associated with the hip and ankle strategies previously identified in the maintenance of quiet stance [8–10,19–22].

Coordination dynamics can be metastable, as well as stable. Metastability occurs due to the competing tendencies of components to couple together and to engage in individual behavior [14,15]. Coordinative states become metastable when the attractor dynamics become unstable. Unstable attractor dynamics are termed 'ghost attractors' and result in phase scattering and phase trapping, with a small degree of attraction to the unstable attractor states. Phase trapping occurs for brief periods of time near these weakly attractive attractor states followed by continued phase scattering. Metastability has previously been found in behavioral [16] and brain dynamics [12,13,17,18].

Wang and Newell [23] found that in quiet stance the phase relation between the center of pressure for the two feet was characterized by epochs of phase synchronization, with the number and duration of these epochs dependent upon stance characteristics. The epochs of phase synchronization found in this study are equivalent to phase trapping and the periods of time outside these epochs equate to phase scattering. This may indicate the presence of metastability in the coordination of the center of pressures of the two feet. However, the determination of metastability in these dynamics would need to include an analysis of the relative phase distributions to determine if the epochs of phase trapping are concentrated around recurrent relative phase values. If so, these areas of higher relative phase concentration would be consistent with metastability and the presence of ghost attractors located at these values of higher relative phase concentration within the intrinsic dynamics landscape.

The present study examined the coordination of the head and center of mass (COM) kinematics during quiet stance to shed light

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on the dynamics that organize standing posture. In this experiment participants performed 4 postural tasks. The movement jerk of the COM and the head were estimated as an index of task difficulty. The variability of coordination for the COM and the head along the anteroposterior (AP) and mediolateral (ML) axes of motion were estimated and the Rao's spacing test was used to determine if a modal distribution was present in relative phase time-series along each axis of motion. The simultaneous occurrence of both phase wrapping and modal distributions would indicate the occurrence of metastable coordination dynamics.

2. Methods

2.1. Participants

Healthy young adult participants ($N = 31$; 14 males, 17 females) with a mean age of 25.19 (*SD* 4.42) years volunteered for this study. All participants signed an informed consent form that was approved by the local Institutional Review Board. All participants stated they had no prior surgery or injury to the lower extremities.

2.2. Task and procedure

Two biometrics (Ladysmith, VA) ACL300 3-D accelerometers were attached to the posterior of the head and of the trunk approximately at the level of the COM. DataLINK software was used to collect acceleration data at a sampling rate of 1000 Hz during movement trials. The accelerometer on the posterior side of the trunk was attached with adhesive tape approximately behind the COM (approximately at the level of the 2nd sacral vertebra). The other accelerometer was attached to the back of a hat that was worn by participants during testing.

Each participant performed 1 trial of 30 s duration for each of 4 postural tasks. A single trial was used to reflect the need for postural control in real life tasks without the opportunity to warm up or practice. Task 1 consisted of two leg stance with the eyes open. Task 2 was 2 leg stance with the eyes closed. Task 3 was balance on only the preferred leg with the eyes open and Task 4 was balancing only on the preferred leg with the eyes closed. The preferred support leg was determined by allowing the participants to self-select which leg they used for support during the 1 leg stance tasks. For Tasks 1 and 3 the participants were instructed to look at a dot located on a wall 1.5 m in front of them. The participants were instructed to stand as still as possible in each task and the task order was counterbalanced. DataLINK software was used to collect acceleration data at a sampling rate of 1000 Hz during movement trials.

2.3. Data analysis

The AP and ML acceleration data were filtered with a 9th order 20 Hz low pass Butterworth filter. Jerk was calculated from acceleration data *via* a finite difference equation. The root mean square jerk (RMSJ) was then calculated for the AP and ML axes of motion for each accelerometer. Data were then down-sampled to 40 Hz.

Rao's spacing test [3] was used to determine if relative phase time-series differed significantly from a uniform distribution. Relative phase time-series that differed significantly from a uniform distribution were examined to determine if they were stable or metastable. Metastability was operationalized *via* the occurrence of phase scattering. Stable relative phase coordination was defined as non-uniform distributions that did not exhibit phase scattering.

