Gait & Posture 68 (2019) 488–493

Contents lists available at ScienceDirect

Gait & Posture

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

Full length article

Voluntary control of breathing affects center of pressure complexity during static standing in healthy older adults

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ARTICLE INFO

Keywords:
Older adults
Postural control
Complexity
Breathing
Sample entropy

ABSTRACT

Background Physiological/biomechanical systems display high degrees of complexity in their corresponding physiological and/or biomechanical outputs, indicative of normal healthy physiological functioning, though little attention has been paid to potential mechanisms which may affect complexity. Center of pressure (CoP) dynamics also display high degrees of complexity and may be affected via altered respiratory-motor interactions such as during voluntary control of breathing.

Purpose The purpose of this study was to investigate the differences in the complexity of CoP dynamics during autonomous vs. voluntary control of breathing and between different voluntarily controlled breathing conditions.

Methods Center of pressure recordings were taken from 18 older adults during static standing under three different breathing conditions: 1) neutral breathing, 2) abdominal breathing, and 3) thoracic breathing, the first constituting the autonomous breathing condition and the latter two constituting voluntarily controlled breathing conditions. CoP dynamics were quantified using sample entropy, standard deviation, 95% sway area, and average radial velocity. Repeated measure MANOVAs were used to assess the effect of breathing on CoP dynamics, with top-down application of ANOVAs and pairwise comparison as needed.

Results Voluntary control of breathing during both conditions resulted in significantly higher CoP variability and lower sample entropy than during autonomous control of breathing in the mediolateral direction, indicating less complex dynamics and loss of system control. No significant differences between voluntary breathing conditions were observed.

Conclusion Voluntary control of breathing significantly affected on CoP dynamics during static standing. The complexity of the postural control system may be affected via alterations in respiratory-motor interactions.

1. Introduction

Over the course of the past few decades, a mounting body of evidence has shown that the deterioration of physiological systems, either due to aging [1–3], injury [4–6], or disease [7–9], resulting in decreased system efficiency is generally accompanied by a corresponding decrease in complexity [10]. This is marked by a loss of a rich, meaningful spatiotemporal structural organization in the physiological and/or biomechanical outputs of the systems, whose dynamics are normally characterized by long-term, fractal-like correlations and non-linear interactions [11]. In this context, a high degree of complexity has been considered by some to be *the* defining feature of normal, healthy physiological functioning [11].

High levels of complexity facilitate the efficacy of reactive tuning, a process in which a perturbation to a system leads to a period in which the system becomes temporarily less complex. During this period, the system is 'tuned' to exact a controlled response before reaching a new dynamic steady state and regaining complexity [12]. In systems with loss of or low complexity, the efficacy of reactive tuning may become hampered as reflected by increases in variability from perturbations; this results from a decreased ability to exert a focused response to the perturbations and reach a new dynamic steady state [12]. For example, older adults, especially frail older adults, display low levels of complexity [13,14]. The use of cognitive dual tasks in older adults during static standing has been shown to result in less complex, yet more variable, center of pressure ("CoP") dynamics [29], reflecting a low efficacy of reactive tuning. Together, low complexity and resultant high variability indicate a loss of system control [15]. In contrast, systems with high levels of complexity display a high efficacy of reactive tuning. This is reflected by the ability to reduce or mitigate increases in

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https://doi.org/10.1016/j.gaitpost.2018.12.032
Received 31 May 2018; Received in revised form 17 December 2018; Accepted 25 December 2018
0966-6362/ Published by Elsevier B.V.

variability and regain complexity following the introduction of a perturbation or change in imposed demands. For example, trained distance runners exhibit more irregular yet less variable stride length intervals than non-runners [15], implying that the trained individuals are able to maintain a high degree of control while also maintaining a high degree of complexity in the spatiotemporal organization of their gait patterns. In addition, young pre-professional dancers exhibit more irregular CoP as compared to non-dancer controls, while at the same time exhibiting lower measures of variability [16].

