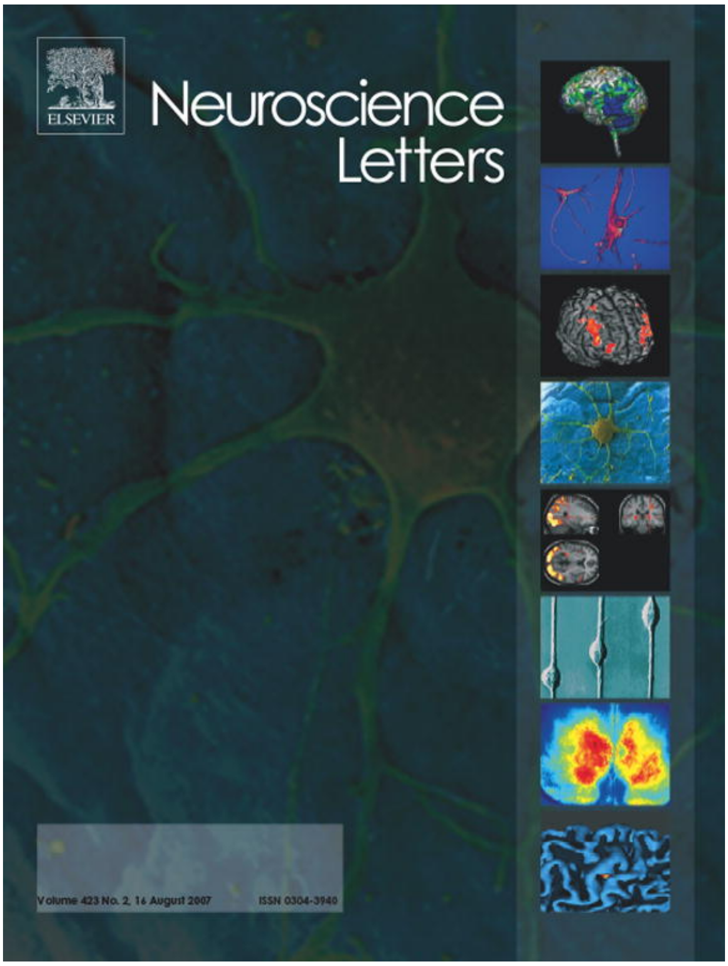
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Stance and sensory feedback influence on postural dynamics

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Abstract

This study examined the effects of ice-induced plantar desensitization and the withdrawal of visual feedback on the magnitude and time-dependent structure of postural sway variability. The magnitude of variability was quantified as the area of an ellipse enclosing 95% of the center of pressure (COP) time-series during normal and tandem stances. The same time-series were also analyzed using Approximate Entropy (ApEn) and Cross-Approximate Entropy (CrossApEn) as indices of irregularity and asynchrony between the mediolateral and anteroposterior COP motions. Variability increased during tandem stance and this increase was compounded by both visual feedback withdrawal and cutaneous desensitization. Both ApEn (mediolateral and anteroposterior COP motion) and CrossApEn increased with the withdrawal of visual feedback during the tandem stance, but decreased significantly during normal stance. The results of the study demonstrate that plantar desensitization only affected the magnitude of sway variability but did not alter its time-dependent structure. Contrasting effects on the structure of postural sway variability with visual feedback withdrawal were observed during the different stances, highlighting the role of task demands in postural dynamics.

Keywords: Posture; Balance; Somatosensory; Vision; Foot; Entropy

Variability is inherent in the maintenance of human posture that is reflective of the contribution of many different joints and muscles, and manifest as postural sway. The structure of sway variability is often used to characterize subtle changes in the organization of the neuro-motor system during the maintenance of upright posture [9]. As such, changes in magnitude [3,17] and structure [1,2,16] of postural sway variability under different task and sensory conditions are essential in understanding their role in the organization of human motor output.

The magnitude of postural sway variability can be affected by stance and the absence of visual feedback. The center of pressure (COP) displacement has been observed to be approximately two-fold higher during tandem stance when compared to a normal bipedal stance [18]. Similarly, the magnitude of sway variability has also been known to increase when visual feedback is withdrawn [2,3,17]. This increase in magnitude of variability has been viewed as an increase in the size of the equilibrium region, where postural corrections are only made following higher amplitude excursions of the COP [1].

