Exp Brain Res (2005) 163: 370–378
DOI 10.1007/s00221-004-2185-6

RESEARCH ARTICLE

Jennifer M. Schmit · Diana I. Regis · Michael A. Riley

Dynamic patterns of postural sway in ballet dancers and track athletes

Received: 11 August 2004 / Accepted: 1 November 2004 / Published online: 18 January 2005

Abstract We compared the variability and spatiotemporal profile of postural sway of trained ballet dancers to college varsity track athletes under variations in the availability of vision and rigidity of the support surface. We found no differences between the groups according to the variability measures, but variability increased for both groups with eyes closed and on a foam surface. Recurrence quantification analysis revealed that the postural sway of dancers was less regular (lower recurrence), less stable (lower maxline), less complex (lower entropy), and more stationary (lower absolute trend) than that of track athletes. Dancers, possibly as a result of focused balance training, exhibited different dynamic patterns of postural sway.

Keywords Balance · Postural control · Recurrence quantification analysis

Introduction

Ballet dancers exhibit high levels of expertise in movement control and balance. Although individuals with a predisposition for fine movement skill and balance control may likely be drawn to dancing (or gymnastics, or athletics), it is also highly likely that the training dancers receive contributes to their skilled balance control. One focus of dance training is technique, which involves strengthening and coordinating the musculature of the body to maintain proper alignment while moving through the positions and shapes intrinsic to the particular technique being studied. When a dancer studies a technique, the student is in a sense learning to mirror the neuromuscular and behavioral patterns of a model. A dancer focuses on sensing the changing relations of the moving body, not just on positions or steps, in order to accomplish the goal of mirroring the model. Training equips dancers with a keen awareness of movement (i.e., kinesthesis), balance, and of the body's orientation to the surrounding layout of surfaces (i.e., *exproprioception*—perception of the self in relation to the environment; Lee 1978).

Several studies have indicated better balance control in dancers than in control participants (Crotts et al. 1996; Golomer et al. 1997a, b, 1999a; see also Mouchnino et al. 1992). However, it has been argued that the specialized balance training received by dancers may only have an effect during challenging balance conditions, and may not transfer to less challenging balance conditions that are more representative of everyday life (Hugel et al. 1999). In the present study we compared postural stability and postural sway dynamics in dancers and a control group composed of physically fit individuals (college varsity track runners) who had not received dance training or any other form of specialized balance training. Sway measurements were obtained under challenging (foam surface) and non-challenging (rigid surface) conditions with the eyes either open or closed. Those manipulations addressed one of the two goals of this study—to clarify whether or not dancers exhibit better balance control in both challenging and normal balance conditions. If under relatively non-challenging stance conditions the dancers exhibit better balance abilities than individuals who lacked balance training, it would suggest that balance training has a pervasive influence on postural control that does not appear only when balance is directly threatened.

Vision plays an important and well-documented role in postural control. In general, postural sway increases in the absence of vision (Edwards 1946; Nashner 1989; Paulus et al. 1984; Witkin and Wapner 1950). The

This research was part of a senior honors thesis by the second author.

J. M. Schmit · D. I. Regis · M. A. Riley (✉)
Department of Psychology, University of Cincinnati,
ML 0376, 429 Dyer Hall, Cincinnati,
OH 45221-0376, USA
E-mail: michael.riley@uc.edu
Tel.: +1-513-5565544
Fax: +1-513-5561904

reduction in postural sway seen when vision is available is generally attributed to greater visual than proprioceptive or vestibular sensitivity to self motion (Easton et al. 1998). Vision seems to play a larger role than other perceptual systems in dancers' regulation of postural control (Hugel et al. 1999). Perrin et al. (2002) found that whereas both dancers and judo specialists exhibited better balance than control participants with the eyes open, only judoists performed better than controls with the eyes closed. The suggestion from this research is that dancers learn specific balance strategies related to visual detection and regulation of self-motion, and rely to a lesser extent than judoists on (haptic) proprioception. Dancers often train in front of mirrors and use visual landmarks (Golomer et al. 1999b), which might engender an increased visual dependency for dancers. However, other research suggests that dancers appear to be less dependent on vision than non-dancers, and that even though vision plays a major role in dancers' balance control they may rely to a greater extent on haptic proprioceptive and/or vestibular information than non-dancers (Golomer and Dupui 2000; Golomer et al. 1997a, 1999a). Since dancers exhibit heightened haptic-proprioceptive awareness of limb position (Ramsay and Riddoch 2001) it is possible that the effects of dance expertise in movement and balance control may not be limited to enhanced visual sensitivity to self-motion or enhanced ability to use visual landmarks for postural stabilization.

The present study employed static posturography to determine how visual perception and support surface rigidity affected postural stability in experienced ballet dancers. Postural sway measurements were obtained from dancers and track athletes under eyes-open and eyes-closed conditions when participants stood on either a rigid or compliant surface. Postural sway was operationalized as the center of pressure (COP), a measure of the displacement of the resultant ground reaction force vector on the force platform, equal to the weighted average of the points of application of all vertical forces acting on the force platform (Hamill and Knutzen 1995). The effects of balance training, vision, and support surface rigidity on postural stability were determined using standard measures of COP variability (standard deviation and path length of the COP). Higher variability is widely assumed to indicated lower postural stability (e.g., Gabel and Nayak 1984; Horak et al. 1989). We predicted less postural sway variability for the dancers.