The postural control system serves the purpose of regulating one's center of mass, manipulations of which are done in order to maintain it within the boundary of one's base of support [17]. Regulation of posture requires a certain degree of attentional involvement proportional to the relative difficulty of imposed demands or task difficulty and inversely so to the efficacy of the system [18], i.e., the ability to receive and monitor sensory input, and coordinate appropriate motor outputs [19]. During dual tasks, postural detriments are thought to result from the reallocation of cognitive resources from posture onto a secondary cognitive task [18], though it has been suggested that these detriments are partially attributable to vocalization [20,21]. Yardley et al. [20] investigated the effects of both attention and vocalization on posture using different dual task conditions, i.e., silently counting down by seven (attention only), repeated articulation of a single number (vocalization only), and counting down by seven aloud (attention and vocalization), reporting only vocalization to have a significant effect on posture. A study by Schmitt et al. [21] investigated the isolated effect of attention on posture using non-vocalization cognitive dual tasks, reporting attention alone to have no significant effect on posture. An effect of vocalization on posture may result from altered respiratory-motor interactions similar to those that occur during voluntary control of breathing. Specifically, voluntary control of breathing has been observed to result in changes in corticospinal excitability of non-respiratory muscles, suggested to reflect a coupling between breathing-associated cortical areas and (distinct) motor cortical areas of non-respiratory muscles [22–24]. These altered respiratory-motor interactions, as induced by voluntary breathing, affect muscles of the lower extremities [24,25], movement of which has been shown to actively compensate for respiratory-induced perturbances to posture [26]. Thus a direct relation between the respiratory and postural control system can be seen.

Manor et al. [27] proposed the term "posturo-respiratory synchronization" to describe the interdependency between the respiratory and postural control system as a clinical biomarker for the postural control system. Specifically, higher degrees of synchronization indicate a greater effect of respiration on posture. In the study, patients with stroke exhibit higher posturo-respiratory synchronization during standing compared to healthy controls, which suggests that the dynamics of their postural control systems were strongly influenced by perturbations induced by respiration. Furthermore, aging also corresponded to increased posturo-respiratory synchronization. Tai Chi training would reduce posturo-respiratory synchronization among elderly population [28]. However, the effect of voluntary breathing on CoP regularity has not been investigated, especially among individuals with a low efficacy of reactive tuning.

Different breathing techniques may vary in their effect on posture. Hamaoui et al. [29] reported that voluntary thoracic breathing had a significantly greater perturbing effect on posture compared to abdominal breathing in healthy adult males. Furthermore, in a preliminary study by Stephens et al. [30], thirteen healthy adults underwent an 8-week intervention focused on breathing exercises that emphasized the use of abdominal breathing while minimizing contributions from thoracic breathing, resulting in improvements to balance. These results may be due to the difference in the vertical positions of the abdominal and thoracic compartments relative to the ground. Larger moment arms from the displacement of the thoracic compartment compared to the abdominal compartment may thus result in a greater contribution of thoracic motion to respiratory-induced perturbations. Breathing techniques that emphasis thoracic breathing may then result in increased perturbances to posture [29]. However, evidence is limited and the effect of different breathing techniques on measures of CoP complexity has not been investigated.

The primary purpose of this study was to assess the effects of voluntary breathing on posture by investigating the differences in CoP dynamics under autonomous vs. voluntary breathing conditions in older adults. A secondary purpose was to investigate potential differences in the effect of voluntary control of breathing on CoP dynamics between different breathing techniques. Specifically, we hypothesize that 1) CoP dynamics during voluntarily controlled breathing will be less complex than that during autonomously controlled breathing and 2) CoP dynamics during thoracic breathing will be less complex than that during abdominal breathing.

2. Methods

2.1. Participants

Eighteen healthy participants (females = 16, males = 2), mean age = 83.3 ± 5.5 years, height = 161.6 ± 7.9 cm, & weight = 73 ± 16.2 kg, were recruited to participate in the study from a local retirement home, specifically those enrolled in a collaborative exercise program with the researchers' affiliated university. Inclusionary criteria included those of age 65 or older. Exclusionary criteria excluded individuals with ambulatory aids, neurological disorders, diagnosed osteoporosis, valvular heart disease, and other non-stable medical conditions. Participants were required to complete a healthy history questionnaire in order to assess eligibility. Written clearance of informed consent was obtained from each participant prior to the start of any data collection protocols, the study receiving ethical clearance from the Institutional Review Board at Northern Illinois University.

2.2. Experimental procedures

Participants were instructed to stand on an Accusway force plate (AMTI, Watertown, MA), sampling frequency set at 50 Hz, positioned 1.5 m away from a wall with feet oriented at 15° apart and focus on a 5 cm diameter spot positioned at eye level on the wall. Participants were asked to maintain balance during static standing for 2 min, and ground reaction force (GRF) data was collected via force plate. Three trials were performed for each participant under three different breathing conditions: 1) neutral/normal breathing, 2) abdominal breathing, and 3) thoracic breathing. The first condition constituted the autonomous breathing condition while the latter two constituted voluntarily controlled breathing conditions. The first trial was completed under neutral breathing conditions, the abdominal and thoracic breathing trials then completed in a random order for each participant constituting trials 2 and 3.