Riley et al. [16] observed an increase in the proportion of determinism within the COP motions as visual feedback was withdrawn, reflecting that future states of the COP were more predictable from previous states in the absence of vision. Meyer et al. [8] reported that plantar cutaneous desensitization through anesthesia only revealed significant differences in the postural sway dynamics, characterized by an increase in short time-scale fluctuations. This occurred when the subjects were either: (a) challenged with a unipedal stance with eyes open, or (b) had their eyes closed while in a normal stance. This finding suggests that the effects of cutaneous desensitization on postural sway dynamics were only significant when feedback from other sources of sensory information is insufficient to overcome the loss of cutaneous sensation.

Changes in the structure of postural sway variability are generally viewed as a reflection of the often subtle reorganization of the motor system output [9,10]. Nonlinear measures of the structure of motor variability (primarily Approximate Entropy [13] and Cross-Approximate Entropy [14]) provide insights into the time-dependent predictability in a sequence of COP positions. One general view is that a more predictable time-series

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(lower Approximate Entropy) reflects a reduced independence in the behaviors of the joints and muscles that are involved in the maintenance of upright posture [9,10]. Further insight can be gained from the use of Cross-Approximate Entropy, which provides an index of the independence of the COP dynamics on the two axes of motion.

In general, the aforementioned findings suggest that the reduction in sensory information results in a more predictable time-dependent structure of the sway dynamics. The unipedal stance, however, reduces the number of joints and muscles that can be invoked for corrections to the upright posture, and, indirectly reduces sources of proprioceptive feedback. In our current experiment, the postural task is made more difficult by employing a tandem stance, which narrows the base of support but still allows both limbs to remain in contact with the ground and their respective joints and muscles to be involved in postural corrections.

The aforementioned studies have demonstrated that the magnitude and structure of COP variability respond differently to changes in stance, visual feedback, and cutaneous sensation. Manipulating these variables and subsequently investigating their interaction will enhance our understanding of the role of each in maintaining upright posture. Therefore, the goal of this study was to investigate the change in magnitude and time-dependent structure of postural sway variability under different stance and sensory conditions. It is hypothesized that the effects of sensory information withdrawal on the magnitude and structure of COP variability are additive and will compound one another, while the tandem stance is expected to magnify the effects of reduced sensory information.

Thirteen college-aged adults (seven men and six women, mean age: 21.3 ± 1.4 years) volunteered to participate in this study. All subjects possessed normal or corrected-to-normal vision and were free of any neurological or neuromuscular disorders. Informed consent was provided by the subjects prior to participation, with approval for the experimental protocol provided by the Institutional Review Board of Louisiana State University.

Subjects were asked to stand under two (Normal and Tandem) stance conditions. Subjects stood with heels 5 cm apart with feet abducted 10° in Normal Stance. During Tandem stance, subjects stood with one leg in front of the other with heel and toe touching [6] at 45° to the axes of the force platform to ensure both feet were supported entirely by the platform. Two (Eyes-Open and Eyes-Closed) vision conditions were crossed with the stance conditions.

Subjects completed the Ice and No-Ice trials at the same time on separate days in random order. Plantar pressure sensitivity (PPS) was assessed with the 5.07 gauge monofilament (North Coast Medical Inc.) according to Kamei et al. [7] while seated with right leg supported and eyes closed. Five plantar sites were tested, including the heel, mid-sole, bases of the first and fifth metatarsals, and hallux [4]. At each site, the monofilament was pressed to the skin at a 90° angle with sufficient force to produce bowing for 1 s. Any callused or scarred areas were avoided by applying the monofilament to the perimeter of the test area. Each site was tested three times in random order with a 2–5 s pause between sites. Two or more affirmative verbal responses at each site were considered intact sensation, and the number of sites with intact sensation was totaled to produce a PPS score ranging from 0 to 5.

