Dynamics of postural control during bilateral stance – Effect of support area, visual input and age

Peter C. Raffalt[a,b,*], Meaghan E. Spedden[c], Svend S. Geertsen[c,d]

[a] *Julius Wolff Institute for Biomechanics and Musculoskeletal Regeneration, Charité – Universitätsmedizin Berlin, Augustenburger Platz 1, 13353 Berlin, Germany*
[b] *Department of Biomedical Sciences, University of Copenhagen, Blegdamsvej 3B, 2200 Copenhagen N, Denmark*
[c] *Department of Nutrition, Exercise and Sports, University of Copenhagen, Nørre Allé 51, 2200 Copenhagen N, Denmark*
[d] *Department of Neuroscience, University of Copenhagen, Blegdamsvej 3B, 2200 Copenhagen N, Denmark*

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ABSTRACT

The present study investigated the effect of support area, visual input and aging of the dynamics of postural control during bilateral stance. Fifteen young (22.1 ± 1.7 years) and fifteen older (68.3 ± 2.7 years) individuals completed four different 90 s bilateral stance trials: 1) shoulder wide feet distance with eyes open, 2) shoulder wide feet distance with eyes closed, 3) narrow feet distance with eyes open, and 4) narrow feet distance with eyes closed on a force plate form. The anterior (AP) and mediolateral (ML) center of pressure (COP) trajectories were calculated from the middle 60 s of the ground reaction forces and moments. Sample entropy (SaEn), correlation dimension (CoD), the largest Lyapunov exponent (LyE) and entropic half-life (ENT½) were calculated for the COP in both directions. In young individuals, a narrower support area resulted in a restricted movement solution space with lower SaEn, lower LyE and longer ENT½ in the executed motor control strategy, whereas it increased the CoD in the older individuals. During the eyes closed trials, SaEn, CoD and LyE increased and decreased ENT½ for both groups in the AP direction and increased SaEn and LyE in the ML direction for the older individuals alone. This indicates that aging is associated with direction- and task-dependent changes in the dynamics of the executed COP movements during postural stance tasks.

1. Introduction

The control of upright stance relies on continuous integration of somatosensory, visual and vestibular information to execute an appropriate movement strategy (Winter, Patla, & Frank, 1990). While studies on postural control traditionally have focused on linear measures of the center of pressure (COP) trajectories, an increased use of various nonlinear methods has aimed at assessing the dynamics of the COP trajectories in different populations (e.g. infants, neurological patients and elderly) (Baltich, von Tscharner, & Nigg, 2015; Donker, Roerdink, Greven, & Beek, 2007; Gurses & Celik, 2013; Harbourne & Stergiou, 2003; Pelykh, Klein, Botzel, Kosutzka, & Ilmberger, 2015; Roerdink et al., 2006). The latter approach embraces the temporal dependency of the COP movements and quantifies how previous completed movements are correlated to current movements (Harbourne & Stergiou, 2009; Stergiou & Decker, 2011). Some of the more frequently used methods includes sample entropy (SaEn), correlation dimension (CoD) and the largest Lyapunov exponent (LyE). These measures provide different characteristics of the time series in question and have been used

to assess the dynamics of utilized movement solutions during various activities (Harbourne & Stergiou, 2003; Raffalt, Guul, Nielsen, Puthusserypady, & Alkjaer, 2017; Raffalt, Vallabhajosula, Renz, Mukherjee, & Stergiou, 2018). SaEn quantifies regularity and CoD quantifies dimensionality (Grassberger & Procaccia, 1983; Richman & Moorman, 2000). Both measures have been used to indicate changes in the utilized functional degrees of freedom within the human movement system either due to external restriction, internal neuromuscular noise, restricted sensory information or altered movement strategy (Kay, 1988; Newell, 1997). Thus, they can be interpreted as a measure of the organization of the movement solution space with higher values indicating an unpredictable and less structured space with more potential movement solutions and lower values indicating a more predictable and structured space with fewer potential solutions. LyE quantifies the rate of divergence in movement trajectories and indicates how fast movement solutions change within the available solution space (Wolf, Swift, Swinney, & Vastano, 1985). Recently, entropic half-life (ENT½) was introduced as a measure of the level of time dependency (Baltich, Von Tscharner, Zandiyeh, & Nigg, 2014; Federolf, Zandiyeh, & Von Tscharner, 2015; Zandiyeh & Von Tscharner, 2013). ENT½ estimates the elapsed time before positional information from previous completed movements no longer influences the control of current movements in a physiological interpretable scale (e.g. time in seconds). Thus, combining these measures to quantify the dynamics of COP movements provides an elaborate description of the motor control strategy utilized to adapt to external or internal constraints.