During neutral breathing conditions, no specific instructions regarding breathing were given to refrain from inadvertently causing participants to focus on breathing during the trials. This was done to ensure autonomous control over breathing. Thoracic and abdominal breathing conditions were ensured by the real-time feedback of chest and abdomen activities for each participant during the training and testing sessions. Each participant was equipped with two BioCapture respiratory inductance belts (CleveMed, Cleveland, OH) to display the activities in respiratory motion of the thoracic and abdominal walls. The belts were placed at the xiphoid and umbilical levels, respectively. Disposable nose nozzles were used to monitor airflow to prevent deep breathing, a metronome synchronized with each participant's respiratory rate at rest and maintained throughout all trials. Two-minute rest periods were taken in between trials.

A training period preceding both abdominal and thoracic breathing conditions was done to aid in familiarizing the participants with the specific breathing conditions. Real-time biofeedback of belt motion was visually displayed by waves, which increase in amplitude with the belt being stretched by thoracic or abdominal activity. During the training period, the following instruction was given to participants for the thoracic breathing training: “please look at the screen and try to breath in a way to make the top line (measured the activity of chest belt) wave and make the bottom line (measured the activity of abdominal belt) as flat as possible.” Similarly, the following instruction was given under abdominal training: “Please look at the screen. Try to breath in a way to make the top line (measured the activity of chest belt) as flat as possible but make the bottom line (measured the activity of abdominal belt) wave.” The training period ended once the participants were able to aptly execute these breathing patterns for both conditions as determined via inspection. Termination of the training period was based on two criteria: 1) the relative peak amplitude of the wave from one belt to another, specifically when the target wave displayed a high peak while the other either approached a flat line or was substantially lower in comparison; 2) the synchronization between waves from the belts and airflow, specifically when target wave was synchronized with airflow to ensure its contribution to breathing.

2.3. Data analysis

CoP data in the anteroposterior (CoPx) and mediolateral (CoPy) directions were derived from GRF data and subsequently filtered through the 4th order low-pass Butterworth filter. The cutoff frequency was set to 10 Hz as it has been shown the majority of the power in CoP time series lies well below [31,32]. CoP-related measures of balance performance were calculated through BioAnalysis software (AMTI, Watertown, MA), i.e., 95% sway area (SA), average radial velocity ($\bar{\mathbf{v}}$), alongside measures of CoP variability, i.e., CoP standard deviation in anteroposterior ($StDev_x$) and mediolateral ($StDev_y$) directions.

Non-linear analysis of the statistical irregularity of the CoP time series was done using sample entropy ($SampEn_{CoPx}$, $SampEn_{CoPy}$) utilizing code as found on PhysioNet [33] [https://physionet.org/physiotools/sampen/]. Sample Entropy is a non-linear measure of the statistical irregularity of a time series in which lower values, or lower degrees of irregularity, are generally indicative of more linear, less complex dynamics. An in-depth view of the algorithm was provided by Richman and Moorman [34]. Parameters were chosen within acceptable theoretical ranges and based on common/standard values [34,35] with embedding dimension set to length 2 and tolerance set to 0.2 multiplied by the standard deviation of individual CoP time series'. Non-linear data analysis was performed using Matlab v.2017a (MathWorks, Natick, MA).

Of note, the presence of underlying pathology may result in higher degrees of irregularity under certain pathological conditions, though the corresponding pathological dynamics are not necessarily complex. Instead, the presence of these underlying pathologies is usually also accompanied by a loss of long-term, fractal-like correlations in the physiological and/or biomechanical outputs of a system, the increase in irregularity then more “random” and thus not “meaningful” [11].

2.4. Statistical analysis

To assess the effect of breathing on the non-linear and variability measures of CoP as well as the measures of balance performance, repeated measure MANOVAs were performed with top-down application of repeated measure ANOVAs (with application of Greenhouse-Geisser corrections when necessary) and pairwise comparisons as needed. Statistical analysis was performed using SPSS v.24 (IBM Corp., Armonk, New York). Alpha level was set to 0.05.

Table 1
Overall summary of the data for each independent variable across all breathing conditions. Data is presented as means ± standard deviation. * indicates a significant difference with neutral breathing.