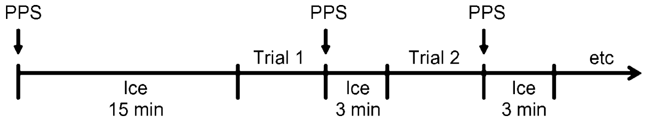

Fig. 1. Schematic of the desensitization protocol. Plantar pressure sensitivity (PPS) was initially assessed, followed by a 15 min exposure of the foot soles to shaved ice. PPS was reassessed *immediately following* each trial. In between each trial, the foot soles were exposed to ice for an additional 3 min to ensure continued desensitization throughout the testing procedure.

Subjects then placed their bare feet on shaved ice for 15 min, a proven procedure that reduce PPS while leaving strength, position sense, or tissue properties of the ankle, feet, and toes unaffected [12]. Following desensitization protocol (Fig. 1), subjects completed a 30 s standing balance trial in one of the four stance and vision conditions, presented in random order. PPS was assessed immediately after each trial to ensure that desensitization persisted throughout the duration of each trial. Subjects placed their feet on ice for an additional 3 min in between each trial. During the day for which the No-Ice protocol was applied, subjects performed the above with trials completed in the same order with ice immersion replaced with seated rest of similar duration.

An AMTI force platform and Accusway software (Advanced Mechanical Technology Inc., Newton, MA) were used to record the center of pressure trajectory of each trial. All data were filtered using a nine-point, third-order polynomial Savitsky–Golay filter. Additionally, data from tandem stance trials were rotated with a rotation matrix in order to re-align the anatomical axes of motion with those of the force platform.

The variability of COP motion was analyzed in terms of both its magnitude and structure. Magnitude of COP variability was quantified using the 95% sway area, estimated from a bivariate confidence ellipse that enclosed 95% of the COP trajectory [15]. The structure of COP variability was measured using the Approximate Entropy (ApEn) and Cross Approximate Entropy (CrossApEn) methods presented in Pincus [13] and Pincus and Singer [14], respectively. The general algorithm for calculating both ApEn and CrossApEn can be described with Eq. (1):

$$\mathrm{ApEn}(\vec{X}, m, r) = \log\left[\frac{C_m(r)}{C_{m+1}(r)}\right] \tag{1}$$

The algorithm obtains the average count of the recurrence of vectors of length m and $m+1$ within a tolerance range of r for a given unit-variance normalized time-series, $\vec{X}$. In a time-series with a high level of regularity, values of $C_m(r)$ will be similar to $C_{m+1}(r)$, where a completely predictable time-series will have a probability ratio of 1, with the log-probability yielding an ApEn of zero. Higher ApEn values reflect an irregular time-series (more unpredictable time-dependent structure) as the recurrence of vectors of length m greatly exceeds that of $m+1$. As per Pincus [13], the values of m and r were set at 2 and 0.2, respectively. ApEn analyses were run on

