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Sway regularity reflects attentional involvement in postural control: Effects of expertise, vision and cognition

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ABSTRACT

We examined the time varying (dynamic) characteristics of center-of-pressure (COP) fluctuations in a group of 14 preadolescent dancers and 16 age-matched non-dancers. The task involved maintaining balance for 20 s with eyes open or eyes closed, and with or without performing an attention demanding cognitive task (word memorization). The main finding was that the time-dependent structure of the COP trajectories of dancers exhibited less regularity than that of non-dancers, as evidenced by a higher sample entropy (decreased statistical regularity). COP irregularity also increased during secondary task performance but decreased during standing with eyes closed. The combined findings indicate that the degree of attentional involvement in postural control – as reflected in the COP dynamics – varies along an automaticity continuum, and is affected by relatively stable subject characteristics (expertise) and more transient factors related to the attentional requirements of the task at hand.

1. Introduction

Standing balance was recently defined as "the ability to stand with as little sway as possible" ([6], p. 501). This definition makes intuitive sense because postural sway often increases with pathology [7,19], aging [11], or when a sensory challenge [4] is added to the standing task. On the other hand, it is highly unlikely that a situation of zero sway is desirable for postural control given that human movement is intrinsically variable and successful regulation of posture requires detection of postural sway [14].

In general, the dynamical structure of postural sway, as captured among others by the statistical regularity, dimensionality or recurrence characteristics of center-of-pressure (COP) time series, appears indicative of the underlying motor control [18,19]. A recent measure to capture the dynamical structure of physiological data, including postural sway [3,4,19], is sample entropy, which indexes the statistical regularity of the time series, with low (high) values indicating more (less) regularity [10,16]. Roerdink et al. [19] found that individuals who had suffered a stroke exhibited overall more regular sway during quiet standing than controls (comparable effects were found for a group of children with cerebral palsy [3]), and that sway regularity decreased in the course of rehabilitation. In addition, performing a mental arithmetic task during standing resulted in more irregular sway, while closing the eyes had the opposite effect. Comparable task effects were found in healthy young adults [4]. A direct relation between COP regularity and the amount of attention invested in posture was therefore proposed [3,4,19]. In brief, increased COP regularity in stroke patients or cerebral palsy children relative to healthy controls was interpreted as a reflection of a greater cognitive involvement in maintaining balance, whereas the increased COP irregularity with rehabilitation (in the case of stroke) was taken to suggest a progressive reduction in the amount of attention invested in posture (or inversely, increased level of automaticity of postural control) [19]. Moreover, COP regularity decreased when attention was experimentally diverted from posture [3,4,19], which is fully in line with the proposed relation between COP regularity and the level of automaticity of postural control.

The abovementioned studies suggest that COP regularity may be used as a marker for the amount of attention invested in postural control. In the present study we extended this line of research to the other end of the presumed automaticity continuum, namely to individuals with superior postural skills, that is, ballet dancers [2,23]. We hypothesized that dancers, compared to non-dancers, would exhibit (1) a smaller amount of sway (i.e. smaller sway area and sway amplitude) possibly reflecting their greater postural stability [20,23] and (2) more irregular postural sway, indicative of a greater level of postural automaticity. We further expected that removal of vision, which is an important information source for postural control, would lead to greater sway regularity. Finally, we expected that performing a

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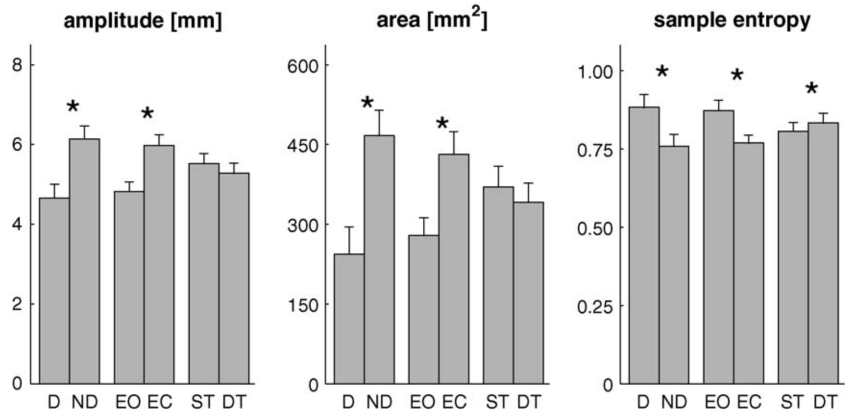

