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RESEARCH ARTICLE

Persistence in postural dynamics is dependent on constraints of vision, postural orientation, and the temporal structure of support surface translations

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Abstract

Activities of daily living require maintaining upright posture within a variety of environmental constraints. A healthy postural control system can adapt to different environmental constraints. Afferent sensory information is used to determine where the body is in relation to the gravitational vertical and efferent motor commands make corrections with the goal of keeping the center of mass within the base of support. The purpose of this research was to understand how vision, direction of translation, and the temporal correlation of the support surface stimuli affected the persistence characteristics of postural dynamics on short and long time scales. Ten healthy young adults performed a standing task with either eyes open or closed, oriented anteriorly or mediolaterally while the support surface underwent structured translations based on different levels of temporal correlation—white noise (no correlation), pink noise (moderate correlation), and red noise and sinusoidal movements (strong correlations). Center of pressure velocity was analyzed using fractal analysis to determine the dynamics of postural control. On the short time scale, persistence was shown to be stronger with eyes closed, in the mediolateral direction, and when the structure of translation contained stronger temporal correlation. On the long time scale, anti-persistence was stronger with eyes closed, in the mediolateral direction, and for all structures of movement except red noise. This study provides deeper insight into the flexibility existing in human movement responses to structured environmental stimuli through the fractal analysis of movement variability.

Keywords Feedforward · Feedback · Fractal · Temporal correlation · Detrended fluctuation analysis · Balance

Introduction

Activities of daily living require the maintenance of upright posture within a variety of environmental constraints. Having a healthy postural control system affords the ability to perform these tasks with little difficulty and allows switching between tasks with ease. Postural control is regulated by combining sensory information to determine where the body is in relation to the gravitational vertical and making corrections with the goal of maintaining the center of mass within the base of support. When adapting to different environments the central nervous system will rely on sensory information about the body's current position as well as the expectation of future states to select the appropriate response. Understanding the ability to adapt to different environmental constraints provides information about healthy postural control.

When analyzing center of pressure (COP) during postural tasks there are position, velocity, and acceleration components. Postural control is commonly thought of as a position task, to keep the center of mass within the base of support, but velocity information may be more meaningful since it will provide information about where the position will be at a future time. Furthermore, several studies have indicated that postural control is velocity based and not position based (Masani et al. 2003; Jeka et al. 2004; Delignieres et al. 2011). There is also research hypothesizing that different time scales preferentially utilize position

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or velocity based on the frequency of movement (Gilfriche et al. 2018). Center of pressure velocity (COP_{vel}) exhibits different behavior at different time scales (Delignieres et al. 2011; Rand and Mukherjee 2018). On a short time scale, COP_{vel} is persistent, i.e., when movement starts the velocity will continue to increase, then when it starts decreasing it will continue to decrease until movement is stopped. On a longer time scale COP_{vel} is anti-persistent; whenever velocity is increasing it will have to be followed by decreasing velocity to stop the center of mass from moving outside of the base of support. Likewise, decreases in velocity must be followed by increases since the body cannot stop moving altogether. This transition between persistent and anti-persistent behavior is thought to stem from processes that exhibit a bounded random walk (Liebovitch and Yang 1997). A random walk is the integration of white noise. What this means is that while each movement is random, the starting point for each movement is the end of the previous movement, which makes the movement both deterministic and stochastic. The random walk results in persistence, but because the system is bounded it will exhibit anti-persistence on a longer time scale. Understanding how COP_{vel} is controlled can provide insights into the overall control of posture.

One method of modeling postural adaptation is through the use of support surface translations. By moving the support surface and then measuring the response to those movements we can better understand how individuals respond to environmental changes. A substantial amount of work has been done utilizing both discrete and continuous translations (Buchanan and Horak 1999, 2000; Corna et al. 1999; Ko et al. 2013). However, the majority of work has been done utilizing sinusoidal translations (Corna et al. 1999; Nardone et al. 2000; Buchanan and Horak 2001). Interactions with the environment are not always periodic or predictable, and the natural fluctuations in human movement exhibit variability, which allows the system to interact with these environments in a flexible manner. This may limit the interpretation of these results. To overcome this limitation the authors previously investigated support surface translations in the AP direction that contained varying strengths of temporal persistence (Rand et al. 2015). Temporal persistence of support surface translations means that a forward translation is more likely to be followed by a forward translation, and a backward translation is more likely to be followed by a backward translation movement. By varying the strength of temporal persistence, the predictability of the somatosensory feedback is changed. Weak temporal persistence makes it difficult for the sensorimotor system to reliably determine future movements. However, if the movement has a very strong temporal persistence then the current movement gives a good indication of what the next movement will be. With young subjects, the temporal persistence of their COP response trended towards the temporal persistence of the support surface movements, indicating that the ability to adapt to the different environmental constraints in the anterior-posterior (AP) direction. It has been demonstrated that as the velocity of movement increases, unpredictable stimuli result in a characteristic postural response different from a predictable stimuli (Rand and Mukherjee 2018). There was an increase in persistence in the short time scale when the stimuli were predictable and a decrease in persistence when the stimuli were unpredictable.

