Gait & Posture 34 (2011) 76–80

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Multi-segmental postural coordination in professional ballet dancers

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ARTICLE INFO

Article history:
Received 3 August 2010
Received in revised form 11 February 2011
Accepted 13 March 2011

Keywords:
Ballet
Coordination
Postural control
Relative phase
Cross-recurrence quantification analysis

ABSTRACT

Ballet dancers have heightened balance skills, but previous studies that compared dancers to non-dancers have not quantified patterns of multi-joint postural coordination. This study utilized a visual tracking task that required professional ballet dancers and untrained control participants to sway with the fore–aft motion of a target while standing on one leg, at target frequencies of 0.2 and 0.6 Hz. The mean and variability of relative phase between the ankle and hip, and measures from cross-recurrence quantification analysis (i.e., percent cross-recurrence, percent cross-determinism, and cross-maxline), indexed the coordination patterns and their stability. Dancers exhibited less variable ankle–hip coordination and a less deterministic ankle–hip coupling, compared to controls. The results indicate that ballet dancers have increased coordination stability, potentially achieved through enhanced neuromuscular control and/or perceptual sensitivity, and indicate proficiency at optimizing the constraints that enable dancers to perform complex balance tasks.

Balance experts, such as dancers, demonstrate balance enhancements due, in part, to faster and more consistent neuromuscular responses and enhanced proprioceptive sensitivity [1–6]. The basis of this expertise may reside in the establishment of coordinative structures (groups of muscles and associated neural, vascular, skeletal, and connective tissues, linked to behave as single autonomous units, i.e., muscle synergies [7]) that are sufficiently stable to allow highly exact control of postural control, while appropriately flexible to accommodate novel movement contexts. Many studies examining the balance capabilities of experts have employed variations of the quiet-stance paradigm, with the participant's primary goal to maintain balance without engaging in any other type of activity [8–11]. These types of studies have yielded inconsistent results; some indicated better performance by experts [8], some showed no differences [10], and others revealed differences only in the temporal structure of postural sway [11]. These findings have led some to conclude that quiet stance is not sufficiently challenging to elicit expertise, or not representative of the conditions in which balance expertise comes into play [9].

Studies that employed perturbations during static balance have reliably shown that experts exhibit faster postural responses resulting in greater overall stability [1,2,4]. These studies tell a more consistent story than those that employed quiet stance, yet an incomplete one. They typically employ unrealistically large perturbations atypical of normal balance demands that uncover response-based processes of coordination, but are limited in revealing processes by which movement coordination is prospectively controlled in anticipation of balance demands [12]. Tasks that evoke prospective, goal-directed coordination might offer new insights into the balance skills possessed by experts, and the goal of the present study was to employ such a task to identify differences in postural coordination between professional ballet dancers and untrained controls.

We employed the dynamic visual tracking task developed by Bardy and colleagues to investigate multi-joint, bi-pedal postural coordination [13,14]. The goal of the task is for the actor to use head motion to track oscillatory anterior–posterior (AP) displacements of a visual target. Maintaining balance while tracking the target requires coordination of angular excursions about the ankles and hips, as well as stabilizing actions at the knees. Typically two stable modes of ankle–hip coordination are exhibited during this task (see Fig. 1), and are expressed in terms of the *relative phase* (ϕ) between the joint angular excursions. The observed coordination pattern depends on parameters of the target's motion (e.g., frequency and amplitude). In-phase coordination ($\phi \approx 0^{\circ}$; the

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0966-6362/$ – see front matter
doi:10.1016/j.gaitpost.2011.03.016

ankle and hip are in the same points in their respective movement cycles, i.e., hip flexion accompanies ankle dorsiflexion) tends to occur at lower frequencies and smaller amplitudes, while anti-phase coordination ($\phi \approx 180^\circ$; the ankle and hip are at opposite points in their movement cycles) tends to occur at higher frequencies and larger amplitudes [13].[1]

This task has been employed to study the ability of expert gymnasts to sustain an in-phase pattern of ankle–hip coordination during high target-frequency conditions associated with anti-phase coordination [15]. The results indicated that gymnasts maintained the putatively more difficult in-phase pattern across a wider range of frequencies than untrained controls. However, one important and open question is how postural coordination stability, per se, changes with expertise.