Measure	Abdominal Mean ± S.D.	Thoracic Mean ± S.D.	Neutral Mean ± S.D.
$SampEn_{CoPx}$	.144 ± .056	.126 ± .03	.146 ± .051
$SampEn_{CoPy}$	.196 ± .077*	.178 ± .079*	.241 ± .104
SA (cm^2)	5.00 ± 3.18	4.14 ± 2.04	3.74 ± 1.23
$\bar{\mathbf{v}}$ (cm/s)	2.33 ± .55	2.10 ± .51	2.37 ± .63
$StDev_x$ (cm)	.407 ± .170	.368 ± .127	.392 ± .105
$StDev_y$ (cm)	.616 ± .169*	.595 ± .156*	.515 ± .098

3. Results

3.1. Measures of balance performance

Results displayed no significant multivariate effect from breathing on measures of balance performance, i.e., SA or $\bar{\mathbf{v}}$ (Wilk's Lambda = .623, F(4,14) = 2.115, p = .133). A summary of the data is presented as part of Table 1.

3.2. Measures of variability

A significant multivariate effect from breathing was observed on measures of CoP variability, i.e., $StDev_x$ and $StDev_y$ (Wilk's Lambda = .678, F(4,14) = 3.544, p = .011). Subsequent univariate ANOVA results indicated a significant effect from breathing on $StDev_y$, (F(1.79, 30.46) = 5.778, p = .009). Pairwise comparisons revealed significant differences in $StDev_y$ between neutral and abdominal (.515 ± .098 cm vs .616 ± .169 cm, p = .013) and neutral and thoracic (.515 ± .098 cm vs .595 ± .156 cm, p = .016) breathing conditions were found. A summary of the data is presented as part of Table 1.

3.3. Non-linear measures

A significant multivariate effect from breathing was seen on non-linear measures, i.e., $SampEn_{CoPx}$ and $SampEn_{CoPy}$ (Wilk's Lambda = .239, F(4,14) = 11.168, p < .0005). Upon further inspection, univariate ANOVA results indicated a significant effect from breathing on $SampEn_{CoPy}$ (F(1.24,21.15 = 12.383, p = .001). Pairwise comparisons revealed significant differences in $SampEn_{CoPy}$ between neutral and abdominal (.241 ± .104 vs .196 ± .077, p = .018) and neutral and thoracic (.241 ± .104 vs .178 ± .079, p < .0005) breathing conditions were found. A summary of the data is presented as part of Table 1.

4. Discussion

The purpose of this study was to investigate the effects of voluntary control of breathing and breathing technique on the dynamic characteristics of CoP time series in healthy older adults. Specifically, we examined whether a shift from autonomous to voluntary control of breathing would significantly affect CoP measures of balance performance alongside CoP variability and irregularity as well as the effect of breathing technique employed during voluntary breathing conditions, i.e., abdominal vs. thoracic. The results support our hypothesis that CoP during autonomous breathing was significantly more complex, being more irregular (higher $SampEn_{CoPy}$) than both voluntarily controlled breathing conditions. CoP during autonomous breathing was also less variable (lower $StDev_y$) than during both voluntary breathing conditions. However, the two voluntarily controlled conditions did not significantly differ from one another and breathing did not have any significant effect on measures of balance performance. These results are in line with previous research displaying decreases in CoP irregularity

[16,36,37] and simultaneous increases in variability [4,38] with increased demands. However, our results showed no difference between breathing conditions in contrast to previous findings [29].

These results indicate a sense of agreement between measures of CoP variability and irregularity, although it is important to note that the context of this agreement is essential for interpretation. During autonomous breathing, the lower variability and high irregularity reflects a high level of efficacy of postural control relative to the imposed demands, maintaining a high degree of complexity in the context of the spatiotemporal structural organization of the CoP time series. In contrast, when control of breathing was regulated by voluntary control, regardless of the breathing technique used, i.e., abdominal vs thoracic, CoP became more regular and less controlled, reflecting a loss of the spatiotemporal complexity and lower efficacy of postural control to meet imposed demands. These results imply: 1) the act of diverting or changing control of breathing from autonomous to voluntary control in and of itself had an effect on postural control; 2) older adults have a low efficacy for reactive tuning, which itself is responsible for the inability to settle into a new dynamic steady state during voluntary breathing; 3) during voluntary breathing posture becomes less autonomous compared to neutral breathing.