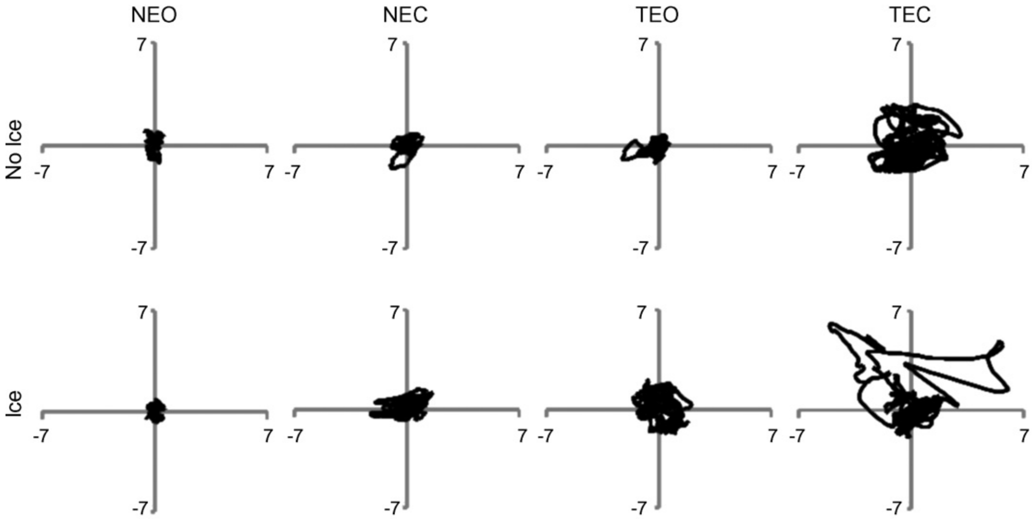

Fig. 2. Exemplar center of pressure trajectories (cm) for each condition. Vertical and horizontal axes represent *x* and *y* directions, respectively.

the mediolateral (ApEn-X) and anteroposterior (ApEn-Y) COP motions.

CrossApEn employs a similar algorithm to ApEn, but obtains counts of the recurrence of m and $m+1$ pairs of data points *across* the mediolateral and anteroposterior COP time-series (both normalized to unit variance) within a given tolerance range, r. CrossApEn provides a measure of synchrony between the two time-series, where higher values are indicative of greater asynchrony. Following Pincus and Singer [14], m and r were set at 1 and 0.2.

Statistical analysis on the dependent variables was performed using Statistix software (Analytical Software Student Edition, V1.0, Boston, MA). 2 (Stance) × 2 (Ice) × 2 (Vision) repeated measures ANOVA were used in the analysis of the four dependent variables, namely 95% COP area, ApEn-X, ApEn-Y, and CrossApEn. Tukey post-hoc analyses were employed where necessary. Significance level was set at $\alpha = .05$.

Prior to ice immersion, subjects were able to detect the monofilament at all five tested sites, giving a mean PPS score of a perfect 5. Following ice immersion, mean PPS scores were less than 1, indicating that plantar sensitivity was reduced to one site or less during the four Ice trials.

Exemplar center of pressure trajectories during each condition are presented in Fig. 2. 95% Area was affected by a significant three-way interaction ($F(1,12) = 21.29, p < .001$) with all main effects significant. The sway area was affected by Stance ($F(1,12) = 51.75, p < .0001$), Vision ($F(1,12) = 41.35, p < .0001$) and Ice ($F(1,12) = 19.39, p < .001$). See Fig. 3 for detailed results. The effects of the withdrawal of visual information and cutaneous desensitization were amplified by the tandem stance. The effect of desensitization was most observable in the absence of visual feedback and the more challenging tandem stance.

On the mediolateral COP motion, ApEn-X was affected by a significant Stance × Vision interaction ($F(1,12) = 11.10, p < .01$) and a significant Stance effect ($F(1,12) = 39.80$, $p < .0001$). Although ApEn-X was higher during the tandem stance, the significant Stance × Vision interaction (Fig. 4A) indicated that ApEn-X was reduced with the withdrawal of visual information in the normal stance ($p = .03$), but increased when visual information was withdrawn during the tandem stance ($p = .01$). No significant effects of Ice and the other interactions were observed ($p > .05$). Similar results were also observed from anteroposterior COP motion, ApEn-Y, with a significant Stance × Vision interaction ($F(1,12) = 56.40$, $p < .0001$ and Stance main effect ($F(1,12) = 23.33$, $p < .001$) (Fig. 4B).

CrossApEn was influenced by a significant Stance × Vision interaction ($F(1,12) = 56.40$, $p < .0001$ and Stance ($F(1,12) = 23.33$, $p < .001$). Similar to the ApEn data, CrossApEn was higher during the tandem stance. The withdrawal of visual information resulted in lower CrossApEn values during the normal stance, but resulted in an increase during tandem stance (Fig. 5). The effect of desensitization and the remaining interactions were not significant ($p > .05$).