Studies that showed heightened proprioceptive sensitivity in experts such as dancers motivated the hypothesis that experts will show greater coordination stability [10].[2] This sensitivity should associate with greater coordination stability, as proprioception is known to play an important role in the establishment of linkages among components of coordinative structures thereby enhancing neuromuscular control, particularly in multi-joint coordination [16–19]. We tested this hypothesis by requiring participants to stand on a single leg rather than bi-pedally to increase task demands, as previous results indicated that differences between experts and controls may not be apparent when postural demands are minimal [9].

We quantified postural coordination stability (i.e., variability) using the within-trial standard deviation of the ϕ time series, SDϕ. Higher SDϕ indicates more variable, less stable coordination patterns. Dancers were expected to exhibit lower SDϕ than untrained controls; however, based on inconclusive results in previous research no predictions were made regarding changes in SDϕ at either frequency [26]. SDϕ alone cannot parse out underlying mechanisms driving stability changes. These effects could arise from changes in the coupling strength of movements across joints, noise magnitude changes, or both [20]. Thus, cross-recurrence quantification (CRQ), a nonlinear time series analysis tool that examines time-correlated activity between two signals, was employed as an additional measure of stability that could distinguish these possible mechanisms. We hypothesized that greater coordination stability of the dancers would result from both stronger coupling (i.e., a higher deterministic coupling allowing the ankle and hip angular excursions to evolve together in a coordinated fashion over time) and less noisy ankle–hip coordination patterns [21,22].

1. Method

1.1. Participants

Twenty-eight professional ballet company dancers (10 males, 18 females; *M* age = 23.59 ± 3.99 years; BMI = 20.04 ± 2.01) and 28 controls with no ballet experience (10 males, 18 females; *M* age = 23.39 ± 4.99 years; BMI = 20.31 ± 2.12) from a university participated. Participants had normal or corrected to normal vision, with no history of neurological disorder, diabetes, or recent injuries to their back, arms, or legs.

1.2. Apparatus

Twin-axis SG-150 goniometers (Biometrics Ltd., Ladysmith, VA) were secured to the right and left ankle and hip using athletic tape (Jobst Cover-Roll Stretch Adhesive Gauze, Charlotte, NC) and measured joint angular displacements in the sagittal (AP) plane. Data acquisition and reduction were completed at 100 Hz using *DataLink PC Software v. 3.00* (Biometrics Ltd., Ladysmith, VA).