The second goal of the study was to determine if dancers merely exhibit a different amount of postural sway variability or if in addition (or instead) they exhibit qualitatively different dynamic patterns of postural sway. Dynamic patterns of postural sway were quantified using recurrence quantification analysis (RQA; Webber and Zbilut 1994, 1996, 1998, 2004; for a detailed description of RQA applied to postural sway data, see Riley et al. 1999; see also Balasubramaniam and Turvey 2001; Balasubramaniam et al. 2000; Riley and Clark 2003). RQA is a nonlinear method for quantifying repeating (recurring) patterns in a time series. RQA involves embedding the measured time series in an n-dimensional space (formally related to the phase space of the system under investigation) to "unfold" the dynamics. Once the dynamics have been unfolded in that space RQA proceeds by (a) identifying instances of recurrence (when the time series revisits the same coordinates in the reconstructed phase space); (b) characterizing whether the recurring values are due to chance or a deterministic rule; (c) characterizing the complexity of the deterministic structure; (d) characterizing the mathematical stability of the dynamical structure; and (e) characterizing the stationarity of the time series. RQA provides five indices of the time-varying properties of postural sway that correspond to the steps just described: (1) *% recurrence* (essentially a nonlinear autocorrelation measure; specifically, % recurrence indicates the degree to which data points repeat themselves in the time series, with repetition defined in terms of proximity in the reconstructed multidimensional phase space); (2) *% determinism* (the degree to which recurrent data points form strings of repeating data, indicative of deterministic structure in the time series); (3) *entropy* (a measure of the complexity or irregularity of the deterministic structure of the data); (4) *maxline* (a measure of mathematical stability, which is *not* equivalent to postural stability; mathematical stability refers to a dynamical system's response to a change in initial conditions); and (5) *trend* (a measure of the degree of nonstationarity of the time series). Prior research comparing a balance-disordered population (Parkinson's disease) to healthy controls suggested that higher values of % recurrence, % determinism, entropy, and maxline, and lower absolute values of trend, are characteristic of decreased postural stability (Schmit et al. 2004). That pattern of RQA variables indicates postural instability is associated with an overall tendency for increased regularity or a loss of complexity of postural sway dynamics (cf. Goldberger 1997). Based on those results, we predicted that the postural sway of dancers—who should be less likely to exhibit postural instability—would produce spatiotemporal sway dynamics that were less regular (lower *percent determinism*, lower *percent recurrence*, lower *entropy*, lower maxline, and higher *trend* magnitude) than the postural sway of the track participants (cf. van Emmerik and van Wegen 2000, 2002).

Method

Participants

Ten undergraduate dance majors from the Department of Dance at the University of Cincinnati College Conservatory of Music (mean age = 20 years; five male, five female) participated. The dancers were pursuing a Bachelor of Fine Arts degree with an emphasis in ballet (Alexander technique). All dancers were trained in ballet for a minimum of 5 years and were physically fit. Ten physically fit, varsity runners from the University of Cincinnati track team (mean age = 19.5 years; five male, five female) also participated. The runners served as a control group consisting of athletic, physically fit individuals who, unlike the dancers, were not trained explicitly in balance control. Participants were screened to ensure they did not have a history of diabetes, arthritis or other illnesses affecting balance, a recent injury, vestibular disorder, dizziness, a history of falls, heavy use of alcohol or other drugs, or chronic back pain.

Apparatus

Postural stability data were obtained using a Bertec 4060-NC force platform and Bertec AM-6701 charge amplifier (Bertec Corporation, Columbus, OH). Data were sampled at 100 Hz and stored on a Pentium-based PC. *Datapac 2000* software (Run Technologies, Inc., Mission Viejo, CA) was used for data acquisition and reduction. *Datapac 2000* calculated the COP from the force and moment signals measured by the force platform and then computed standard statistical descriptors of the COP (described below).

Procedure

Participants signed a written informed consent document prior to the experimental session. The study was approved by the University of Cincinnati Institutional Review Board.

Within-subjects manipulations of vision (eyes open vs. eyes closed) and rigidity of the support surface (rigid surface of the force platform vs. 10.5 cm thick foam block) were factorially combined, yielding four experimental conditions (eyes open/rigid; eyes open/foam; eyes closed/rigid; eyes closed/foam). Those manipulations were chosen to create balance conditions that varied in difficulty (eyes closed being more difficult than eyes open, and foam more difficult than rigid). Four trials were conducted in each condition, resulting in a total of 16 randomly ordered trials per participant. Testing sessions lasted approximately 30 min.

Participants stood barefoot on the force platform or foam with, in both conditions, their feet centered with respect to the force platform. They were instructed to adopt a shoulder-width stance, and were asked to relax and to allow the arms to suspend naturally and comfortably at their sides. Participants were further directed not to speak, gesture, or make any large-scale voluntary movements (e.g., of the arms) during trials. At the beginning of each trial participants assumed the aforementioned stance. Data collection was initiated following notification from participants that they felt stable and were ready to begin. Each trial lasted 30 s. Participants were allowed to take breaks as needed to avoid fatigue.

Data analysis and reduction

There were two primary sets of dependent measures in this study. The first set (postural stability measures) consisted of standard measures of postural sway that are presumed to be inversely related to postural stability. The within-trial standard deviation (SD) of the anterior-posterior (AP) and medial-lateral (ML) COP time series and COP path length (total distance traveled by the COP over a trial) were computed by *Datapac 2000* as indices of postural sway variability.