It is well established that visual information can be used in the regulation and adaptation of postural sway (Nashner et al. 1982; Asslander et al. 2015). However, it is unclear what role vision may play in the response to a structured stimulus based on different strengths of persistence. When completing a tracking task, where individuals were asked to sway with a moving target, they demonstrated stronger entrainment of their posture and gaze with complex structured stimuli compared to periodic or uncorrelated stimuli (Hatzitaki et al. 2015). This task had the participants actively attempting to match their sway with the external stimuli as opposed to the authors' previous research (Rand et al. 2015; Rand and Mukherjee 2018) where the stimuli was presented with no instructions to match it. While presence of visual feedback will allow subjects to anchor to an external visual frame of reference and reduce postural sway, it is unclear how the absence of vision will affect responses to structured support surface oscillations.

Postural control has frequently been analyzed separately in the AP and mediolateral (ML) directions. It is known that there is greater overall sway in the AP direction and greater sway variability in the AP direction (Diener et al. 1984), which is likely due to increased biomechanical degrees of freedom in that direction as well as visual input being directed in that direction during forward gaze. The ML components of postural control play a very important role in upright stance and have been indicated as being the most important when investigating falls (Maki et al. 1994; Bergland et al. 2003). Because of this relationship between ML sway and falls, it is important to further understand how the sensorimotor system adapts to structured stimuli in the ML direction. The authors' previous work (Rand et al. 2015; Rand and Mukherjee 2018) analyzed support surface translations that were presented in the AP direction, but it is not known if similar responses would be observable for such stimuli presented in the ML direction.

The purpose of this research was to understand how vision, direction of translation, and the persistence of the support surface stimuli affect the persistence and anti-persistence of COP_{vel} on short and long time scales. We hypothesized that COP_{vel} would exhibit stronger persistence on the short time scale and stronger anti-persistence on the long time scale in three situations; the ML direction compared to AP, eyes closed compared to eyes open, and when the stimulus contained stronger persistence.

Methods

Subjects

Ten young participants were recruited from the University of Nebraska at Omaha (6M/4F; age 25 ± 5 years; height 174.1 ± 11.1 cm; mass 71.6 ± 7.1 kg). Inclusion criteria included being between the ages of 19 and 35 and being able to stand for approximately 1 h with breaks as needed. Exclusion criteria included any neuromuscular disease that would affect the ability to stand. All procedures were approved by the Institutional Review Board at the University of Nebraska Medical Center and all participants provided informed consent.

Experimental design

The Neurocom® Balance Manager® (Neurocom International, Clackamas, OR) was used to provide support surface translations and record the COP data. The research module of the Neurocom has the ability to translate the support surface in the AP direction according to any input waveform. This study utilized a condition with no input waveform (NN), and then four conditions with movement: white noise (WN), pink noise (PN), red noise (RN), and sine wave (SW). These waveforms were chosen to represent a range of temporal persistence in the support surface movements. The WN is completely uncorrelated so it is neither persistent nor anti-persistent, PN has a moderate persistence, RN has a strong persistence, and SW has very strong persistence on the time scale of one cycle and strong anti-persistence on time scales greater than one cycle. The WN, PN, and RN signals were created using Matlab (Mathworks, Natick, MA). The sine wave function was entered directly into the Neurocom. Each waveform was created with 1800 data points and the frequency of support surface translations was set at 10 Hz, which resulted in 3-min trials. This frequency was determined through trial and error and was low enough such that the different structures of input signals were perceptible, but high enough such that the movements were smooth and not jerky. Participants stood on the force platform barefoot in a side-by-side stance with the lateral calcanei separated by 22 cm, 26 cm, or 30 cm based on three height ranges (76–140 cm, 141–165 cm, and 166–203 cm, respectively). Participants were asked to stand in a comfortable manner with their arms at their sides, and while they were not instructed to look at anything specifically, they were instructed to maintain a forward gaze. Each condition was repeated with eyes open and eyes closed in both AP and ML directions for a total of 20 conditions. For ML translations, participants had to stand orthogonal to the direction of translation, because of which the visual surround was removed from the Neurocom for all trials (Fig. 1).

Data analysis

The COP data were exported from the Neurocom and all data processing was done using Matlab (Mathworks, Natick, MA). All COP position data were converted to COP_{vel} and downsampled to 50 Hz. Previous research has shown that downsampling from 100 to 50 Hz has a minimal effect on the persistence of COP_{vel} (Rhea et al. 2015). Then the COP_{vel} was analyzed using detrended fluctuation analysis (DFA) for the short and long time scales. The DFA algorithm determines the relationship between the root mean square fluctuations and time scale of observation. If this relationship is a power law, then plotting it on a log/log plot results in a linear slope, where the slope (α-value) describes the type and strength of persistence. An α-value of 0.5 is uncorrelated (white noise), meaning it is neither persistent nor anti-persistent. An α value from 0 to 0.5 is anti-persistent, with smaller values indicating stronger anti-persistence, while an α value greater than 0.5 is persistent with the larger values indicating stronger persistence. In brief, the procedures of DFA are as follows: the time series is integrated and divided