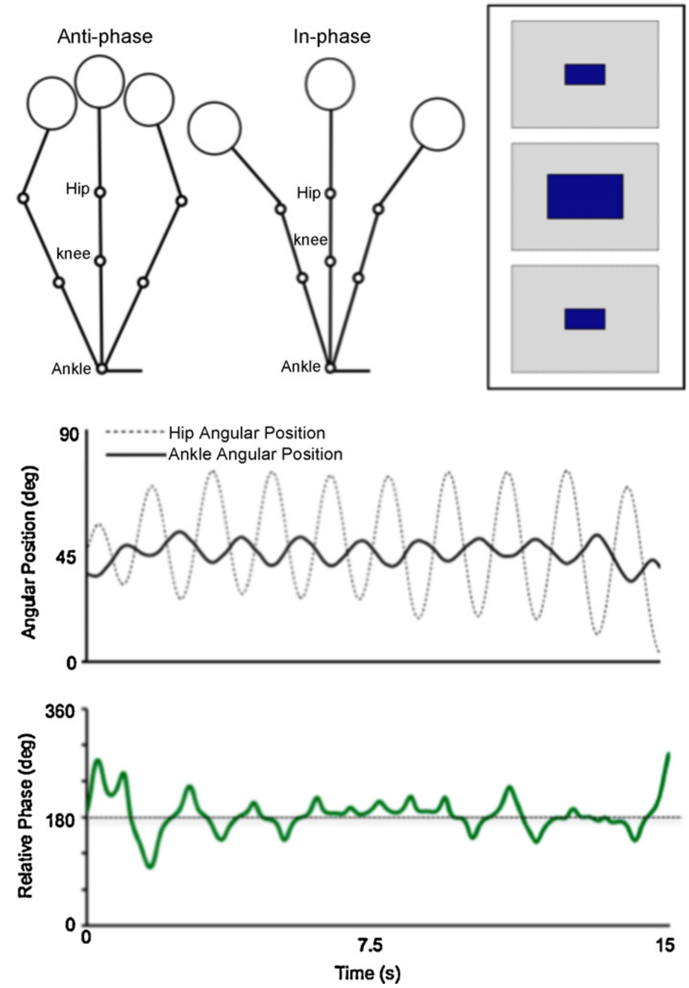

Fig. 1. Example of the two primary coordination patterns during the dynamic postural task (top left and top middle), a representation of one complete fore–aft oscillation cycle of the visual stimulus (top right), the ankle (transformed for viewing purposes) and hip angular position time series' (middle), and the ankle/hip relative phase time series (bottom).

1.3. Procedure

The university Institutional Review Board approved all procedures. Participants gave informed consent prior to participation. Participants stood barefoot on their left or right leg while tracking a computer-generated visual target with the head. They were instructed to maintain a perceived equal distance between the head and target at all times (apparent AP target amplitude = 63 cm). This amplitude was higher than in previous studies (typically 5–35 cm) but preliminary testing demonstrated it was possible to perform [13,14]. The target oscillated at a low (0.2 Hz) or high frequency (0.6 Hz) for 10 complete cycles on a given trial. These frequencies were selected because they fell within previously identified stable regions that produced in-phase (0.2 Hz) and anti-phase (0.6 Hz) coordination patterns [13]. Four trials (one per condition) were conducted.

1.4. Data reduction and analysis

1.4.1. Relative phase analysis

Hip and ankle joint angle time series were down-sampled to 25 Hz, smoothed using a 50 point (low-frequency condition) and 12 point (high-frequency condition) moving-window average, and then filtered using a low-pass Butterworth filter with a cut-off frequency of 5 Hz. Filtering and smoothing were utilized prior to relative phase analysis to allow for more clearly identifiable peak angular flexions of the ankle and hip time series.

We quantified coordination of ankle and hip excursions by first computing the respective phase angles (θ) of the ankle and hip joints, and then computing relative phase ($\phi = \theta_{\text{ankle}} - \theta_{\text{hip}}$). Joint angular displacements were used to calculate the

[1] Actual mean $\phi \approx 29^\circ$ (in-phase; low frequency) and 171° (anti-phase; high frequency) in the Bardy et al. experiment. This indicated that during in-phase coordination the ankle led the hip by almost 30° [13].

[2] The same participants as in the present study exhibited proprioceptive group differences during a separate experiment [10]. Specifically, the ballet dancers exhibited increased proprioceptive sensitivity compared to controls.