The second set of dependent measures (postural sway dynamics measures) was obtained using RQA and reflected the dynamic patterns of postural sway. RQA was performed using the following input parameters for the analysis algorithms: for AP sway, time delay = 9 samples, embedding dimension = 11, and radius = 24% of the mean distance separating points in reconstructed phase space; for ML sway, time delay = 10 samples, embedding dimension = 10, and radius = 20% of the mean distance separating points in reconstructed phase space (see Riley et al. 1999 for details). The selection of

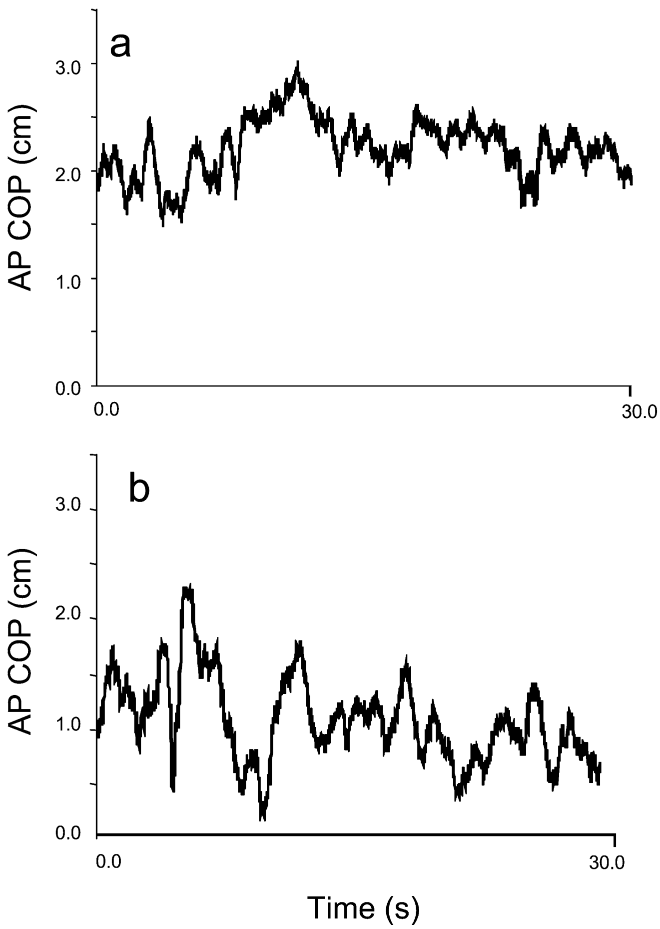

Fig. 1a, b COP time series in the AP axis for a dancer (**a**) and a track athlete (**b**) those values was based on the procedures suggested by Riley et al. (1999) and resulted in the identification of locally recurrent structure in the time series without saturation of % determinism at the ceiling of 100. Variation of the input parameters did not substantially alter the qualitative appearance of recurrence plots or the overall pattern of quantitative results. RQA yielded dependent measures of % recurrence, % determinism, entropy, maxline, and trend.

Dependent measures were averaged over repeated trials in the same condition, yielding for each participant an average value of each dependent measure in each of the four experimental conditions. Data were evaluated using a 1-between (group), 2-within (vision and surface) analysis of variance (ANOVA). Separate ANOVAs were conducted for each dependent measure.

Results

Time series plots and recurrence plots

Figure 1 depicts typical COP time series plots for a dancer and a track athlete. These data indicate that COP time series of participants from each group exhibit irregular and variable spatiotemporal profiles. Recurrence plots for the same time series are shown in Fig. 2. A recurrence plot is constructed by plotting a pixel at specific coordinates (i, j) whenever pairs of data vectors are identified as close (i.e., recurrent) in n-dimensional, reconstructed phase space (Eckmann et al. 1987). Structure not observable in the one-dimensional time series can be identified as specific patterns within constellations of recurrent points in a recurrence plot (Webber and Zbilut 1998). The recurrence plot of the dancer's data depicts a smaller number of darkened pixels, indicating that the dancer's time series has lower % recurrence. The recurrence plot of dancer's data also is characterized by shorter line segments (strings of vector patterns in the time series that repeat themselves multiple times over the observation period) than the plot of the track athlete's data, indicating lower mathematical stability in the dancer's COP time series. The recurrence plot of the track athlete's data exhibits a paling of recurrent points away from the main diagonal, indicating drift in the COP time series. That pattern is not present in the dancer's plot, which suggests that that the dancer's time series is characteristically more stationary than the track athlete's time series.

Postural stability measures

In the AP axis, main effects were found for surface, $F_{(1,18)} = 111.86$, $p < .01$, and vision, $F_{(1,27)} = 100.44$, $p < .01$. When standing on the foam surface (mean AP COP standard deviation for foam: 0.786 cm; rigid: 0.404 cm) and in eyes closed conditions (eyes closed: 0.728 cm; eyes open: 0.462 cm), there was a significant increase in AP COP variability. A significant interaction between vision and surface was also found in the AP axis (see Fig. 3a). The difference between eyes-open and eyes-closed conditions was magnified when participants were on the foam relative to the rigid surface, $F_{(1,18)} = 63.36$, $p < .01$.

The same effects were detected in the ML axis. Significant main effects were found for surface, $F_{(1,18)} = 211.63$, $p < .01$, and vision, $F_{(1,18)} = 33.47$, $p < .01$. When standing on the foam surface (foam: 0.583 cm; rigid: 0.240 cm) or with the eyes closed (eyes closed: 0.484 cm; eyes open: 0.351 cm) there was a significant increase in ML COP variability. A significant interaction between vision and surface was also found in the ML axis (see Fig. 3b). The difference between eyes-open and eyes-closed conditions was magnified when participants stood on the foam relative to the rigid surface, $F_{(1,18)} = 28.84$, $p < .01$.