The current results are in line with previous reports that the withdrawal of visual feedback significantly alters the structure of COP variability. However, it was also demonstrated that the effects of the withdrawal of visual information on the structure of COP variability are dependent on the task (stance) demands. Most importantly, removing plantar cutaneous sensation through

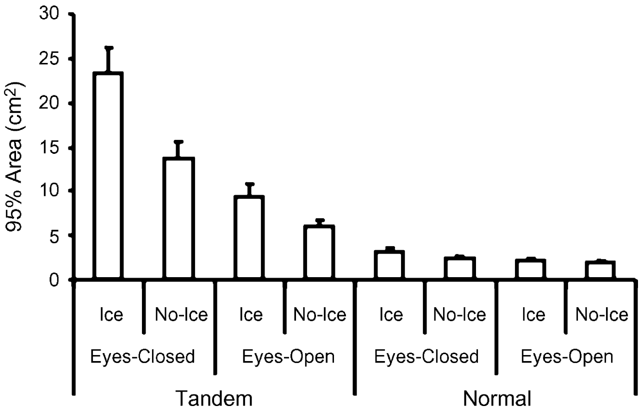

Fig. 3. 95% COP area at different stance, vision and desensitization conditions. Error bars denote standard error of the mean (S.E.M.). All pairwise comparisons revealed significant differences ($p < .05$).

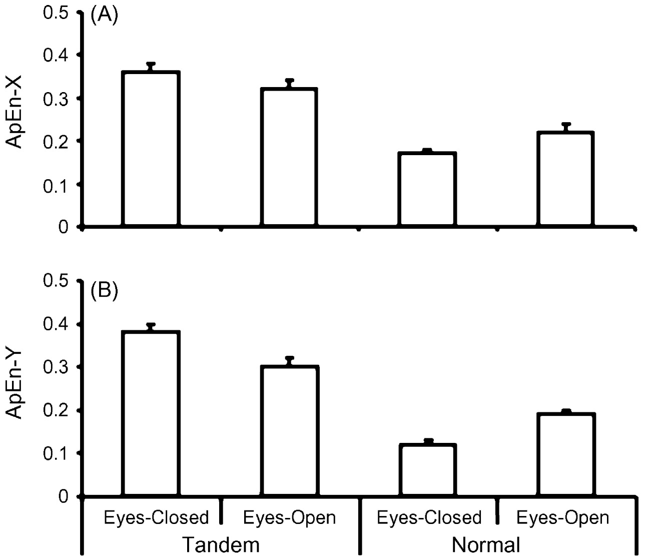

Fig. 4. Stance × vision interactions for both the ApEn analysis of irregularity of the mediolateral (ApEn-X, A) and anteroposterior (ApEn-Y, B) COP motions. Error bars denote S.E.M. All pairwise comparisons revealed significant differences ($p < .05$).

ice immersion only affected the magnitude and not the structure of COP variability.

The 95% COP area was affected by each of the different conditions placed on the subjects. Magnitude of sway variability was most strongly affected by stance. 95% COP area increased significantly when the subjects stood in the tandem stance, in agreement with Winter et al. [19]. As hypothesized, the increased difficulty of the tandem stance was compounded by the withdrawal of visual and cutaneous feedback [8]. This finding shows that the magnitude of sway variability increases as less sensory feedback was available to the subject. The greater effect of the withdrawal of vision when compared to cutaneous information demonstrates the high level of reliance on visual information during the maintenance of upright posture [3].

Our observations concur with the idea that the increased magnitude of sway variability is representative of an enlargement of the stability area [1,2]. As such, postural corrections are made only after larger amplitude excursions of the COP, as the neuromotor system is now presented with fewer sources of sensory input and is less sensitive to the changes in COP position. When visual information was withdrawn and cutaneous sensation was reduced, the control of posture is proposed as being increasingly reliant on proprioceptive and vestibular information [8]. One possibility is that the increased sway magnitude increases the load placed on the muscles and invoking their stretch–reflex response, taking into account the muscle force–length relationship [5].