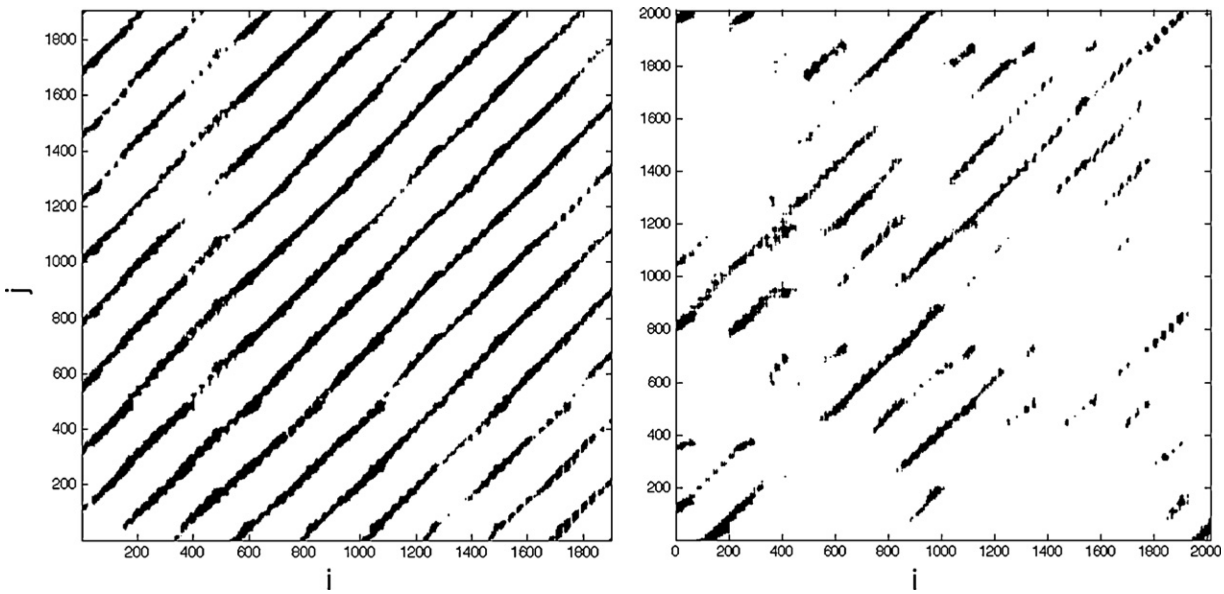

Fig. 2. Sample cross-recurrence plots for a single trial for a control (left) and dancer (right) during the low frequency tracking condition. The percentage of darkened pixels (i.e., of recurrent data points) equate to %CREC. The percentage of those points that fall on upward diagonal lines make up %CDET, which indicates a sequence of recurrent points (i.e., how often the ankle and hip trajectories evolved together). CML is the length of the longest diagonal line (i.e., the longest amount of time the ankle and hip trajectories evolved jointly). The group difference in %CDET is reflected in the tendency for the recurrent points (darkened pixels) of the control to occur in sequences (diagonal lines) compared to the dancers.

phase angles $\theta = \arctan(\dot{x}_i/\Delta x_i)$, where $\dot{x}_i$ is the angular velocity at sample i (normalized by the trial mean angular frequency) and Δx_i is the angular displacement at sample i (position at sample i minus the trial mean angular position). Continuous relative phase was calculated as the difference between the ankle and hip phase angles (i.e., $\phi = \theta_{\mathrm{ankle}} - \theta_{\mathrm{hip}}$) at each sample (Fig. 1). The within-trial mean relative phase for each time series was calculated to obtain ϕ, which expressed the average relative locations of the oscillating joints in their respective cycles. Values of ϕ departing from exactly 0° or 180° indicated a phase lead by one of the joints, with the sign reflecting which joint led the other (by convention a positive value indicates an ankle phase lead). SDϕ for each ϕ time series was also computed.

1.4.2. Cross-recurrence quantification (CRQ)

CRQ is a multivariate, nonlinear analysis in which time-correlated activity between two signals (e.g., sagittal-plane ankle and hip joint angular position) is quantified by embedding the pair of time series in a multidimensional space using the measured time series as the first dimension and successive time-delayed copies of that signal as additional dimensions [20,22,23]. Percent cross-recurrence (%CREC) was quantified by tracking when the two time series were in similar locations in embedding space (i.e., the embedded configuration of one time series was within some tolerance, i.e., radius, of the embedded configuration of the other). %CREC expresses the degree of overlap of the two trajectories and has shown to be inversely proportional to noise magnitude [21,24]. Cross-maxline (CML) is sensitive to coordination stability changes associated with coupling strength between the two joints, independent of noise magnitude. Specifically, CML measures the longest time that the ankle–hip angular trajectories were coupled [21,24]. %CREC and CML may indicate whether changes in SDϕ are linked to the specific mechanisms of noise magnitude or coupling strength, respectively. Percent cross-determinism (%CDET), an index of the regularity in the coordination of the two joints, was also computed. %CDET quantifies the extent to which two trajectories overlap for successive strings of data points (rather than isolated points along the trajectory)—that is, the degree to which the shared activity corresponds to shared patterns (i.e., sequences of common configurations) as opposed to simply shared configurations.