Manipulating the support area (e.g. foot placement or unilateral vs. bilateral stance) and the visual input during upright stance tasks has been used to investigate the underlying motor control strategies in healthy and injured individuals (Delignieres, Torre, & Bernard, 2011; Federolf et al., 2015; Song, Burcal, Hertel, & Wikstrom, 2016; Wang, Jordan, & Newell, 2012). In a recent study, Federolf and colleagues observed that during bilateral stance, the CoP trajectory in the mediolateral (ML) direction had lower time dependency compared to the anterior-posterior (AP) movements (Federolf et al., 2015). These observations emphasize the importance of differentiating the postural control of the AP direction from that of the ML direction. Adopting the degrees of freedom problem, first described by Nicolai Bernstein in 1967 (Bernstein, 1967), and its later reinterpretation as abundance of states to bilateral stance would suggest that due to the body sway around primarily one joint in the AP direction, a limited number of mechanically equivalent states exists to provide mechanical equilibrium (Gelfand & Latash, 1998). In contrast, the body sways around two support points (the two feet) in the ML direction which enables a wider range of possible configurations to provide mechanical equilibrium (Federolf et al., 2015).

Furthermore, with age, the sensation and integration of sensory input and the neuromuscular control deteriorates, which increases the neuromuscular noise (Bemben, 1998; Campbell, McComas, & Petito, 1973; Delbono, 2003; Luff, 1998; Stanley & Taylor, 1993; Tudorascu et al., 2014). Additionally, the mechanical properties of passive structures such as tendons and ligaments will also change with age (Carroll et al., 2008; Svensson, Heinemeier, Couppe, Kjaer, & Magnusson, 2016). These age-related changes are associated with altered movement pattern during various tasks in elderly compared to younger individuals (Ketcham, Seidler, Van Gemmert, & Stelmach, 2002; Newell, Mayer-Kress, & Liu, 2009; Seidler, Alberts, & Stelmach, 2002). According to the 'loss of complexity' theory formulated by Lipsitz and Goldberger (1992), aging is related to a loss of complexity in biological signals with a corresponding loss of adaptability. In 2006, Stergiou and colleagues formulated a theory of 'optimal movement variability' suggesting that the loss of complexity in movements can be characterized by both reduced regularity (i.e. towards a random pattern) and increased regularity (i.e. towards a periodic pattern) (Stergiou, Harbourne, & Cavanaugh, 2006). Thus, these theories encourage the use of nonlinear tools to assess the effect of aging on movement dynamics. In a recent study on unilateral stance, Baltich and colleagues observed that elderly individuals had lower time dependency in their AP movements but not in their ML movements compared to younger individuals (Baltich et al., 2015). In line with the aforementioned theory by Stergiou and colleagues, this could indicate that the aging related loss of complexity is characterized by an increase in irregularity (Stergiou et al., 2006). The study by Baltich and colleagues included only one standing task (unilateral stance) and did not include any manipulation of the sensory input (Baltich et al., 2015). Thus, it is unknown if this age difference also is present during stance tasks with larger support area or manipulated sensory information. Specifically, depriving visual input during both bi- and unilateral stance has been shown to alter the regularity, dimensionality, rate of trajectory divergence and the time dependency in healthy adults (Baltich et al., 2014; Donker et al., 2007). To the best of our knowledge, this has not been investigated in elderly individuals.

Therefore, the purpose of the present study was to investigate the effect of support area, visual input and aging on the dynamics of postural control during bilateral stance. To fulfill this purpose, the present study included elderly and young subjects and exposed them to four different stance tasks with different support area (wide and narrow foot position) and with and without visual input. The characteristics of the COP dynamics were quantified using SaEn, CoD, LyE and ENT½. Three hypotheses were formulated related to each of the three standing tasks and one additional hypothesis was formulated addressing the age effect.

1) Reducing the support area would restrict the available movement solution space (decrease in SaEn and CoD) in the ML direction but not in the AP direction (no significant change in SaEn and CoD). Furthermore, to control the movements in the altered solution space in the ML direction, the rate of changes in movements would increase and the level of time dependency would decrease (increase in LyE and decrease in ENT½), while no changes would occur in the AP direction (no significant change in LyE and ENT½).

2) Depriving visual input would increase the utilized movement solution space (increase in SaEn and CoD) in both directions in the search for stable movement solutions. The relatively few mechanically equivalent states in the AP direction would require more rapid changes in movement solutions (increase in LyE) and less time dependency (decrease in ENT½), whereas this would not be required in the ML direction (no significant change in LyE and ENT½).

3) The combination of support area restriction and visual deprivation would not change the characteristics of the movement solution space due to the opposing effects of each of individual constraints in the ML direction (no significant change in SaEn and CoD) but

Table 1
Subject demographics.

	Age (yrs)	Body mass (kg)	Body height (m)	Gender (M/F)	MMSE
Young	22.1 ± 1.7	73.0 ± 15.9	1.76 ± 0.08	7/8	29.0 ± 1.1
Elderly	68.3 ± 2.7	81.5 ± 14.1	1.73 ± 0.11	7/8	28.9 ± 1.0

Values presented in mean ± standard deviation. MMSE: Mini-Mental State Examination (score out of 30).

would increase SaEn and CoD in the AP direction. In order to maintain a stable postural control, the rate of changing movement solutions would increase (increase in LyE) and the time dependency would be reduced (decrease in ENT½) for both directions.
4) During the control trials, the elderly subjects would utilize a wider solution space with higher irregularity (higher CoD and SaEn) with higher rate of changes in movement solutions (higher LyE) and lower level of time dependency (lower ENT½) compared to the young subjects. Furthermore, when exposed to alterations in the support area and deprivation of visual input, the elderly subjects would alter their movement strategy more compared to the young subjects.