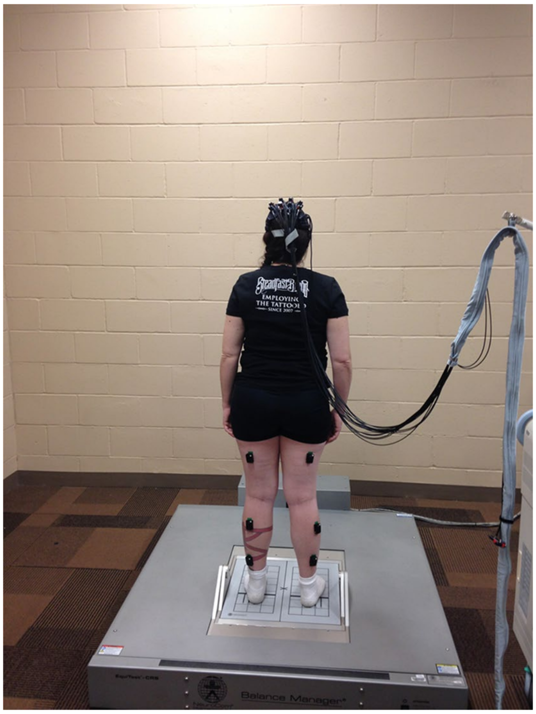

Fig. 1 Participant standing on the Neurocom with the visual surround removed. The force plate translates in the AP direction. For ML conditions the participants stood orthogonal to the direction of translation

into boxes of length n, where n ranges from 3 to the length of the data/2. Each box is detrended by subtracting a linear line of best fit and the root mean square is calculated for the remaining data. The root mean square fluctuations are averaged across the number of boxes for each size n and the relationship between box size and root mean square fluctuations are plotted on a log/log plot. A scaling region is chosen which represents the time scale of observation and a line of best fit is calculated in log space for that scaling region. The slope of the line of best fit is the α-value. Because COP_{vel} has distinct short and long-term behaviors, the data were first inspected to find common scaling regions where all the subjects had linear slopes in the DFA log/log plot. Through visual inspection, it was determined that the scaling region from 10 to 100 (0.2–2.0 s) and 500–1000 (10–20 s) was linear for all subjects (Fig. 2), these regions were therefore used to analyze the behavior at short and long time scales, respectively.

Statistical analysis

All statistics were considered significant with an alpha value of <0.05. Two separate three-way repeated measures ANOVAs were used to determine the effect of structure of translation (5 levels), direction of translation (2 levels), and vision (2 levels) on short and long time scale behavior. Interactions were determined from the results of the ANOVA and pairwise comparisons were made using a Bonferroni correction which accounts for multiple comparisons. Additionally, eight separate one-way repeated measures ANOVAs with Bonferroni post hoc corrections were used to assess the effect of structure of translation within each vision and direction condition. Statistical analysis was performed using IBM SPSS Statistics for Windows, version 23 (IBM Corp., Armonk, N.Y., USA).

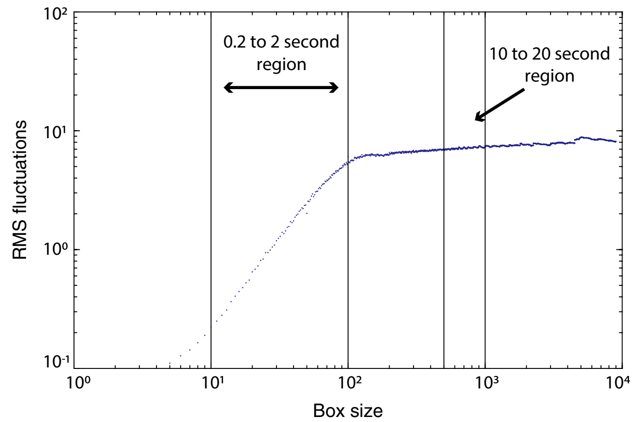

Fig. 2 Example of a log–log plot showing the regions where the data were analyzed. Box sizes of 10–100 were used to analyze the short-term persistence and box sizes of 500–1000 were used to analyze the anti-persistent region

Results

Short time scale

The short time scale of COP_{vel} showed an overall effect for vision, direction, and structure of translation (Fig. 3a–d). The effect of vision [$F(1,9)=12.11$, $P=0.007$, $\eta_p{}^2=0.574$] showed that eyes closed versus eyes open resulted in a stronger persistence (α-values = 0.95 and 0.90, respectively; Fig. 3a). The effect of direction [$F(1,9)=21.37$, $P=0.001$, $\eta_p{}^2=0.704$] showed that ML versus AP resulted in a stronger persistence (α-values = 0.96 and 0.89, respectively; Fig. 3b). The effect of translation structure [$F(4,36)=83.05$, $P<0.001$, $\eta_p{}^2=0.902$] showed that the movement responses followed the persistence of the input signal, with WN structure being the weakest persistence (α-value = 0.70), PN structure being stronger than WN (α-value = 0.81), RN structure being stronger than PN (α-value = 0.92; Fig. 3c), and SW having the strongest persistence (α-value = 1.26). Baseline persistence (NN) had an α-value of 0.94, so WN and PN were weaker than baseline, RN was no different, and SW was stronger than baseline.