Fig. 1. Mean values of the three dependent posturographic measures, collapsed over group, vision and task. Error bars represent the standard error. *Asterisks* indicate a significant ($p < .05$) difference between the two levels of a factor. D = dancers; ND = non-dancers; EO = eyes open; EC = eyes closed; ST = single task; DT = dual task.

secondary cognitive task, which was assumed to divert attention from postural control, would lead to more irregular postural sway. We adopted a complete factorial design, which allows us to test whether the expected attentional effects would combine in an additive (independent) or non-additive (interactive) manner. Specifically, in line with [4] we anticipated that diverting attention from postural control in standing with eyes open would have a smaller effect on sway regularity of ballet dancers than controls, reflecting the expected greater level of automaticity of dancers.

2. Methods

2.1. Participants

Fourteen young preprofessional dancers (mean age = 12.4 years, range 11.5–13.3 years, 11 girls) from the Preliminary Dance Education of the Dutch National Ballet Academy in Amsterdam participated in the experiment. They were in their second dance education year. Preliminary Dance Education takes about 9 years, from age 10 to 18, during which daily dance training (3–4 h per day) is combined with regular school education; a successful audition is necessary for entering the Academy.[1] Sixteen children attending a regular primary school served as a control group (mean age = 12.0 years, range 11.0–13.2 years, 12 girls). All children's parents gave their informed consent. The study was approved by the local Ethics Committee.

2.2. Procedure

Participants stood barefoot on a custom made strain gauge force plate (dimensions: 1 m × 1 m; sampling frequency: 100 Hz; resolution: 0.28 N/bit; resonance frequency: 30 Hz), with the feet placed 8 cm apart and the arms hanging relaxed alongside the body. COP recordings were made under four experimental conditions: eyes open, eyes closed, eyes open while performing a dual task, and eyes closed while performing a dual task. Each participant performed each condition four times, resulting in a total of 16 trials per participant. The trials were presented in random order. Trial duration was 20 s. During the eyes open trials participants were instructed to stand still and look straight ahead at a white sheet of paper which was attached at eye-height to a wall two meters in front of them.

The dual task consisted of a memory task. An audiotape was played containing previously recorded words (Dutch nouns). Ten words were presented at a frequency of 0.5 Hz per trial and participants were instructed to fully concentrate on these words and to memorize as many words as possible. At the end of each dual task trial participants were asked to verbally report the words they memorized. The experimenter scored the number of correctly remembered words.

2.3. Data analysis

Prior to all analyses, the mean was subtracted from mediolateral and anterioposterior COP trajectories, which were subsequently bi-directionally filtered (2nd order low-pass Butterworth filter, cut-off frequency 12.5 Hz). Two participants (1 dancer, 1 non-dancer) were excluded from further analyses because their COP recordings contained artifacts. For the remaining participants postural sway was quantified by means of two common, scale-dependent posturographic measures. First, the average COP distance to the origin of the mean-centered posturogram was determined (i.e. sway amplitude in mm; see [13]; Eq. (4)). Second, the area of postural sway was determined from the posturogram, defined as the area covered by the ellipse enclosing approximately 95% of the samples along the COP trajectory (i.e. sway area in mm^2; see [13]; Eq. (18)).

To examine the dynamical structure of COP trajectories in more detail, independent of their size or scale, COP time series were normalized to unit variance by dividing them by their respective standard deviations, resulting in a normalized posturogram. A scale-independent COP measure was obtained from this normalized posturogram, namely sample entropy [3,4,19]. Sample entropy is defined as the negative natural logarithm of an estimate of the conditional probability that subseries (epochs) of length m that match pointwise within a specific tolerance also match at the next point. Lower sample entropy values imply more regular COP time series, that is, a greater likelihood that sets of matching epochs in a time series will be followed by another match within a certain tolerance. Conversely, highly irregular COP time series are characterized by the fact that sets of matching epochs tend to be followed by data samples of different values, resulting in larger sample entropy estimates (for a more formal and detailed treatment see [10,15,16]). Sample entropy was quantified from the normalized posturogram by using the polar coordinate time series, which was first normalized to unit variance for this purpose. To optimize the choice of the tolerance for a given m (in our case, $m = 3$) we selected the median value of the optimal tolerance over all trials [10,19] (in our case, 0.05; median value of the efficiency metric (±standard deviation) 3.91% (±0.64%)). The algorithm used for calculating sample entropy was obtained from PhysioNet ([8]; http://www.physionet.org). Note that sample entropy is conceptually and computationally very similar to approximate entropy [12,16]. Both measures were originally developed to quantify regularity in heart rate dynamics. Like sample entropy, approximate entropy has also been applied to COP time series and proved to be a reliable index of the recovery of postural control after cerebral concussion [1].