The CRQ parameters for the low-frequency (i.e., embedding dimension = 6, delay = 30 data points [i.e., 1/4 period], and radius within which points are counted as recurrent = 40% of the mean distance) and high-frequency (embedding dimension = 6, delay = 10 data points, and radius within which points are counted as recurrent = 40% of the mean distance) conditions were determined, respectively, using the average mutual information function and false nearest neighbors analysis [25]. CRQ was performed on unfiltered, unsmoothed time series that were down-sampled to 25 Hz to avoid artifacts in the identification of recurrences, which can result from over-sampling.

1.4.3. Statistical analyses

Participants performed the task standing on either the left or right leg; however, because the dancers did not consistently favor their "dominant" leg for take-offs and landings, which effectively rendered leg an uninterpretable factor, each measure was averaged across leg within a given trial (preliminary analyses including leg as a variable indicated that leg did not interact with group, regardless). The dependent measures (mean ankle–hip ϕ, SDϕ, %CREC, %CDET and CML) were submitted to separate 2 (group) × 2 (frequency) mixed-model analyses of variance (ANOVAs).

2. Results

2.1. Mean ϕ

Participants produced mostly anti-phase ($\phi \approx 180°$) coordination regardless of target frequency ($M = 182.86 \pm 11.94°$; 95% confidence interval ranging from 166.02° to 180.76°). No significant differences were observed for mean ϕ ($p > .05$).[3]

2.2. SDϕ

A significant main effect of group was found, $F(1,54) = 4.38$, $p = .041$, $\eta_p^2 = .08$, indicating that, overall, dancers exhibited lower SDϕ ($M = 30.86 \pm 17.79°$) than controls ($M = 40.15 \pm 18.43°$). No other significant effects were observed ($p > .05$).

2.3. CRQ

Fig. 2 depicts sample cross-recurrence plots, from which the CRQ measures are derived. Prior to analyzing %CDET and CML, a square root transform was applied to correct for unequal group variances. A significant group main effect was found for %CDET, $F(1,54) = 4.11$, $p = .047$, $\eta_p^2 = .07$, indicating a greater tendency for the ankle–hip trajectories produced by controls to share patterns of consecutive data points, compared to the dancers ($M = 92.51 \pm 5.68$, $M = 87.51 \pm 14.34$, respectively). A significant frequency main effect was found for CML, $F(1,54) = 71.37$, $p < .001$,

[3] Fourteen participants (seven per group) adopted in-phase coordination during at least one of the low frequency conditions. Analyses were run excluding these participants and the effects did not differ from the analyses including these participants for SDϕ and all CRQ measures. Thus, all analyses reported include these participants.

$\eta_p^2 = .57$, indicating more stable trajectories in the low- ($M = 360.26 \pm 305.76$) than the high-frequency condition ($M = 112.28 \pm 73.37$). No other effects were significant for %CREC, %CDET, or CML ($p > .05$).

3. Discussion

Participants mostly adopted anti-phase coordination ($\phi \approx 180^\circ$) with 25% of participants adopting in-phase coordination ($\phi \approx 0^\circ$) for at least one low-frequency trial. Both patterns are exhibited during bi-pedal stance [13–15], but anti-phase has shown to be the preferred coordination pattern for the single-leg version of this task [26]. This may be because ankle rotation produces an insufficient amount of torque with in-phase coordination (magnified in a single-leg context) and because in-phase coordination has not been observed at stimulus amplitudes greater than 30 cm [13,27]. In-phase coordination could also reflect a preference for a more energetically efficient mode whenever it was possible to produce sufficient amounts of torque to satisfy the target tracking demands [27]. Drawing conclusions is difficult given that an equal number of participants in both groups exhibited in-phase coordination, but expertise does not seem to play a role in the adoption of coordination patterns in this experimental context.