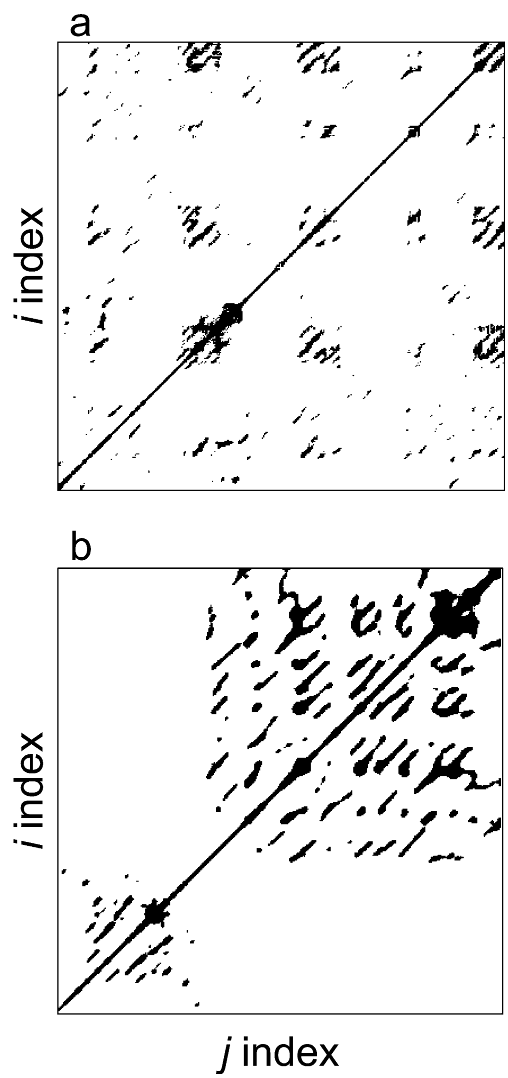

Fig. 2a, b Recurrence plots of the data depicted in Fig. 1. **a** Dancer. **b** Track athlete

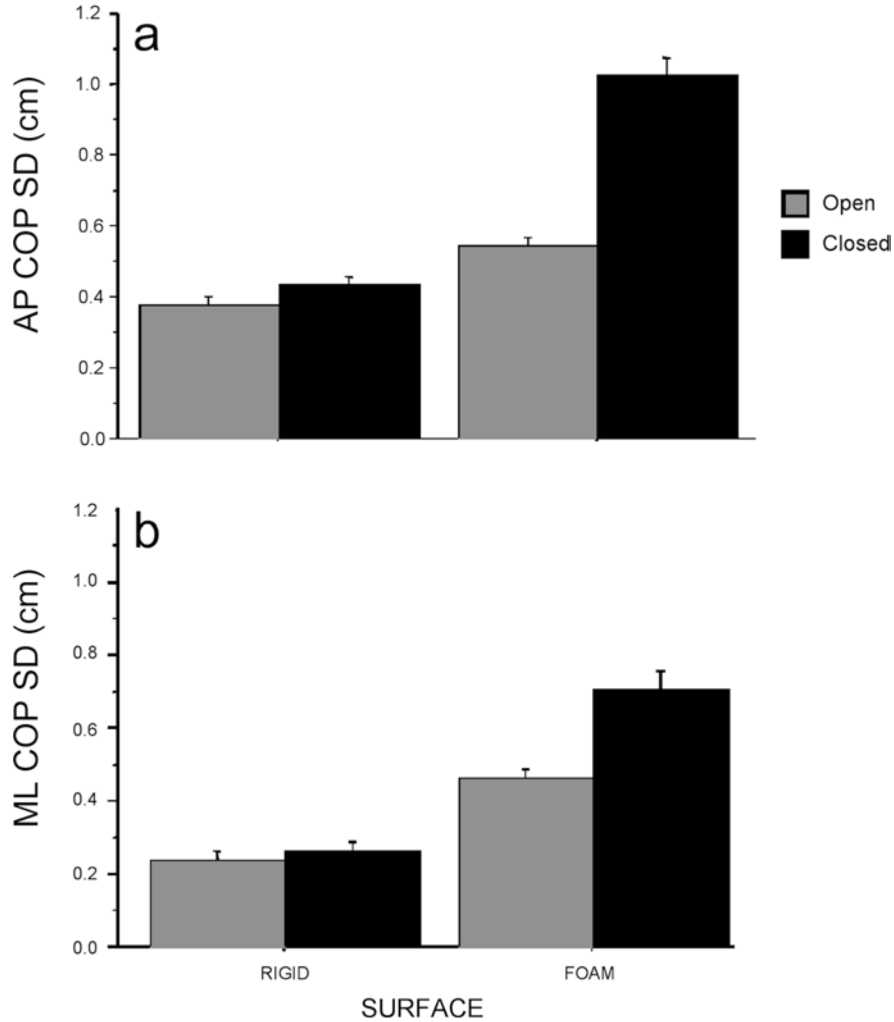

Fig. 3a, b Standard deviation (SD) of the COP in the (**a**) AP and (**b**) ML axes as a function of vision and surface conditions

The exact same pattern was seen for COP path length. There were main effects of surface, $F_{(1,18)} = 23.03$, $p < .01$ (foam: 242.90 cm; rigid: 234.39 cm), and vision, $F_{(1,18)} = 23.90$, $p < .01$ (eyes closed: 243.46 cm; eyes open: 233.84 cm), as well as a surface × vision interaction, $F_{(1,18)} = 38.72$, $p < .01$. The interaction indicated that the difference between the eyes-open and eyes-closed conditions was much larger on the foam surface than the rigid surface.