2. Material and methods

2.1. Participants

Thirty healthy individuals (fifteen young and fifteen older) participated in the study (Table 1). All subjects were free from neurological disease or lower limb injuries and did not take any medication which could affect motor control. No subject showed sign of cognitive impairment (determined by the Mini-Mental State Examination, in which all subjects scored above 26 out of 30). Upon arrival to the laboratory, the subjects were informed about the experimental setup and protocol, after which they all gave their informed written consent to participate. The study was approved by the ethics committee for the Capital Region of Denmark (approval number H-16021214), and the experiment was conducted in accordance with the Helsinki declaration. At a separate session, the included subjects completed a different experimental protocol with the purpose of investigating corticospinal function during isolated ankle movement tasks (Spedden, Nielsen, & Geertsen, 2018). However, besides the subject demographics, no data from the present study have been previously published.

2.2. Experimental setup

The subjects wore socks and performed four 90 s standing trials on a force platform (AMTI OR6-6-1000) in the following order: 1) shoulder wide feet distance with eyes open (EO-WIDE), 2) shoulder wide feet distance with eyes closed (EC-WIDE), 3) narrow feet distance with eyes open (EO-NARROW), and 4) narrow feet distance with eyes closed (EC-NARROW). All subjects were instructed to place their hands on their hips. During the eyes open trials, the subjects were instructed to fix their gaze on a target placed on the wall 3.8 m in front of them. Approximately 1 min rest was given between each trial to avoid fatigue influencing the performance.

2.3. Analysis

During each trial, three dimensional ground reaction forces and moments were sampled at 1000 Hz. COP time series for the AP and ML directions were extracted from 60 s after removing the initial and final 15 s of each trial. Following the procedure presented by Federolf et al. (2015), Baltich et al. (2014) and Baltich et al. (2015), the COP time series were filtered using a Daubechies wavelet and down sampled to 100 Hz. To investigate the effect of this filtering procedure all analyses were performed on the unfiltered down sampled data from the EO-WIDE trial. The results of these additional analyses are presented in the Supplementary material and summarized in the discussion.

SaEn was calculated using the equation by Richman and Moorman (2000) with the vector length, m = 1, and the tolerance limit, r = 0.2. To evaluate the input parameter consistency, SaEn was calculated using combinations of m = 2 and m = 3 and r = 0.1, 0.15, 0.2, 0.25 and 0.3. The results for these calculations are presented in the Supplementary material and summarized in the discussion.

CoD and LyE were calculated using the equations by Grassberger and Procaccia (1983) and by Wolf et al. (1985), respectively. Before calculating CoD and LyE, each time series was reconstructed in state space using the method of delayed embedding (Sauer, Yorke, & Casdagli, 1991; Takens, 1981). Time delay and embedding dimension were calculated using the Average Mutual Information and False Nearest Neighbor algorithms, respectively. To best represent all investigated time series, the mean time delay and embedding dimension across subjects, trials and directions were rounded to nearest integers (time delay = 30 and embedding dimension = 5). The time delay and embedding dimension of each subject, direction and each trial are presented in the Supplementary material.

ENT½ was calculated using the procedure presented by Zandiyeh and Von Tscharner (2013) and Baltich et al. (2014). The procedure included 4 steps: Step 1) The original time series was gradually randomized through a reshaping procedure according to the following principle. The first reshaped time series (RTS) was equal to the original time series (e.g. [1 2 3 4 5 6 7 8 9 10 11 12]). The second RTS would have a reorganization of every second data point (e.g. [1 3 5 7 9 11 2 4 6 8 10 12]), the third RTS would have a reorganization of every third data point (e.g. [1 4 7 10 2 5 8 11 3 6 9 12]) and so on. When a time series was sampled at 100 Hz, there

was 10 ms between each data point. For the second RTS, there was 20 ms between two adjacent data points, for the third RTS, there was 30 ms between two adjacent data points and so on. This reshaping procedure was iterated 100 times. Step 2) SaEn was calculated for each RTS with m = 2 and r = 0.2. Step 3) The SaEn from each RTS were normalized by first subtracting the SaEn of the original time series and then dividing it by the difference between the average SaEn of 50 completely randomized time series and the SaEn of the original time series. The randomized time series were created by a random permutation of the data points in the original time series. Step 4) The normalized SaEn values from the RTS were plotted in a semi logarithmic plot as a function of the reshaping time. ENT½ was identified as the time at which the normalized SaEn increased above 0.5 (Zandiyeh & Von Tscharner, 2013).