The short time scale also demonstrated a direction by translation structure interaction [$F(4,36)$, $P<0.001$, $\eta_p{}^2=0.574$; Fig 3d]. This is because in the ML direction, all movements besides RN resulted in a stronger persistence in comparison to AP. In the AP direction, each movement trial was different from the other, with the strength of persistence in the COP_{vel} increasing as the strength of persistence in the translation structure increased. The effects of temporal persistence on the short time scale are further highlighted within each condition in Fig. 4.

Long time scale

The long time scale of COP_{vel} showed an overall effect for vision, direction, and structure of translation (Fig. 3e, f). The effect of vision [$F(1,9)=28.93$, $P<0.001$, $\eta_p{}^2=0.763$] showed that eyes closed versus eyes open resulted in a stronger anti-persistence (α-values = 0.1 and 0.14, respectively; Fig. 3e). The effect of direction [$F(1,9)=15.71$, $P<0.003$, $\eta_p{}^2=0.636$] showed that ML versus AP resulted in a stronger anti-persistence (α-values = 0.09 and 0.15 respectively; Fig. 3f). The effect of translation structure [$F(4,36)=41.63$, $P<0.001$, $\eta_p{}^2=0.822$] showed that WN, PN, and SW resulted in stronger anti-persistence (α-values = 0.067, 0.083, and 0.081 respectively) compared