No main effects of group or interactions involving group were found for the postural stability measures (all $p > .05$).

Postural sway dynamics

ANOVA yielded significant main effects of group, $F_{(1,18)} = 4.73$, $p < .05$, vision, $F_{(1,18)} = 9.00$, $p < .01$, and surface, $F_{(1,18)} = 15.80$, $p < .01$, for AP % recurrence. A main effect of group was also found for ML % recurrence, $F_{(1,18)} = 5.19$, $p < .05$. The time series for dancers (AP: 5.38%; ML: 1.62%) was less recurrent (fewer repetitions in time, or less auto-correlated) than for track athletes (AP: 7.01%; ML: 2.46%) in both sway axes. AP % recurrence was greater in the eyes-open (6.70%) than in the eyes-closed (5.68%) condition, and greater when

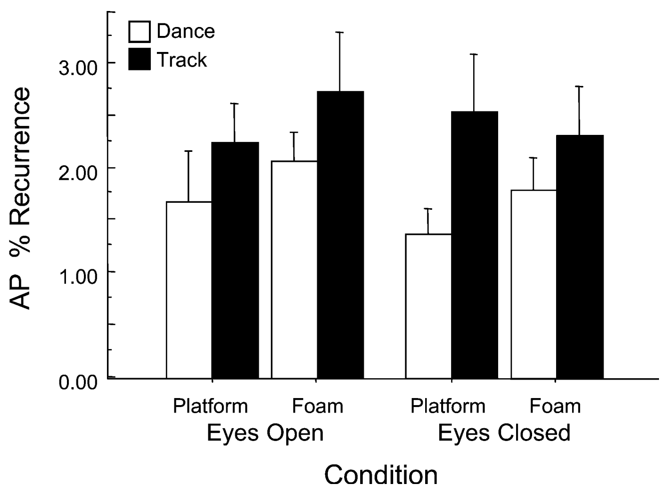

Fig. 4 % recurrence in the AP axis as a function of vision and surface conditions for each group. The surface × vision interaction and the group main effect were significant

participants stood on the foam surface (7.38%) than on the rigid surface (5.00%). A vision × surface interaction was observed in the AP axis for % recurrence, $F_{(1,18)} = 6.93$, $p < .05$. The differences in % recurrence between eyes-open and eyes-closed conditions were minimized when participants stood on the foam relative to the rigid surface (see Fig. 4).

Significant effects of vision and surface were found for % determinism in both the AP [vision: $F_{(1,18)} = 7.28$, $p < .05$; surface: $F_{(1,18)} = 70.00$, $p < .01$] and ML [vision: $F_{(1,18)} = 50.50$, $p < .01$; surface: $F_{(1,18)} = 44.76$, $p < .01$] axes. For both sway axes % determinism was greater in eyes-closed (AP: 76.15%; ML: 67.19%) than in eyes-open conditions (AP: 62.30%; ML: 64.63%), and when participants stood on the foam surface (AP: 84.76%; ML: 83.05%) relative to the rigid surface (AP: 44.75%; ML: 57.73%).

Main effects of group, vision, and surface were found for maxline in both the AP [group: $F_{(1,18)} = 5.50$, $p < .05$; vision: $F_{(1,18)} = 12.11$, $p < .01$; surface: $F_{(1,18)} = 130.30$, $p < .01$] and ML [group: $F_{(1,18)} = 4.50$, $p < .05$; vision: $F_{(1,18)} = 29.29$, $p < .01$; surface: $F_{(1,18)} = 66.75$, $p < .01$) axes. Maxline for both sway axes was higher in the time series of track athletes (AP: 1,909.01; ML: 2,217.21) than of the dancers (AP: 1,480.21; ML: 1,730.98). Maxline was greater in the eyes-closed (AP: 1,807.80; ML: 2,254.07) than in the eyes-open condition (AP: 1,581.42; ML: 1,694.12), and when participants stood on the foam surface (AP: 2,709.87; ML: 2,562.26) relative to the rigid surface (AP: 779.35; ML: 1,385.91), for both sway axes.

ANOVA yielded a significant main effect of group for ML entropy, $F_{(1,18)} = 7.49$, $p < .05$. ML entropy was higher for track athletes (3.72 bits) than dancers (3.20 bits). Main effects of vision and surface were found in both the AP [vision: $F_{(1,18)} = 20.65$, $p < .01$; surface: $F_{(1,18)} = 144.63$, $p < .01$] and ML axes [vision: $F_{(1,18)} = 71.06$, $p < .01$; surface: $F_{(1,18)} = 47.57$, $p < .01$].