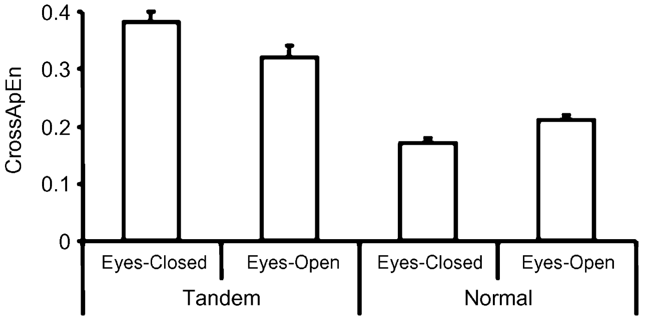

Fig. 5. CrossApEn analysis leads the interaction of stance and vision and indicates the synchrony between the mediolateral (ApEn-X) and anteroposterior (ApEn-Y) COP motions. Error bars denote S.E.M. All pairwise comparisons revealed significant differences ($p < .05$).

While standing in a normal stance, the removal of visual feedback reduced the irregularity on both the M–L and A–P directions, and also reduced asynchrony of the COP motions. Our findings are similar to Riley et al. [16], where an increase in the deterministic structure of the COP motions increased with reduced vision, analogous to an increase in time-dependent predictability of the dynamics. An increased predictability of future states of the COP based on prior states can be viewed as being reflective of fewer postural corrections and increased independence in the behaviors of the muscles and joints of the motor system [9]. This is further supported by the decrease in CrossApEn, showing increased co-dependence of the postural sway dynamics on both the M–L and A–P dimensions.

During tandem stance, both irregularity and asynchrony of the COP motions is increased in the absence of visual feedback. The greater CrossApEn values reflect an increased independence between the COP motions on the two axes during the tandem stance, with this independence increased further when the subjects were required to close their eyes. As sway area is increased in the absence of visual feedback, our current observations suggest that the subjects made fewer postural corrections when visual information was available during the tandem stance and made more numerous, larger amplitude postural corrections when visual feedback is withdrawn. Furthermore, the CrossApEn results suggest that the COP motions on the A–P and M–L axes are more independent of one another during tandem stance. Unlike the normal stance, their asynchrony is increased with the absence of visual information. This shows that the withdrawal of visual information does not necessarily lead to more predictable dynamics greater synchrony, and that the changes in postural sway under different sensory conditions are task dependent.

Though it was hypothesized that the effect of ice immersion on COP structure would become more pronounced during the more difficult tandem stance, this was not the case. The lack of a significant effect or interaction of this manipulation on ApEn or CrossApEn suggests that the reduction of cutaneous information did not alter the dynamics of postural corrections. A potential explanation, as the PPS results demonstrate, is that a complete loss of plantar sensation did not occur. Thus, it may be that the remaining plantar sensation was sufficient to maintain COP structure, as the significant changes reported by Meyer et al. [8] occurred with anesthesia resulting in the complete loss of cutaneous information.

Unlike Meyer et al. [8], the increased stance difficulty did not exacerbate the effects of the cutaneous desensitization, as Ice × Stance interaction was not statistically significant ($p < .05$). One possible explanation for this difference is that the exacerbation of the effects of cutaneous desensitization in Meyer et al. [8] occurred as the result of reduced proprioceptive feedback from having only one limb in contact with the force platform. This would have also reduced the number of joints and muscles that were involved in postural corrections, raising the possibility that the change in postural dynamics with the anesthetization of the foot under the unipedal stance would not be due to the increase in stance difficulty alone. Increasing stance difficulty through the narrowing of the base of support does not necessarily reveal underlying differences in the control of posture in when sensory information is reduced. Our current findings show that the direction of change in postural dynamics with a reduction in sensory information is greatly changed during the tandem stance, where the occlusion of visual feedback results in a decrease, rather than increase in predictability in the time-dependent structure of sway variability.

A key finding of this current study was that cutaneous desensitization altered only the magnitude but not the structure of postural sway variability. This suggests that a reduction in cutaneous sensation does not result in the re-organization of the control of the postural sway during upright standing, but rather, the equilibrium region for the COP excursions is expanded. Moreover, changes in dynamics were not compounded by the withdrawal of visual information, suggesting that the effects of sensory information withdrawal are not additive. Such an expansion in the equilibrium region could potentially be due to a shift toward greater reliance on the proprioceptive system and a shift in muscle properties, a possible focus for further investigation.

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