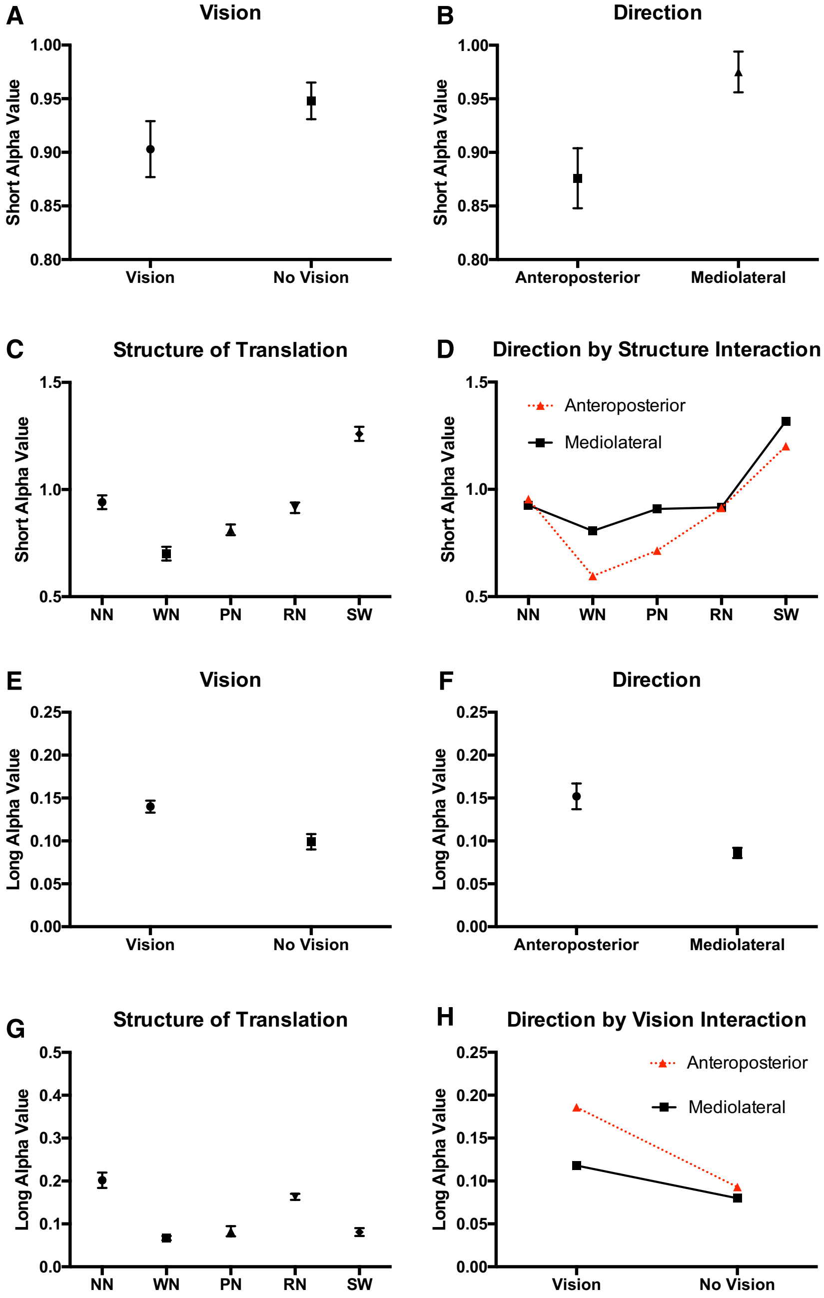

Fig. 3 Significant results from the 3-way ANOVA. All levels are collapsed across the other levels to visualize the ANOVA. For the short time scale (0.2–2 s; **a**–**d**) the persistence was stronger with eyes closed (**a**), in the ML direction (**b**), and progressively became stronger as the persistence of the stimulus became stronger (**c**). There was also a direction by structure interaction (**d**), the persistence in the AP direction became weaker in the WN condition and strengthened as the persistence of the stimulus strengthened. The persistence in the ML direction stayed the same in the noise conditions and then increased in the sine wave condition. In the long time scale (10–20 s; **e**–**g**) the anti-persistence was stronger with eyes closed (**e**) and in the ML direction (**f**). There was also a direction by vision interaction (**h**). The anti-persistence in the ML direction was stronger with eyes open and slightly reduced with eyes closed, in the AP direction the anti-persistence was weaker in the eyes open and then experienced a greater strengthening with the eyes closed

to baseline (α-value = 0.202), with no difference in RN (α-value = 0.163; Fig. 3g).

In the long time scale, there was a vision by direction interaction [$F(1,9) = 17.29$, $P = 0.002$, $\eta_p^2 = 0.658$; Fig. 3h]. This was due to the anti-persistence already being stronger in the ML direction with the eyes open, when participants closed their eyes there was strengthening of the anti-persistence in the AP direction, but no change in the ML direction. The effects of temporal persistence on the long time scale are further highlighted within each condition in Fig. 5.

Discussion

The purpose of this research was to investigate COP_{vel} responses to structured translations with and without vision in both AP and ML directions. Velocity responses were investigated on both short and long time scales. It is known that postural dynamics can characteristically demonstrate behavioral transitions between short and long time scales based on the structure of support surface translations (Rand and Mukherjee 2018). The purpose of this study, however, was to specifically investigate the behavior within each time scale, therefore, the time scales were standardized to include