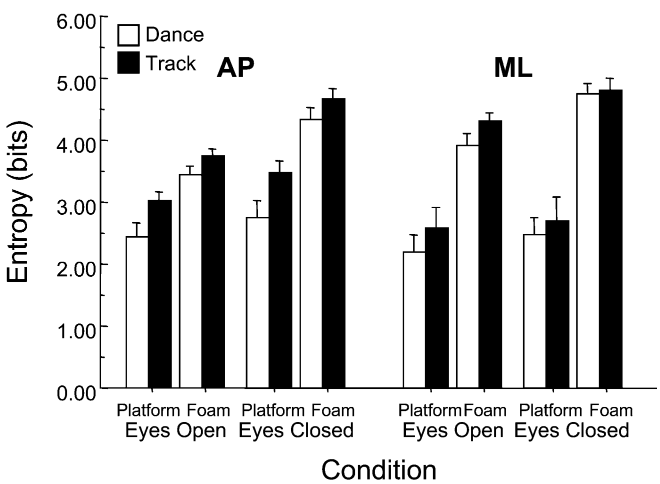

Fig. 5 Entropy in the AP and ML axes as a function of vision and surface conditions for each group. The surface × vision interaction and the group main effect were significant

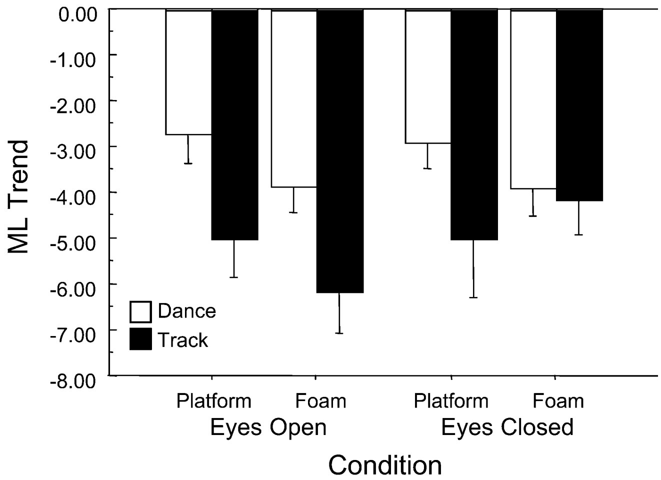

Fig. 6 Trend in the ML axis as a function of vision and surface conditions for each group. The surface × vision interaction and the group main effect were significant

Entropy was greater in eyes-closed (AP: 3.68 bits; ML: 3.80 bits) than in eyes-open condition (AP: 3.25 bits; ML: 3.13 bits), and when participants stood on the foam surface (AP: 4.44 bits; ML: 4.01 bits) relative to the rigid surface (AP: 2.49 bits; ML: 2.92 bits). A significant vision × surface interaction for entropy was found in both the AP, $F_{(1,18)} = 8.79$, $p < .01$, and ML, $F_{(1,18)} = 12.82$, $p < .01$, axes (see Fig. 5). Entropy differences between eyes-open and eyes-closed conditions were greater when participants were standing on the foam.

Finally, ANOVA on trend revealed a significant main effect of group in both the AP, $F_{(1,18)} = 6.41$, $p < .05$, and ML, $F_{(1,18)} = 5.98$, $p < .05$, axes. Trend absolute magnitudes were smaller for dancers (AP: −3.24; ML: −1.44) than track runners (AP: −5.12; ML: −2.25). A significant interaction between vision and surface was found in the ML axis, $F_{(1,18)} = 7.44$, $p < .05$ (see Fig. 6). The difference between eyes-open and eyes-closed conditions was greater when participants stood on the foam.

Discussion

The purpose of this study was to determine the effects of dance experience and balance training (over and above the effects of physical fitness) on postural stability and postural sway dynamics under variations in the availability of vision and the rigidity of the support surface. RQA revealed several differences in postural control between dancers and the physically fit control group (track athletes), but our variability measures (COP standard deviation in the AP and ML sway axes and path length) did not reveal any differences between the groups. Previous research has generated inconsistent results regarding differences between dancers and other groups. Crotts et al. (1996) found superior balance performance by dancers, but they did not employ objective posturography methods that provide quantitative measures of COP variability or amount of postural sway. They recorded the length of time subjects could maintain a given posture, and found that dancers could stand for longer periods of time than controls. Two other studies that employed static posturography produced conflicting findings. Hugel et al. (1999) found better balance performance by dancers in eyes-open conditions. In contrast, Perrin et al. (2002) found no differences between dancers and controls in eyes-open conditions (although judoists performed better than dancers in this condition). Moreover, Perrin et al. observed inferior performance by dancers relative to both groups in eyes-closed conditions.

Our results indicate that the balance skills of dancers may not be manifest in the amount or variability of postural sway, but instead are apparent in the nature of dynamic patterns of postural sway. An assumption in many studies of postural control is that the SD or path length of the COP is a straightforward index of the quality of postural control—the greater the sway variability, the less effective is postural control (i.e., reduced postural stability). The same logic applies to other postural stability measures such as sway area, root mean square variability, or sway amplitude (Gabel and Nayak 1984; Horak et al. 1989). However, a number of researchers have cautioned that this assumption should not be made without further consideration of the dynamic patterns of the COP (Newell and Slifkin 1998; Newell et al. 1993; Riccio 1993; Riley 2001; Riley and Turvey 2002; Slifkin and Newell 1999; van Emmerik and van Wegen 2000, 2002). Our analysis of the dynamic patterns of the COP revealed differences in postural control between the dancers and track athletes that were not apparent in the variability measures. One interpretation of this result is that postural control is qualitatively, not quantitatively, different in dancers. Since the spatiotemporal patterns manifest in motor behavior are reflections of the underlying control and organization of the perceptual-motor system (e.g., Newell et al. 1993; Riley 2001; Riley and Turvey 2002; van Emmerik and van Wegen 2000), the qualitatively different dynamic patterns of sway for the dancers suggest dancers exhibit differences in the underlying organization of postural control.