2.4. Statistics

Dependent posturographic measures were averaged over the four repeated trials in each condition. A repeated measures analysis of variance was conducted for each dependent measure with the between-subjects factor group (2 levels: dancers, non-dancers) and the within-subject factors vision (2 levels: eyes open, eyes closed) and task (2 levels: single task, dual task).

3. Results

The means of the three dependent variables collapsed over independent variables are depicted in Fig. 1.

3.1. Sway amplitude

Group and vision significantly affected sway amplitude ($F(1, 26) = 9.72$, $p < .01$ and $F(1, 26) = 36.86$, $p < .001$, respectively); sway amplitude was smaller for dancers than for non-dancers and for standing with eyes open than for standing with eyes closed. No other main or interaction effects were significant.

[1] Although we did not collect data on the young dancers' pre-academy dance experience, we know from an extensive earlier study ($N = 175$) with young dancers in three Dutch pre-professional dance academies (including the present one in Amsterdam) that the majority of these children start their dance education at a local dance school at the age of 4–6 years [22].

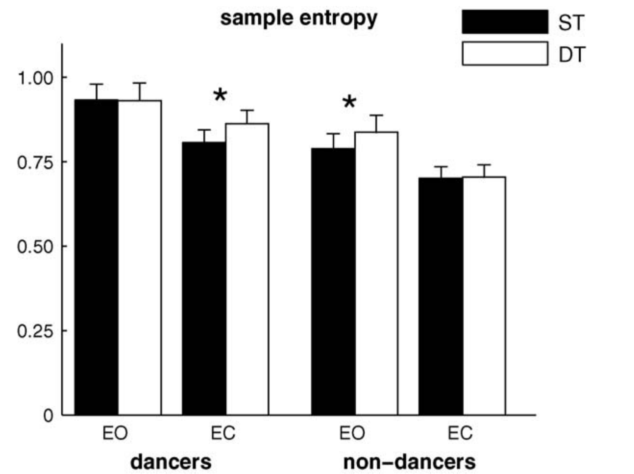

Fig. 2. Group (dancers versus non-dancers) × vision × task interaction on sample entropy. Error bars represent the standard error for each condition. *Asterisks* indicate a significant ($p < .05$) difference between paired conditions. EO = eyes open; EC = eyes closed; ST = single task; DT = dual task.

3.2. Sway area

Group and vision significantly affected sway area ($F(1, 26) = 10.07$, $p < .01$ and $F(1, 26) = 26.02$, $p < .001$, respectively), as did the group × vision interaction ($F(1, 26) = 5.65$, $p < .05$). The interaction revealed that postural sway of both groups covered a greater area in the posturogram when the eyes were closed, but that this effect was greater for non-dancers (355 mm^2 versus 578 mm^2) than for dancers (203 mm^2 versus 284 mm^2). No other main or interaction effects were significant.

3.3. Sample entropy

Group and vision significantly affected sample entropy ($F(1, 26) = 4.88$, $p < .05$ and $F(1, 26) = 50.31$, $p < .001$, respectively); sample entropy was higher for dancers than for non-dancers and lower with eyes closed than with eyes open. In addition, the effect of task was significant ($F(1, 26) = 5.05$, $p < .05$), revealing that sample entropy was higher when performing the memorization task than without. Finally, the group × vision × task interaction was significant ($F(1, 26) = 6.72$, $p < .05$; see Fig. 2 for mean values). A posteriori *t*-tests revealed that the introduction of a cognitive task had no effect on sway regularity in the eyes open condition for dancers ($t(12) = 0.09$, $p > .1$); the same was true in the eyes closed condition for controls ($t(14) = 0.18$, $p > .1$). In line with the main effect of task, the *t*-tests revealed increased sample entropy in the eyes closed condition for dancers ($t(12) = 2.58$, $p < .05$) and in the eyes open condition for non-dancers ($t(14) = 2.87$, $p < .05$) with the addition of the cognitive task.