In general, nonlinear methods are known to be sensitive to the data length. In order to investigate the effect of data length in the present study, SaEn, CoD, LyE and ENT½ were calculated on time series from the EO-WIDE trial with 1000, 2000, 3000, 4000, 5000 and 6000 data points, respectively. The results of these analyses are presented in the Supplementary material and summarized in the discussion.

2.4. Statistics

Due to technical issues, data from one subject during the EO-WIDE trial was lost and omitted from the statistical analyses. To investigate the effect of task, age and vision on the SaEn, CoD, LyE and ENT½, a three-way linear mixed model ANOVA with subject as a random factor and task, age and vision as independent factors. In case of an overall effect of the independent factors or the two-way or three-way interactions, a Holm-Sidak post hoc test was applied. Level of significance was set at 5%. The ENT½ analysis could not be completed in 9 out of 120 cases in the AP direction and 4 out of 120 cases in the ML direction due to the normalized SaEn of the RTS increasing above 0.5. Thus, these data points were omitted from the statistical analyses. All statistical analyses were performed in SPSS (IBM, SPSS Statistics, version 24, NY, USA).

3. Results

3.1. Regularity

There was a significant overall effect of task (df = 26.8, F = 4.6, p = 0.042), age (df = 23.3, F = 4.8, p = 0.039) and vision (df = 16.2, F = 23.7, p < 0.0001) on the SaEn in the AP direction, but no significant interactions. The post-hoc test revealed that the SaEn was significantly higher during the narrow feet distance trials compared to the wide feet distance trials, significantly higher in the older group and significantly higher during the eyes closed trials (Fig. 1A).

There was a significant overall effect of task (df = 23.5, F = 5.8, p = 0.025) and vision (df = 24.8, F = 7.7, p = 0.010) and a two-way interaction of group-task (df = 23.5, F = 17.7, p < 0.0001), group-vision (df = 24.8, F = 12.4, p = 0.002) and task-vision (df = 23.4, F = 12.4, p = 0.002) on the SaEn in the ML direction (Fig. 1B). The SaEn was significantly higher during the wide feet
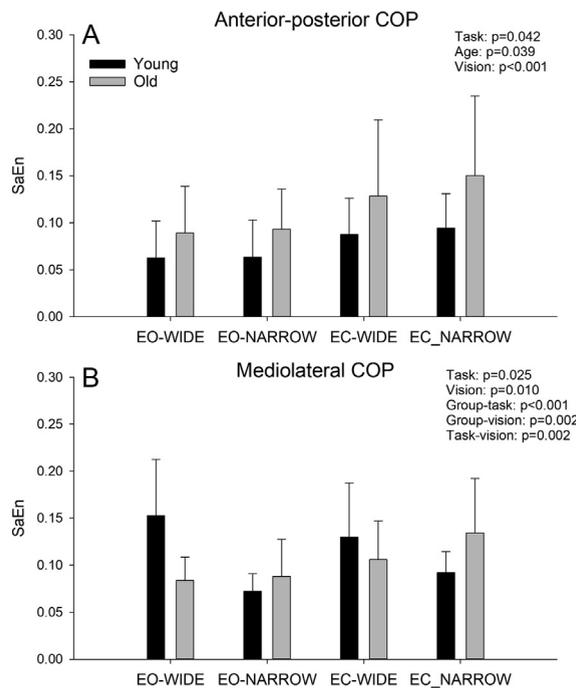

Fig. 1. Sample entropy of the center of pressure trajectory in A) the anterior-posterior direction and B) the mediolateral direction during the four trials. Overall significant effects of task, age, vision or two-way interaction of group-task, group-vision and task-vision are indicated by p-values.
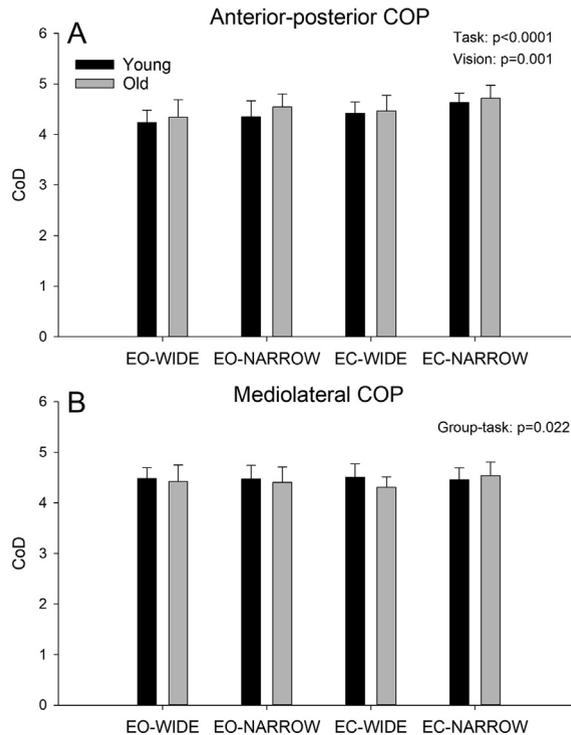
Fig. 2. Correlation dimension of the center of pressure trajectory in A) the anterior-posterior direction and B) the mediolateral direction during the four trials. Overall significant effects of task, vision or two-way interaction of group-task are indicated by p-values.