Specifically, the RQA results indicated that dancers' COP time series were less nonlinearly autocorrelated (% recurrence was lower for dancers), less mathematically stable (maxline was lower for dancers), less complex (entropy was lower for dancers), and more stationary (trend magnitude was lower for dancers) than the track athletes' COP time series. Taken together these results point toward an overall tendency for dancers to exhibit postural motions that were somewhat noisier (i.e., reduced recurrence—lower nonlinear autocorrelations) but that occurred about a relatively constant mean position (i.e., lower trend value). The lower mathematical stability and increased noisiness in the COP time series of dancers may reflect a means of behavioral flexibility—less stable, noisy mathematical systems can exhibit transitions across behavioral modes and greater flexibility than more regular and stable systems (see Kelso 1995 for a discussion of this issue in the context of movement coordination).

Differences between the groups did not depend upon vision and surface conditions (cf. Hugel et al. 1999; Perrin et al. 2002). However, vision and surface effects were observed in most dependent measures in both the AP and ML sway axes. Eyes-closed and foam-surface conditions were associated with greater sway variability and with increased % recurrence, % determinism, maxline, entropy, and trend of the time series. Those results for the most part replicated the effects observed by Riley et al. (2004; see also Riley et al. 1999, for a comparison of vision effects), except that Riley et al. (2004) found lower % recurrence on the same foam surface than on the same rigid surface (however, participants in that study performed a cognitive task while standing during half of the trials, so this comparison must be treated circumspectly). The present RQA results indicated an overall trend toward increasing regularity of the COP time series as balance conditions became more challenging, which is consistent with results obtained during the Sensory Organization Test in a study by Riley and Clark (2003).

Differences in balance skills have been found between non-specialized control participants and other subject groups such as judoists (Perrin et al. 2002), gymnasts (Kioumourtzoglou et al. 1997; Robertson et al. 1994; Vuillerme and Nougier 2004; Vuillerme et al. 2001), and acrobats (Golomer et al. 1997a, b). A question that emerges from this line of research is whether the changes in balance function are a reflection of intrinsic balance skills that predispose individuals to specialize in those professions, a result of training, or some combination of those factors. This question has important implications for devising balance intervention programs for the elderly, people with neurological disorders, or people who work in dangerous environments in which balance control and falling are critical issues (e.g., high-rise construction). There is some evidence that suggests activities such as tai chi and social dance may improve balance function in individuals prone to falls (see reviews by Judge 2003; Wu 2002). The effects of balance training on postural control and the extent to which balance training generalizes to a broad range of postural control conditions are important research issues.

The elite dancers we studied exhibited postural sway dynamics that were quite different from another group—individuals with Parkinson's disease—that we examined in another study (Schmit et al. 2004). Whereas the dancers tended to show less correlated, less complex, and less mathematically stable sway dynamics than the control group (track athletes), people with Parkinson's disease tended to exhibit highly variable postural sway that was more autocorrelated, more deterministic, more complex, and more mathematically stable than a group of age-matched, healthy control participants. While it is imprudent to make direct comparisons of the data of dancers and Parkinson's patients across these two studies, it nonetheless may be informative in future studies to directly compare people with elite balance abilities to people with known balance impairments. Such comparisons may elucidate the nature of postural stability and normal postural control and shed light on how postural control differs in cases of elite balance performance and balance disorders.

References

Balasubramaniam R, Turvey MT (2001) The handedness of postural fluctuations. Hum Mov Sci 19:667–684

Balasubramaniam R, Riley M, Turvey MT (2000) Specificity of postural sway to the demands of a precision task. Gait Posture 11:12–24

Crotts D, Thompson B, Nahom M, Ryan S, Newton RA (1996) Balance abilities of professional dancers on select balance tests. J Orthop Sport Phys 23:12–17

Easton RD, Greene AJ, DiZio P, Lackner J (1998) Auditory cues for orientation and postural control in sighted and congenitally blind people. Exp Brain Res 118:541–550

Eckmann JP, Kamphorst SO, Ruelle D (1987) Recurrence plots of dynamical systems. Europhys Lett 4:973–977

Edwards AS (1946) Body sway and vision. J Exp Psychol 36:526–535

Gabel A, Nayak USL (1984) The effect of age on variability in gait. J Gerontol 39:662–666

Goldberger AL (1997) Fractal variability versus pathologic periodicity: Complexity loss and stereotypy in disease. Perspect Biol Med 40:543–561

Golomer E, Dupui P (2000) Spectral analysis of adult dancers' sways: sex and interaction vision-proprioception. Int J Neurosci 105:15–26

Golomer E, Dupui P, Monod H (1997a) The effects of maturation on self-induced dynamic body sway frequencies of girls performing acrobatics or classical dance. Eur J Appl Physiol 76:140–144

Golomer E, Dupui P, Monod H (1997b) Sex-linked differences in equilibrium reactions among adolescents performing complex sensorimotor tasks. J Physiol 91:49–55

Golomer E, Cremieux J, Dupui P, Isableu, Ohlmann T (1999a) Visual contribution to self-induced body sway frequencies and visual perception of male professional dancers. Neurosci Lett 267:189–192

Golomer E, Dupui P, Sereni, P, Monod H (1999b) The contribution of vision in dynamic spontaneous sways of male classical dancers according to student or professional level. J Physiol 93:233–237

Hamill J, Knutzen K (1995) Biomechanical basis of human movement. Williams & Wilkins Publishing Company, Baltimore

Horak FB, Shupert CL, Mirka A (1989) Components of postural dyscontrol in the elderly: a review. Neurobiol Aging 10:727–738