Dancers exhibited more stable ankle–hip coordination than controls (i.e., lower SDϕ). Enhanced stability might be a general feature of the advanced balance skill exhibited by dancers, as dancers have exhibited enhanced neuromuscular responses and proprioceptive sensitivity [1–6]. It is unclear whether greater postural coordination stability might be associated with speed of neuromuscular responses, but research does suggest these stability results could be related to enhanced proprioceptive sensitivity [16–19]. The tracking task entails proprioceptive feedback to establish and maintain reciprocal, functional linkages between the various muscles and joints and our results are consistent with the hypothesis of a direct relation between proprioceptive sensitivity and coordination stability, although this must be further examined.

The dancers exhibited less regular coordination (i.e., lower %CDET), differing from the controls in the opposite direction than predicted. We believed that tightly coupled ankle–hip trajectories would underlie increased stability (indexed by SDϕ). Taken with the SDϕ results, this could be revealing regarding the necessity of balancing stability of coordination patterns with flexibility and adaptability of the coordinative structures (e.g., Marin et al. demonstrated that gymnasts maintained difficult coordination patterns at non-optimal tracking frequencies) [15]. Higher %CDET could reflect an over-abundance of constraints in the coupling of ankle–hip oscillations, reflecting a less adaptive, highly rigid coupling ultimately limiting balance performance [27]. Dance training may reduce the number of constraints on ankle–hip coordination in order to enhance adaptability and flexibility of movement patterns. Dancer-like skill perhaps reflects an optimal level of deterministic coupling among movement system degrees of freedom [28]. If coupling strength is too low, performance may be unstable, but if it is too high, movement patterns may become rigid and less adaptable to changing conditions. In the tracking task, rigidly constrained ankle–hip coupling may not allow for an optimal level of reciprocal compensation that could dampen out variability that detracts from the desired movement outcome [29]. Thus, a study of how these coordination patterns develop in dancers throughout the course of training would be useful.

No group differences were found for %CREC or CML. It is generally difficult to show between-subjects effects using CRQ measures because of large variability in the magnitudes of recurrence measures across participants, and a lack of statistical significance for between-subjects factors must be cautiously interpreted. It has been demonstrated that when a between-subjects manipulation, indicating a clear trend for %CREC but no significant differences across conditions, was converted to a within-subjects manipulation, the manipulation showed the same pattern but was statistically significant [30]. The obvious interpretation is that the group differences in SDϕ do not reflect a difference between dancers and controls in either magnitude of neuromotor noise or the coupling strength of ankle–hip coordination, as indicated by data from bi-manual coordination and simulations [21,24], but this must be considered with caution. CML was higher in the low-frequency condition (irrespective of group), so this measure is indeed sensitive to the changes in stability detected by SDϕ in this context.

A limitation of this research is that the control population did not consist of athletes, making it difficult to ascertain whether the observed effects are due to ballet training or to the dancers' athletic expertise. Identifying an appropriate control group is challenging because of differences in athlete body types, and because sport training can involve implicit or explicit balance training. Regardless, future studies should examine sport-specific populations as comparison groups.

The postural coordination task employed in this study is useful for studying expert coordination given that postural control is not the primary task but must be organized functionally in order to complete an ulterior action; this is similar to the activities these experts engage in on a daily basis. This task also affords the use of dynamic coordination measures that may offer new and important insights into the organization and control of coordinative structures, ultimately leading to a new understanding of the nature of stability, variability, and flexibility of movement patterns in experts. Based on the present results, we conclude that dancer-like balance skill involves the ability to produce stable coordination patterns without rigidly constraining the coupling between movement system degrees of freedom.

Acknowledgements

Time and equipment support by NSF grants BCS 0716319, DHB 0728743, and BCS 0926662 and the University of Cincinnati William Seeman Fund. We would also like to thank Michael Tolston and Linda Kohne for their time contributions, and the Cincinnati Ballet Company and their dancers for their participation.

Conflict of interest statement

Jacqui Hass is employed by the Cincinnati Ballet Company, and the company could potentially benefit from the findings of this study, through the increased participation of children in their dance training programs. However, Jacqui was only involved with subject recruitment/manuscript preparation and not involved in the data collection or analysis process, while the Cincinnati Ballet Company did not contribute any funds or sponsor this work in any way that aided in the completion of this project. No financial or personal relationships exist between any of the other authors and other people or organizations that could inappropriately influence this work.

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