distance trials compared to the narrow feet distance trials and during the eyes closed trials compared to the eyes open trials. While the SaEn decreased significantly (p = 0.001) for the younger group as feet distances narrowed, it did not change for the older group. During the wide feet distance trials, the younger group had significantly higher SaEn compared to the older group (p = 0.013) and during the narrow feet distance trials, the older group had significantly higher SaEn (p = 0.018). During the eyes open trials, the younger group had significantly higher SaEn compared to the older group (p = 0.028) but there was not group difference during the eyes closed trials. While the younger group did not display significant difference in SaEn between eyes open and eyes closed trials, the older group had significantly higher SaEn during the eyes closed trials (p = 0.002). During the eyes open trials, the SaEn was significantly higher (p < 0.0001) during the wide feet distance trial compared to the narrow feet distance trial, and during the narrow feet distance trials, the SaEn was significantly higher (p < 0.0001) with eyes closed compared to eyes open (Fig. 1B).

3.2. Dimensionality

There was a significant overall effect of task (df = 26.7, F = 18.1, p < 0.0001) and vision (df = 26.8, F = 15.2, p = 0.001) on the CoD in the AP direction. The CoD was significantly higher during the narrow feet distance trials compared to the wide feet distance trials and significantly higher during the eyes closed trials (Fig. 2A). There was a significant overall two-way interaction of group-task (df = 27.0, F = 5.0, p = 0.034). The post hoc test revealed that for the older group the CoD was significantly higher (p = 0.022) during narrow feet distance trials compared to the wide feet distance trials (Fig. 2B).

3.3. Rate of divergence

There was a significant overall effect of vision (df = 23.0, F = 14.0, p = 0.001) on the LyE in the AP direction. The LyE was significantly higher during the eyes closed trials compared to the eyes open trials (Fig. 3A). There was a significant overall effect of vision (df = 23.5, F = 8.9, p = 0.007) on the LyE in the ML direction. There was a two-way interaction of group-task (df = 26.0, F = 6.3, p = 0.019) and group-vision (df = 23.5, F = 4.6, p = 0.043). The post hoc test revealed that for the younger group the LyE during the wide feet distance trials was significantly higher than during the narrow feet distance trials. No task difference was observed for the older group. The older group had significantly higher LyE (p = 0.001) during the eyes closed trials compared to the eyes open trials but no difference was observed for the younger group (Fig. 3B).

3.4. Level of time dependency

There was a significant overall effect of age (df = 13.6, F = 7.2, p = 0.018) and vision (df = 10.2, F = 35.8, p < 0.0001) on the
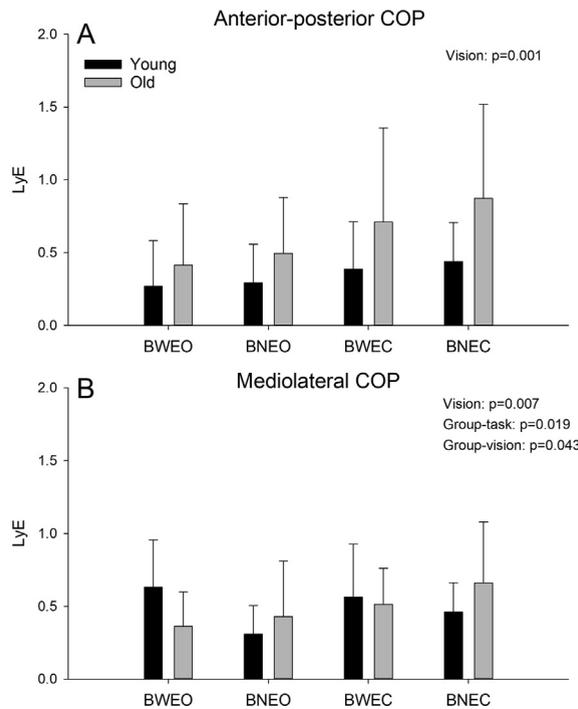
Fig. 3. Lyaponov exponent of the center of pressure trajectory in A) the anterior-posterior direction and B) the mediolateral direction during the four trials. Overall significant effects of vision or two-way interaction of group-task and group-vision are indicated by p-values.