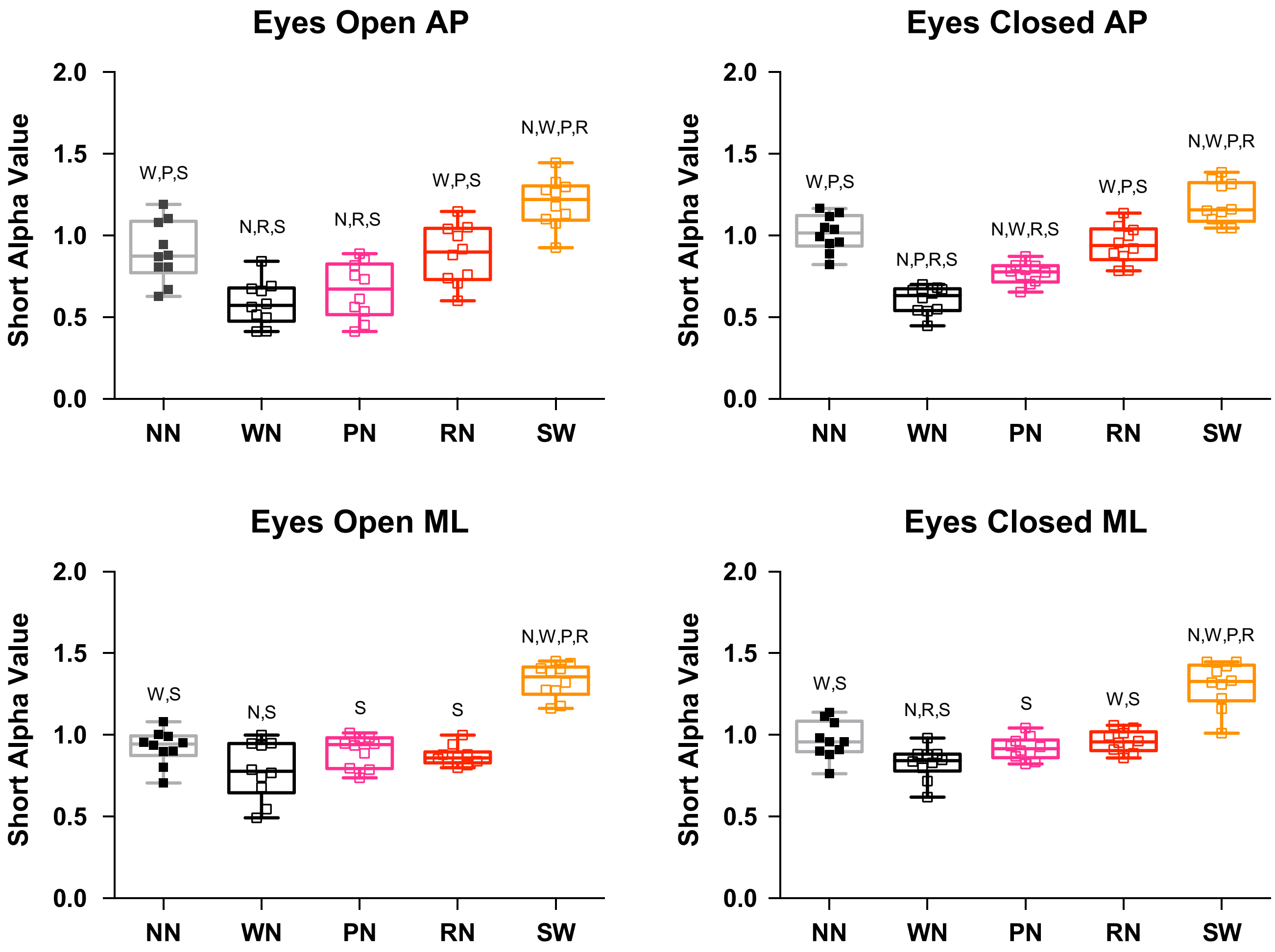

Fig. 4 Results of the one-way ANOVAs for persistence at the short time scale of 0.2–2 s. In both AP (top row) and ML (bottom row) directions, there was a weakened persistence (lower alpha value) during WN and strengthened persistence (higher alpha value) during SW conditions compared to the NN condition. The Left column shows the *Eyes Open* and the right column shows the *Eyes Closed* conditions. Differences from the Bonferroni post hoc analysis are noted above each bar, *N* no noise, *W* white noise, *P* pink noise, *R* red noise, and *S* sine wave

only linear regions of the log/log plot for all participants. It was hypothesized that the persistence on the short time scale and anti-persistence on the long time scale would be stronger in the ML compared to the AP direction, in the eyes closed compared to eyes open condition, and in conditions where the persistence of the structured translation was stronger.

Understanding the effects of vision, direction of translation, and structure of translations on the short and long time scales of COP$_{vel}$ was anticipated to provide unique information about the adaptability of the postural control system in response to environmental demands. Our findings were mostly consistent with our hypotheses. The short time scale demonstrated persistence that was stronger with eyes closed, in the ML direction, and when the structure of translation contained stronger persistence. The long time scale demonstrated anti-persistence that was stronger with eyes closed, in the ML direction, and for all structures of translation except RN.

Temporal persistence in COP$_{vel}$

The strength of persistence in COP$_{vel}$ indicates how smoothly the velocity is increasing and decreasing, with stronger persistence indicating smoother fluctuations. The strength of anti-persistence in COP$_{vel}$ may indicate how periodic such velocity fluctuations are, with stronger anti-persistence indicating more periodic changes. Stronger anti-persistence can also indicate similar amplitudes of COP$_{vel}$ changes, which consequently indicates a more consistent and predictable movement pattern. Literature regarding the true-meaning of the strength of anti-persistence from a biological perspective, is lacking, therefore, warranting further investigations