The relative phase of the head and COM was estimated from accelerometry data for the AP and ML axes of motion. The acceleration and jerk time-series from each accelerometer and each axis of motion were normalized from −1 to 1. Phase angle time-series were calculated by plotting the acceleration *vs.* the jerk of the head and COM for each axis of motion. Continuous relative phase was determined as the head phase angle minus the COM phase angle. The variability of coordination was estimated with the Information Entropy of relative phase. Information entropy [24] is calculated as:

$$I_w = -\sum_{i=1}^{N} P_i \log P_i \qquad (1)$$

where I_w is information entropy, i is each of a total of N data values and P is the probability of data occurring in each bin. A bin size of 10° was used to determine the probability of relative phase occurrences across the $0^\circ \leftrightarrow 360^\circ$ range. This statistic was used as an estimate of variability because it does not depend upon the assumption of a von Mises distribution (the circular counterpart to the Gaussian distribution), as does the use of the circular *SD*.

Four 2 (effector) × 4 (stance) ANOVA were used to analyze the RMSJ and relative phase entropy data from the AP and ML axes of motion. The calculation of all dependent variables was performed with coded MATLAB (Mathworks, Natick, MA) programs. Inferential statistical analyses were performed using the SPSS software package (version 19.0) and an alpha of 0.05 was used to determine statistical significance.

3. Results

3.1. Root mean square jerk

3.1.1. Anteriorposterior

The ANOVA revealed a significant task effect, $F(3,90) = 91.857$, $p < 0.001$. In *post hoc* analysis the RMSJ in Task 1 was significantly lower than in Task 2 ($p = 0.048$). Tasks 1, 2 and 3 RMSJ were lower than in Task 4, and Tasks 1 and 2 were lower than in Task 3 (all $p < 0.001$). There was a significant accelerometer × task interaction, $F(3,30) = 35.519$, $p < 0.001$ (see Fig. 1a). *Post hoc* revealed that at the COM there was no significant difference between Tasks 1 and 2 ($p = 0.300$). Also, the RMSJ at the COM in Tasks 1, 2 and 3 were all significantly lower than in Task 4 (all $p < 0.001$) and Tasks 1 and 2 were significantly lower than Task 3 (both $p < 0.001$). Within the head accelerometer there was no significant difference between Tasks 1 and 2 ($p = 0.058$). Tasks 1, 2 and 3 were all significantly lower than Task 4 (all $p < 0.001$). Task 1 was significantly lower than Task 3 ($p < 0.001$) and Task 2 was significantly lower than Task 3 ($p = 0.009$).

Within Tasks 1 and 2 the RMSJ at the COM was significantly lower than in the head accelerometer (both $p < 0.001$). In Task 3 there was no significant difference between the head and COM ($p = 0.213$). In Task 4 the head RMSJ was significantly lower than at the COM ($p < 0.001$). The main effect for accelerometer, $F(1,30) = 0.020$, $p = 0.889$, was not significant.

3.1.2. Mediolateral

In the ML direction the head accelerometer RMSJ was significantly lower than at the COM, $F(1,30) = 13.184$, $p = 0.001$. There was also a significant main effect for task, $F(3,90) = 128.166$, $p < 0.001$ (see Fig. 1b). In *post hoc* analysis Tasks 1, 2 and 3 were significantly lower than Task 4 (all $p < 0.001$) and Tasks 1 and 2 were significantly lower than Task 3 (both $p < 0.001$). There was no significant difference between Task 1 and 2 ($p = 0.450$).

The accelerometer × task interaction was significant, $F(3,90) = 72.886$, $p < 0.001$. In *post hoc* analysis the RMSJ at the COM for Tasks 1, 2 and 3 were all significantly lower than in Task 4 (all $p < 0.001$). Tasks 1 and 2 were significantly lower than Task 3 (both $p < 0.001$) and Task 1 RMSJ was significantly lower than in Task 2 ($p = 0.026$). The RMSJ of the head for Tasks 1, 2 and 3 were significantly lower than in Task 4 (all $p < 0.001$). Task 1