Hugel F, Cadopi M, Kohler F, Perrin P (1999) Postural control of ballet dancers: a specific use of visual input for artistic purposes. Int J Sports Med 20:86–92

Judge JO (2003) Balance training to maintain mobility and prevent disability. Am J Prev Med 25:150–156

Kelso JAS (1995) Dynamic patterns: the self-organization of brain and behavior. MIT Press, Cambridge, MA

Kioumourtzoglou E, Derri V, Metzanidou O, Tzetzis G (1997) Experience with perceptual and motor skills in rhythmic gymnastics. Percept Motor Skill 84:1363–1372

Lee DN (1978) The functions of vision. In: Pick HL, Saltzman E (eds) Models of perceiving and processing information. Erlbaum, Hillsdale

Mouchnino L, Aurenty R, Massion J, Pedotti A (1992) Coordination between equilibrium and head-trunk orientation during leg movement: a new strategy built up by training. J Neurophysiol 67:1582–1598

Nashner LM (1989) Sensory, neuromuscular and biomechanical contributions to human balance. In: Proceedings of the American Physical Therapy Association Forum. APTA, Nashville, pp 5–12

Newell KM, Slifkin AB (1998) The nature of movement variability. In: Piek JP (ed) Motor behavior and human skill: a multidisciplinary approach. Human Kinetics, Champaign, pp 143–160

Newell KM, van Emmerik REA, Lee D, Sprague RL (1993) On postural stability and variability. Gait Posture 4:225–230

Paulus WM, Straube A, Krafczyk S, Brandt T (1984) Visual stabilization of posture: physiological stimulus characteristics and clinical aspects. Brain 107:1143–1163

Perrin P, Deviterne D, Hugel F, Perrot C (2002) Judo, better than dance, develops sensorimotor adaptabilities involved in balance control. Gait Posture 15:187–194

Ramsay JRE, Riddoch MJ (2001) Position-matching in the upper limb: professional ballet dancers perform with outstanding accuracy. Clin Rehabil 15:324–331

Riccio GE (1993) Information in movement variability about the qualitative dynamics of posture and orientation. In: Newell KM, Corcos D (eds) Variability and motor control. Human Kinetics, Champaign, pp 317–357

Riley MA (2001) The temporal structure of spontaneous postural sway. In: van der Burg JCE, Fong BF, Hijl MIJ, Huys R, Pijnappels M, Post AA (eds) Balance at all times: proceedings of the fifth symposium of the Institute for Fundamental and Clinical Human Movement Sciences. Digital Printing Partners, Utrecht, pp 94–109

Riley MA, Clark S (2003) Recurrence analysis of human postural sway during the sensory organization test. Neurosci Lett 342:45–48

Riley MA, Turvey MT (2002) Variability and determinism in motor behavior. J Motor Behav 34:99–125

Riley MA, Balasubramaniam R, Turvey MT (1999) Recurrence quantification analysis of postural fluctuations. Gait Posture 9:65–78

Riley MA, Baker AA, Schmit JM, Weaver E (2004) Effects of visual and auditory short-term memory tasks on the spatio-temporal dynamics and variability of postural sway. J Motor Behav (in press)

Robertson S, Collins J, Elliot D, Starkes J (1994) The influence of skill and intermittent vision on dynamic balance. J Motor Behav 26:333–339

Schmit JM, Riley MA, Shear PK, Shockley K (2004) Recurrence quantification analysis as a technique for quantifying postural instability. Proc of the Human Factors and Ergonomics Society 48th Annual Meeting, pp. 2512–2516

Slifkin AB, Newell KM (1999) Is variability in human performance a reflection of system noise? Curr Dir Psychol Sci 7:170–176

van Emmerik REA, van Wegen EEH (2000) On variability and stability in human movement. J Appl Biomech 16:394–406

van Emmerik REA, van Wegen EEH (2002) On the functional aspects of variability in postural control. Exercise Sport Sci R 30:177–183

Vuillerme N, Nougier V (2004) Attentional demand for regulating postural sway: the effect of expertise in gymnastics. Brain Res Bull 63:161–165

Vuillerme N, Danion F, Marin L, Boyadjian A, Prieur JM, Weise I, Nougier V (2001) The effect of expertise in gymnastics on postural control. Neurosci Lett 303:83–86

Webber CL Jr, Zbilut JP (1994) Dynamical assessment of physiological systems and states using recurrence plot strategies. J Appl Physiol 76:965–973

Webber CL Jr, Zbilut JP (1996) Assessing deterministic structures in physiological systems using recurrence plot strategies. In: Khoo MCK (ed) Bioengineering approaches to pulmonary physiology and medicine. Plenum Press, New York, pp 137–148

Webber CL Jr, Zbilut JP (1998) Recurrent structuring of dynamical and spatial systems. In: Colosimo A, Lesk A (eds) Complexity in the living: a modelistic approach. World Scientific, Singapore, pp 101–133
Webber CL Jr, Zbilut JP (2004) Recurrence quantification analysis of nonlinear dynamical systems. To appear in: Riley MA, Van Orden G (eds) Tutorials in contemporary nonlinear methods for the behavioral sciences. Digital publication to appear at www.nsf.gov/sbe/bcs/pac/start.htm (in press)
Witkin HA, Wapner S (1950) Visual factors in the maintenance of upright posture. Am J Psychol 63:31–35
Wu G (2002) Evaluation of the effectiveness of tai chi for improving balance and preventing falls in the older population—a review. J Am Geriatr Soc 50:746–754