ENT½ in the AP direction. The younger group had significantly longer ENT½ compared to the older group and ENT½ was significantly longer during the eyes open trials compared to the eyes closed trials (Fig. 4A). There was a significant overall effect of vision on the ENT½ in the ML direction (df = 25.3, F = 5.6, p = 0.026) with ENT½ being significantly longer during the eyes open
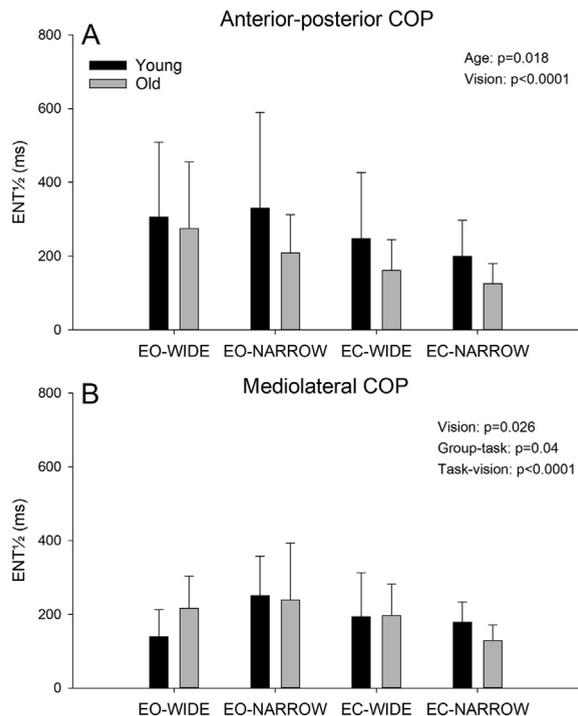

Fig. 4. Entropic half-life of the center of pressure trajectory in A) the anterior-posterior direction and B) the mediolateral direction during the four trials. Overall significant effects of age and vision or two-way interaction of group-task and task-vision are indicated by p-values.

trials (Fig. 4B). There was a significant two-way interaction of group-task (df = 18.1, F = 4.9, p = 0.04) and task-vision (df = 23.9, F = 24.0, p < 0.0001). While the post hoc test did not reveal any significant differences for the group-task interaction, during the eyes open trials the ENT½ was longer with the narrow feet distance compared to the wide feet distance (p = 0.013). In contrast, during the eyes closed trials, the ENT½ was shorter with the narrow feet distance compared to the wide feet distance (p = 0.026). Additionally, during the narrow feet distance trials, the ENT½ was significantly shorter when eyes were closed (p = 0.001).

4. Discussion

The purpose of the present study was to investigate the effect of support area, visual input and aging on the dynamics of postural control during bilateral stance. The present study applied multiple nonlinear metrics for quantifying different characteristics of the COP dynamics. This approach have previously been used to investigate the development of postural control in infants (Harbourne & Stergiou, 2003) enabling detailed assessment of the underlying motor control. In relation to this purpose, four hypotheses were formulated.

4.1. Reduction of surface area

The first hypothesis stated that the change in foot placement would affect the characteristics of the COP trajectory in the ML direction but not in the AP direction. This hypothesis could be partly confirmed since there was a significant effect of task or group-task interaction on all four variables in ML direction but only SaEn and CoD was affected in the AP direction. The results showed an age-dependent difference in the response to the change in feet placement. While the SaEn decreased and the LyE increased for the younger adults as feet distance was reduced, this was not the case for the older adults. In contrast, the reduction in feet placement increased the CoD of the older adults and not in the younger adults. These observations suggest that a reduction in the support area alters the utilized function degrees of freedom towards an increase in the regularity and an increased rate at which movement solutions are changed in the younger adults alone and increase in the dimensionality of the movement solutions alone in the older adults. Interestingly, the increase in the SaEn and CoD in AP direction as feet distance was narrowed did appear age-dependent. These observations also suggest a directional specificity in the executed motor control strategy when exposed to task constraints like reduced support area (Baltich et al., 2015). While the post hoc test did not reveal any effect of feet placement, a closer inspection of Fig. 4 showed that for the younger adults the ENT½ in the ML direction was substantially increased when the support area was restricted and eyes were kept open. This corresponds well to the pattern observed for the SaEn and LyE in the ML direction, where a significant decrease was observed for the young individuals alone. This could indicate that these individuals actively adapted their motor control strategy to the reduction in support area by increasing the regularity of the solution space, decreasing the rate of changes between movement solutions and increasing the time dependency (i.e. increasing the time elapsing before position information from previous completed movements no longer influences the control of current movements).

The results of the present study are in line with previous studies showing that change in foot placement significantly changed the variation and dynamics of the COP trajectory. Wang et al. (2012) observed that the variation in COP displacement in AP direction increased when changing foot placement from side-side position to staggered position and decreased when changing to tandem position. In contrast, the variation in the ML direction increased from the side-to-side position to the staggered position and increased further to the tandem position. Similarly, King, Wang, and Newell (2012) investigated the recurrence dynamics of the COP displacement during the aforementioned foot positions and observed that while the dynamics in the ML direction was affected by altered foot position, this was not the case for the AP direction (King et al., 2012). Using a similar protocol, Federolf et al. (2015) observed that the ENT½ (i.e. time dependency) was shorter in the ML than in the AP direction when standing in the side-by-side position compared and that this relationship was reversed in the side-by-side position.