Our results indicate a significant difference between the effect on sway regularity from autonomic vs. voluntarily controlled breathing, with an altered control mechanism in voluntarily breathing condition. It is known that, during autonomous breathing, regulation of breathing is controlled by the pontomedullary respiratory networks of the brainstem [39], however, during voluntary control of breathing, cortical influences are also known to mediate control of breathing [40]. Of particular interest, voluntary control of breathing has been shown to be associated with increased activity of the primary motor cortex, premotor cortex, and supplementary motor areas along with the cerebellum [41–43]. Although this may predominantly reflect a mechanism for voluntary command of diaphragmatic function [44] and corresponding support from other respiratory muscles for the purpose of controlling respiration alone, the muscles also serve important secondary roles related to postural control [45]. In cases of forceful voluntary control, such as during forced expiration and inspiration, non-respiratory muscles such as the muscles of the lower extremities or hands have also been shown to be affected via changes in corticospinal excitability that occurs as a result of voluntary breathing [22–24]. Respiratory muscles related to postural control may be affected during voluntary control of breathing plausibly via similar mechanisms. Regardless, voluntary control of breathing may have resulted in altered respiratory-motor interactions via additional cortical influences on the postural muscles, which resulted in affected postural control.

While respiration has been seen to result in small internal perturbations to posture due to the respiratory-induced motion of the thorax and abdomen [26,46], these perturbations are often negligible or absent in healthy adults [47,48]. The central nervous system accounts for and minimizes the effect of predictable perturbations via anticipatory postural adjustments [49,50]. In healthy adults, movement of the hips and lower extremities actively seek to compensate for respiratory-induced postural perturbances via small angular displacements to maintain stability [26]. However, these perturbations been shown to be have a greater effect in populations with known postural issues, such as those with lower back problems [48,51] and older adults [27]. This interdependency between the respiratory and postural control system has been previously documented as a clinical biomarker for the “efficiency” or “automaticity” of postural control [25,26,45,52–54]. Manor et al. [27], defined “posturo-respiratory synchronization” as the degree to which respiratory and postural sway are synchronized over time, i.e., higher degrees of synchronicity indicate a greater effect of respiration on posture. During eyes closed conditions, stroke patients showed higher degrees of posturo-respiratory synchronization compared to non-stroke patients. Furthermore, posturo-respiratory synchronization was also shown to increase with age in older adults during static standing [27]. Holmes et al. [28], reported that a 12-week Tai Chi intervention significantly decreased posturo-respiratory synchronization in older adults. These findings suggest that increased levels of posturo-respiratory synchronization reflect a decreased efficacy of reactive tuning, i.e., the ability of the postural control system to exact an appropriate response to mitigate respiratory perturbations. This is consistent with our findings that older adults displayed a low efficacy of reactive tuning, Under the act of voluntarily breathing, the decrease in CoP irregularity and increased variability indicate a loss of system control, implying a low efficacy for reactive tuning among older adults.

The amount of attention required for the control of standing posture is dynamic and continuously changes in response to perturbations. When one’s attention is directed towards the task of maintaining postural control, the fluctuations of postural sway increase in regularity. “Internal” perturbations refer to postural stressors that increase the difficulty of postural control task itself, e.g., blocking one’s vision [55], altering respiratory activity [56–58], etc. Typically, the investment of attention to posture increases during an internal perturbation thus decreasing the degree of automaticity of postural control [59,60]. This is supported by our results that voluntary breathing, as internal perturbation, leads to a lower sample entropy of CoP (more regular) during standing. Therefore, another potential explanation on the effect of voluntary breathing on sway regularity could be a decrease in the automaticity of posture. In the present study, the average participant can be categorized as overweight (average BMI 28 ± 6.2 kg/m^2) and some participants can be categorized as obese. This may result in less autonomous posture to compensate since obesity plays a negative role in balance control [61].

Our findings indicate no significant difference between the effects of thoracic and abdominal breathing during voluntary breathing. This is in contrast with previous findings [29] reporting thoracic breathing to have a significantly greater perturbing effect on balance compared to abdominal breathing. While there was a trend for thoracic breathing conditions to display less complex CoP dynamics, this finding was not significant. However, considering the categorization of most participants as overweight or obese, a confounding factor may have been a greater repartition of mass in the abdominal area. This would result in larger moment arms from displacements of the abdominal compartment and potentially lead to a greater contribution of abdominal motion to respiratory-induced perturbations. Also, the effects of both breathing techniques were assessed only during voluntary control of breathing, which resulted in a negative effect on posture compared to autonomous breathing. Thus, potential negative effect from thoracic breathing may have also been subsumed by the negative effect of voluntary breathing.

5. Conclusion

The present study showed that the complexity of CoP dynamics is affected by voluntary control of breathing. Specifically, CoP dynamics during voluntary control of breathing were less complex than that during autonomous control of breathing. This may be due to altered respiratory-motor interactions and/or decreased automaticity of posture over breathing from autonomous to voluntary control. Future research should also investigate whether different breathing techniques, i.e., abdominal vs thoracic breathing, differ with regards to their effects on posture if done autonomously as compared to voluntarily.

Conflict of interest

None.

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