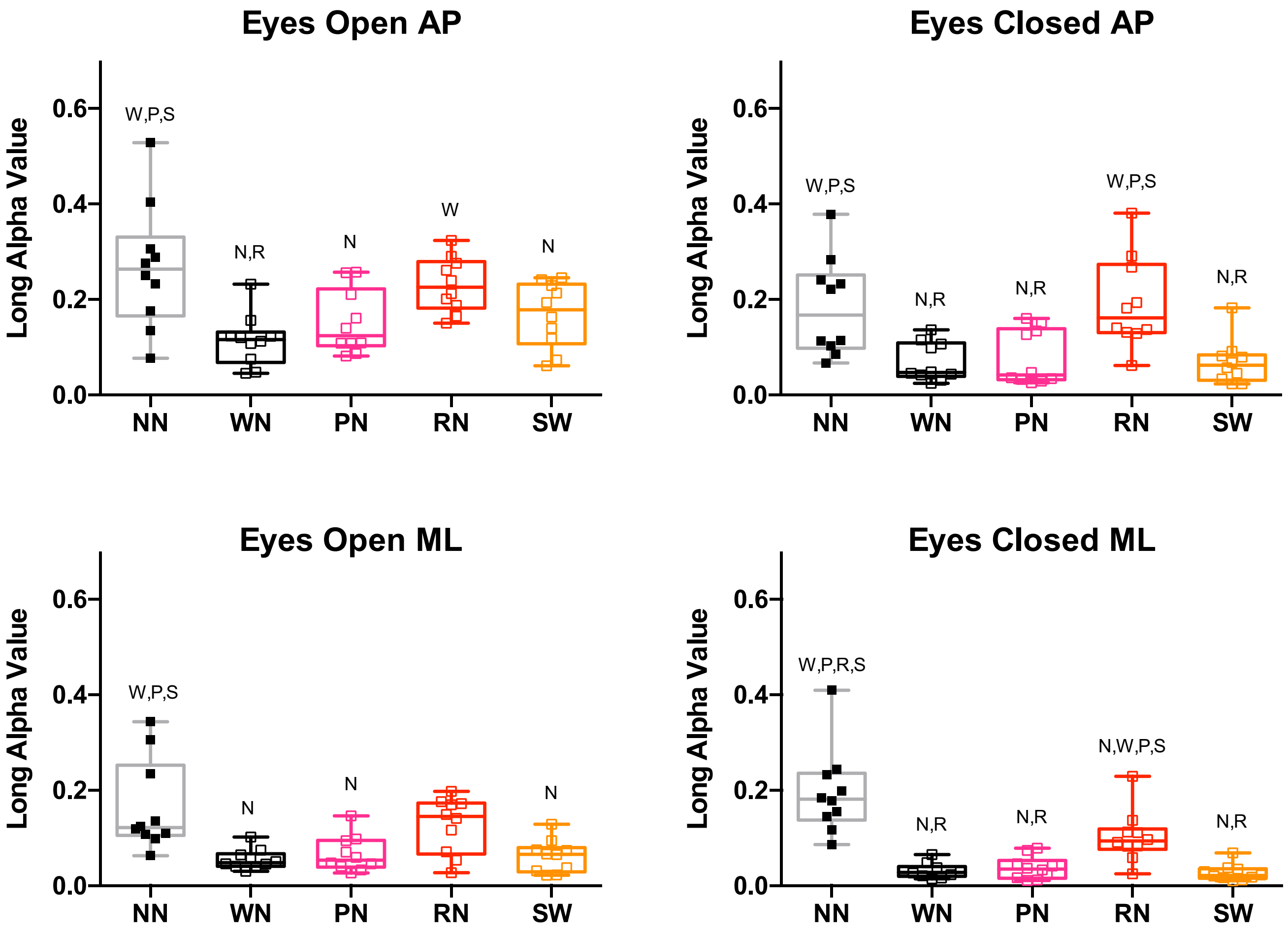

Fig. 5 Results of the one-way ANOVAs for anti-persistence at the long time scale of 10–20 s. The Left column shows the *Eyes Open* and the right column shows the *Eyes Closed* conditions. In both AP (top row) and ML (bottom row) directions, and visual conditions, there was strengthened anti-persistence (lower value) for WN, PN and SW, when compared to NN. Differences from the Bonferroni post hoc analysis are noted above each bar, *N* no noise, *W* white noise, *P* pink noise, *R* red noise, and *S* sine wave

in this area to fully interpret these results. However, it is likely that there is an optimal strength for both the persistent and anti-persistent regions.

Human movement tends to have an affinity for PN, which contains a moderate strength of persistence. It is believed that PN results in a flexible system that can maintain a consistent pattern, yet be able to switch to a new pattern if needed (Hausdorff 2007; Stergiou and Decker 2011; Rhea et al. 2014). With $\mathrm{COP}_{\mathrm{vel}}$ a weak persistence would result in "jerky" or inconsistent sway velocities, and too strong of a persistence could result in the inability to switch from increasing to decreasing as quickly. In this research the short time scale was typically in the region of PN ($\alpha \sim 1.0$) and in most conditions the system demonstrated the flexibility needed to adjust based on the imposed demands of support surface translations. However, the RN translations ended up resulting in similar postural responses as no translations. The response to the RN signal exhibited a persistence strength that was close to PN and not RN. In our previous study (Rand et al. 2015) postural responses to RN (Brownian motion) was not significantly different from NN or PN. While specific differences between the responses to the different structured stimuli were hard to ascertain, the overall inverted-u shaped pattern followed the order of predictability of stimuli through a significant quadratic trend (Rand et al. 2015). In this study in some situations, the PN translations resulted in a weakening of persistence, where the RN resulted in no change. This could be due to the higher predictability of the RN signal compared to the PN signal. This is supported by the SW signal resulting in even stronger persistence, as it is almost perfectly predictable. Increased predictability of the stimuli allows the maintenance or enhancement of persistence or anti-persistence at the different time scales.

Although the anti-persistent nature of time series has not been studied as much, we hypothesize that a similar phenomenon exists. Weak anti-persistence means that the switches from increasing to decreasing are more random and inconsistent, whereas strong anti-persistence means the switches are very periodic and may also lack flexibility. There is likely an ideal strength to the anti-persistence which allows increasing and decreasing velocity to fluctuate in a consistent manner, while maintaining the flexibility needed to switch at irregular intervals when needed.

It is being hypothesized that there exists an optimal strength for persistence and anti-persistence, with a weakening resulting in a movement pattern that is not as consistent, and a strengthening resulting in a movement pattern that is more constrained. However, it is important to emphasize that movements away from this optimal strength do not necessarily imply a degradation of the sensorimotor system. On the contrary, adjusting the strength of persistence and anti-persistence can be seen as a method of the sensorimotor system adapting to constraints imposed on the system, for example when maintaining postural control in response to changes in support surface velocity (Rand and Mukherjee 2018).