4.2. Deprivation of visual input

The second hypothesis stated that depriving visual input would increase the utilized solution space (increased SaEn and CoD) in both directions and increase the rate of change in movement solutions (increased LyE) and decrease the time dependency (decreased ENT½) in the AP direction. This hypothesis could also be partly confirmed. While all four variables were significantly affected by visual deprivation in the AP direction, age-dependent differences in the response were observed in the ML direction. In the AP direction the irregularity, dimensionality and rate of change in movement solutions increased and the time dependency decreased for both groups and during both feet placement trials confirming the hypothesis. Thus, as visual information is deprived, the subjects search for stable movement solutions in the AP direction by utilizing a greater solution space with more rapid changed in solutions and less time dependency (i.e. decreasing the time elapsing before position information from previous completed movements no longer influences the control of current movements). This suggests that the visual information about the surrounding environment (e.g. the distance to the wall in front) affects the motor control strategy greatly. In line with the present results, Robert and colleagues observed an increased total COP length during the eyes closed condition when applying traditional linear measures of the COP trajectories to quiet stance (Robert, Ballaz, & Lemay, 2016). However, other studies have not been able to differentiate the two conditions (Chiarovano et al., 2015; Luo et al., 2018). This could suggest that the nonlinear tools applied in the present study are more sensitive to detect the motor control adjustment made during the tasks (Harbourne & Stergiou, 2003). Interestingly, a significant group-vision interaction was observed for SaEn and LyE in ML direction with both variables increasing for the older group but not for the younger group. This is in agreement with previous observations (see appendix in Ramdani, Seigle, Lagarde, Bouchara,

and Bernard (2009)) and could indicate that while the younger adults were able to limit the motor control adjustments made in response to the deprivation of visual input to the AP direction, the older adults seemed to have a "spillover effect" from the AP direction to the ML direction. It could be speculated that this phenomenon potentially increases the risk of sideways falls, if visual information is compromised in older adults.

In line with visual deprivation, virtual reality has been used to alter the perception of the surrounding environment during upright stance and has been shown to alter the COP trajectory substantially (Luo et al., 2018; Robert et al., 2016). Thus, providing erroneous visual information to the nervous system as well as depriving visual information appears to disturb the motor control during upright stance.

4.3. Combination of surface area reduction and visual deprivation

The third hypothesis stated that the combination of a narrow support area and visual deprivation would increase the SaEn and CoD in the AP direction but not change the dynamics in the ML direction. While this part of the hypothesis was confirmed, it is noteworthy that the lack of change in SaEn in the ML direction was a result of a substantial decrease in the younger adults and an increase in the older adults. The increase of SaEn and CoD in the AP direction indicates more unpredictable and unstructured movement solutions. Furthermore, the third hypothesis stated that LyE would increase and ENT½ would decrease for both directions. This was confirmed for the AP but not for the ML direction. This suggests that in order to maintain balance in the AP direction during the supposedly most challenging task, less time elapsed before position information from previous completed movements no longer influenced the execution of current movements. Additionally, the subjects applied more rapid changes between movement solutions in the AP direction. These observations also support the notion that during bipedal stance, the limited number of movement configurations that provides mechanical equilibrium in the AP direction makes the motor control system more vulnerable to restricted sensory input compared to the ML direction. As a consequence, the motor control strategy is significantly altered in order to maintain stable upright balance.

4.4. Effect of age

The fourth hypothesis stated that the older adults would exhibit higher SaEn, CoD and LyE and lower ENT½ during the EO-WIDE compared to the younger adults. This part of the fourth hypothesis could not be confirmed. In contrast, the SaEn and LyE in the ML direction were significantly lower in the older adults. This shows that the older adults reduced their solutions space towards more regular movements between which the rate of changes was decreased indicating a lower adaptability during postural stance. According to the 'loss of complexity' theory by Lipsitz and Goldberger (1992) aging is associated with a loss of complexity of the biological system. Thus suggests that any age differences in movement dynamics would be related to the loss of complexity. Applying this notion to movements, Stergiou et al. (2006) formulated the 'optimal movement variability' theory which considered young, healthy individual to display an optimal movement variability characterized by a high complexity with chaos like behavior. According to this theory, aging and diseases would reduce the complexity and alter the movement dynamics towards either a more random-like pattern or a more predictable pattern. The present results supports this theory and suggest that the age related loss of complexity results in more regular movement dynamics with less adaptability. The nature of the completed task has been shown to affect the exhibited movement dynamics (Vaillancourt & Newell, 2003). Thus, in a continuous index finger force production task older adults displayed more regular dynamics compared to younger adults, whereas the opposite pattern was observed during a discrete index finger force production task where older displayed less regular dynamics (Vaillancourt & Newell, 2003).

It has previously been shown that aging is associated with reduced spatial and temporal margin of stability (Kilby, Slobounov, & Newell, 2014; Slobounov, Moss, Slobounova, & Newell, 1998) and it could be speculated that this reduced stability is associated with the altered dynamics in the older adults. It is noteworthy that the change in regularity for the older adults seems highly dependent on the feet placement. Thus, while the SaEn was lower in the older adults compared to the younger adults during the wide feet trials, it was higher during the narrow feet trials. These apparently contradictory results are well in line with previous observations by Borg and Laxaback (2010) who observed significantly higher SaEn in the AP direction in older adults across various postural stance tasks (e.g. eyes open/closed, foam surface) compared to younger adults. Additionally, the authors observed a tendency to a higher SaEn in the ML direction in the older adults. Borg and Laxåback use a relative narrow feet distance (2 cm between heels) comparable to the narrow feet distance condition used in the present study (Borg & Laxaback, 2010).