3.4. Memory performance

The dancers correctly recalled significantly more words (5.3 ± 1.1) than the non-dancers (4.3 ± 0.8, $t(26) = 2.63$, $p < .05$). Main and interaction effects on secondary task performance with vision were not significant.

4. Discussion

The results of the present study were in line with our expectations. Dancers exhibited a smaller amount of postural sway (i.e. smaller sway amplitude and sway area), suggesting that their balance was overall more stable than that of non-dancers (see also [9,20,23]). As hypothesized, postural sway of dancers was characterized by more irregular COP fluctuations (as exemplified by higher sample entropy), indicating that their balance was somewhat more automatized (less attention demanding) than non-dancers. This finding is in agreement with Schmit et al. [20], who – using recurrence quantification analysis [18] – also found that dancers exhibited less regular sway patterns than controls. They [20] postulated that the increased 'noisiness' of postural motions in dancers was indicative of greater behavioral flexibility, allowing them to more easily switch between behavioral modes. Furthermore, as in our previous study [4], we observed more regular postural sway for standing with eyes closed (see also [9]), while performing an attention-demanding memory task resulted in less regular postural sway. This joint result is consistent with an attentional interpretation of sway irregularity [3,4,19].

There may be several reasons for the observed differences in sway characteristics between dancers and non-dancers such as better balance control [2] and increased use of somatosensory information [21], to name a few. Foremost, however, our findings hint at the possibility that the attentional requirements for maintaining balance are skill dependent. A previous study involving stroke survivors suggested that automaticity of postural control was compromised in this group, and was then regained to some degree in the course of rehabilitation, as evidenced by systematic increases in the irregularity of sway [19]. This finding is consistent with a recent study by Donker et al. [3], who found that children with cerebral palsy exhibited a larger amount of sway characterized by more regular COP fluctuations than typically developing children. We submit that the converse holds for dancers: their perceptual-motor skill seems to afford more automatic balance control, and hence requires less cognitive involvement, resulting in a less regular sway pattern. Presumably, the observed three-way interaction of group, vision, and task may have reflected a ceiling effect regarding the level of automaticity of dancers when standing with eyes open, in that the addition of an attention-diverting memorization task did not result in a further decrease in COP regularity (see also [4]). Put differently, it could well be that the level of automaticity had already reached its maximum in the condition where dancers were standing with their eyes open, so that the addition of an attention-diverting task did not result in an even further increase in postural automaticity. This finding is consistent with our hypothesis regarding differential effects of expertise on COP regularity when standing with eyes open. However, we did not anticipate the absence of a task effect in the eyes closed condition, as observed for the controls (see Fig. 2). A tentative explanation for this finding could be that this condition was so challenging that controls paid less attention to listening to and memorizing the words, and instead prioritized postural control over cognitive performance. In other words, there could have been a trade-off between the challenges imposed by the balance task and the demands of the memorization task, yet the associated decrease in memory performance of controls in the eyes closed condition was not observed. However, this effect could well have failed to emerge due to the limited discriminative power of the memory task as a result of the integer scoring. This admittedly ad hoc explanation at least underscores the fact that subjects may prioritize task performance in unexpected ways [5,17]. Thus, we propose that the observed three-way interaction results from the combination of a ceiling effect in dancers on automaticity, and a strategic trade-off between cognitive effort and postural control in non-dancers. The finding that dancers were better able to integrate postural activity (standing) with the task of memorization, as evidenced by superior word recall, is at least consistent with this interpretation. In a similar vein, Vuillerme and Nougier [23] interpreted the faster (relative to controls) probe reaction times observed for dancers during unipedal upright standing to imply that maintaining a difficult posture requires less cognitive involvement in dancers than in controls.

To conclude, the present results indicate that the organization of human stance is dependent on stable subject characteristics (expertise) and transient attentional factors (induced by sensory and cognitive challenges), as evidenced by systematic changes in COP regularity.

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Conflict of interest statement

No conflict of interests.

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