Role of vision

When participants stood with eyes closed their $\mathrm{COP}_{\mathrm{vel}}$ exhibited a stronger persistence on the short time scale and a stronger anti-persistence on the long time scale. This means that the sway velocity was fluctuating in a more consistent manner and the fluctuations between the increases and decreases became more periodic and/or reached a more consistent magnitude. In the absence of visual feedback, the system must re-weight the vestibular and somatosensory information to provide a representation of the body's state of equilibrium. In this case the sensorimotor system uses increased persistence of the sway velocity as a method of constraining the system to be more adaptable. The increased strength of anti-persistence was likely serving the same purpose. By making the fluctuations between increasing and decreasing $\mathrm{COP}_{\mathrm{vel}}$ more periodic or predictable, it may put a constraint on the system that allowed it to maintain a consistent pattern in the presence of the biological stress of not having visual input (West and Scafetta 2003).

Direction of translation

When the support surface was translated in the ML direction, postural dynamics was characterized by a strengthening of short-term persistence and long-term anti-persistence. This could be due to a number of reasons. There are inherent anatomical and biomechanical differences in standing posture between the AP and ML directions. There are greater degrees of freedom at the ankle, knee, and hip joints in the AP direction. Furthermore, ML sway is primarily controlled at the hip joint where the AP sway tends to utilize a combination of ankle and hip strategies. Previous work has associated reduction of degrees of freedom with increases in regularity (Vaillancourt and Newell 2000) and reduction in dimensionality (Newell et al. 1995). In a similar manner, the reduced degrees of freedom in the ML direction could itself result in stronger short-term persistence. One previous study that teased out directional differences in body sway looked at standing on a ship (Varlet et al. 2015). When individuals would stand in the fore-aft direction, which makes the roll of the ship in the frontal plane, they would couple their sway to the roll of the ship. This coupling was not seen in other directions, indicating that ML sway responds differently to environmental perturbations. Another possibility is how the tactile sensory receptors are arranged on the soles of the feet. It has been shown that mechanoreceptors demonstrate directional sensitivity and although the arrangement of plantar mechanoreceptors appears to be random, the temporal patterns of activation may not be so (Kennedy and Inglis 2002). Postural sway being greater in the AP direction than the ML, if the tactile receptors are tuned to respond in the AP direction then it would be reasonable that support surface translations in the AP direction would result in a more fine-tuned response then the same receptor's response in the ML direction. The lack of changes in the ML direction also likely resulted in the interactions seen within this study. It may be that the stimulus was not appropriate to induce changes in the ML direction. Further experimentation with different frequencies or movement velocities of support surface translations may result in ML responses that follow a similar pattern to those seen in the AP direction.

Feedforward and feedback mechanisms

In our previous investigation into postural dynamics (Rand and Mukherjee 2018), we had raised the possibility that our observation of the predictability and velocity of support surface oscillations affecting the time scale threshold between persistent and anti-persistent postural responses was indicative of factors critical for choosing feedforward versus feedback mechanisms for postural control. This study provides further insight into the flexibility and adaptability of postural control by extending the thought that such a choice could also be influenced by visual feedback and postural orientation. To maintain appropriate postural control, there is a combination of feedforward and feedback mechanisms at work continuously. A feedforward system would entail accurately predicting the stimuli parameters for eliciting appropriate postural responses while a feedback system would require sensory feedback to detect and respond to such stimuli. The emergence of stronger persistence in the short time scale and stronger anti-persistence in the long time scale in the no visual feedback and ML orientation in response to support surface translation conditions indicates that in such constraining conditions with reduced sensory reliability, postural control switches to a predictable mode that can function in a feedforward manner. The central nervous system, therefore, predicts the fluctuations of COP_{vel} for responding to the specific structured stimuli. On the other hand, when reliability of the environmental stimuli is higher, e.g., in the presence of vision or when a greater natural sway is possible in response to support surface oscillations, e.g., the AP stance, the persistence and anti-persistence in postural dynamics are not so tightly controlled. Therefore, feedback mechanisms could intuitively be considered to be at play in these situations allowing for the emergence of a rich repertoire of postural responses.

Limitations and future directions

There are several limitations that should be noted with this research. One of the limitations of the study is that only visual feedback is constrained which may have enhanced the gain of the other sensory systems through multisensory integration. Future work should investigate whether similar effects are observable when there is somatosensory deterioration, for example, with age. In addition, whether other sensory systems also have a role to play in perceiving and responding to such structured perturbations is also open for investigations. Additionally, there are characteristic differences between AP and ML sway that were not controlled for, such as the natural frequency of sway. Experimenting with movement frequencies and/or velocities that are specific to the direction of sway could be a future direction of investigation.

In summary, this study showed the adaptability of postural control to environmental demands. It provided further insight into the flexibility existing in human movements through the analysis of movement variability (Mukherjee and Yentes 2018). We demonstrated that responses to structured translations that differ in their temporal persistence, depend on the orientation, visual feedback and temporal persistence of the stimuli. Short term persistence was shown to be stronger in the absence of vision, in the ML direction, and when the structure of translation contained stronger persistence. Long-term anti-persistence was stronger in the absence of vision, in the ML direction, and for all structures of translation except RN.

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