Furthermore, the fourth hypothesis stated that the older adults would be more sensible to changes in the support surface area and visual input. This hypothesis could be partly confirmed as the older adults tended to have larger changes in SaEn, LyE and ENT½ in AP direction across the four trials compared to younger adults. This suggests that the larger alteration in motor control strategies exhibited by older individuals is characterized by an increased irregularity, an increased rate of change in movement solutions and a reduced time dependency compared to younger individuals when exposed to bilateral stance tasks with manipulated support area and visual input. Furthermore, as mentioned previously the older adults tended to be more affected by vision deprivation in ML direction. These age-related differences in motor control strategy could be linked to both an increase in neuromuscular noise and altered mechanical properties of soft tissue in older individuals (Bemben, 1998; Campbell et al., 1973; Carroll et al., 2008; Delbono, 2003; Luff, 1998; Stanley & Taylor, 1993; Svensson et al., 2016; Tudorascu et al., 2014). The direction specific group difference supports previous observations by Baltich and colleagues who observed a lower ENT½ in the AP direction in older individuals compared to younger individuals (Baltich et al., 2015). The lower number of mechanically equivalent states in the AP direction compared to the ML direction appears to challenge the motor control system of the older individuals more than the younger adults forcing them to

adapt their executed strategy. Using subsensory noise applied to the feet during postural stance, Costa et al. (2007) showed that the complexity of CoP trajectories in older adults can be restored to the level of younger adults. This highlights the importance of sensory information for maintaining postural control.

4.5. Study limitations and methodological considerations

The present study included bilateral stance with altered support area in the ML direction alone. It could be speculated that the applied stance tasks did not challenge the subjects enough. Furthermore, exposing the subjects to more challenging tasks such as unilateral stance or bilateral stance on an uneven or unstable surface (e.g. wobbling board or foam cushion) could potentially induce additional adaptations in the executed motor control strategies.

In agreement with the theory of 'optimal movement variability' by Stergiou and colleagues (Harbourne & Stergiou, 2003), the present study used the COP displacement trajectory to assess the executed motor control. While it has been shown that this type of signal is non-stationary which violates the assumption for various nonlinear methods (Govindan, Wilson, Eswaran, Lowery, & Preißl, 2007; Ramdani et al., 2009), it has also been argued that the use of non-stationary signals does not compromise the calculations (Myers, 2016). In the present study, the nonlinear analyses of the COP displacement were used to provide different characteristics of the executed movement. In our opinion, using velocity signals as suggested by Previously Jeka, Kiemel, Creath, Horak, and Peterka (2004) would make the interpretation of the results in relation to a motor control theory very difficult, as the executed movements are based on an integration of displacement, velocity and acceleration related sensory information.

The present study used the same filtering and down sample procedure as presented by Federolf et al. (2015), Baltich et al. (2014) and Baltich et al. (2015). The additional analyses of the unfiltered data presented in the Supplementary material showed that while the absolute values were different between filtered and unfiltered data, the between-group differences remain in general the same. Out of eight comparisons between the younger and older adults, only ENT½ in the ML did not show the same between-group difference when comparing filtered and unfiltered data. This suggests that the potential bias of the chosen filtering technique was relative small. This is also in line with previous observations on the effect of filtering on SaEn from CoP displacement trajectories (Rhea, Kiefer, Wright, Raisbeck, & Haran, 2015).

The test of parameter consistency for the SaEn calculations revealed that while changes in input parameters (r and m) changed the size of the calculated SaEn, the observed between-trial or between-group differences did not change (see Supplementary material for details).

The analysis of the effect of data length presented in the Supplementary material showed that while 6000 data point seemed reliable for the SaEn, CoD and LyE variables, the ENT½ was highly sensitive to the data length used. This calls for caution when interpreting these results as they could be an artifact of the chosen data length. Future studies should clarify the appropriate data length when applying ENT½ to COP data.

4.6. Conclusion

The results of the present study indicate that change in support area has both a direction specific and age-dependent effect on the dynamics of the COP. In young individuals, a narrower support area results in a restricted movement solution space with higher regularity, lower rate of changes in movement solutions and higher time dependency in the executed motor control strategy, whereas it increased the dimensionality in the older individuals. Similarly, while deprivation of visual input affected both younger and older individuals in the AP direction by increasing the irregularity, dimensionality and rate of change in movement solutions and decreased the time dependency, it increased irregularity and rate of change in movement solutions in the ML direction for the older individuals alone. Furthermore, the results of the present study are in line with both the 'loss of complexity' theory and the 'optimal movement variability' theory suggesting that aging is accompanied by a loss of complexity in postural control and that this loss is characterized by a task-dependent change in the regularity of the movement pattern resulting in less adaptability.

Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.05.007.

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