Journal of Motor Behavior

Interleg Coordination in Quiet Standing: Influence of Age and Visual Environment on Noise and Stability

Jeffrey M. Kinsella-Shaw, Steven J. Harrison & M. T. Turvey

Department of Kinesiology, University of Connecticut, Storrs
Department of Psychology, University of Connecticut, Storrs


To cite this article: Jeffrey M. Kinsella-Shaw, Steven J. Harrison & M. T. Turvey (2011): Interleg Coordination in Quiet Standing: Influence of Age and Visual Environment on Noise and Stability, Journal of Motor Behavior, 43:4, 285-294

To link to this article: http://dx.doi.org/10.1080/00222895.2011.580389

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.
ABSTRACT. The authors reexamined reported effects of age, illumination, and stationary visible structure on the net center of pressure (COP) derived from dual, side-by-side force plates (J. Kinsella-Shaw, S. Harrison, C. Colon-Semenza, & M. Turvey, 2006) from the perspective of axial postural control. They questioned how left and right COP, COP, and vertically oriented ground reactive force, GRF, coordinated during quiet standing. The Cross-recurrence Quantification (CRQ) revealed that coordination was primarily between fluctuations of similar direction, with coordination of left and right COP and (anteroposterior fluctuations) dominant. CRQ also revealed that (a) illumination and structure affected the interlimb dynamics of older (M age = 72.2 ± 4.90 years) participants more than their younger (M age = 22.8 ± 0.83 years) counterparts, and (b) older participants exhibited greater interlimb entrainment (dynamical stability) in the presence of greater interlimb noise.

Keywords: aging, illumination, interlimb coordination, nonlinear dynamics, postural control

Reports on between-leg coordination during quiet standing are rare. Using dual force plates, Winter, Prince, Frank, Powell, and Zabjek (1996) found that with left and right vertical forces signaled by a visual meter, young participants readily satisfied a requirement to partition load equally between the two limbs across variations in the spatial relation between the force plates: whether they were side by side, one behind the other, or at 45°. Similarly, measuring quiet standing on dual force plates, Blaszczyk, Prince, Ràiche, and Hébert (2000) examined whether younger and older adults differ in the free selection of limb load distribution. Both age groups revealed a left-right load asymmetry, with the magnitude larger for the older adults and amplified for the older adults by closing the eyes. Whereas Winter et al. highlighted the facility to control the individual contributions of the two limbs, Blaszczyk et al. pointed to the potential variation in, and idiosyncratic nature of, this facility as a function of age and vision.

Kinsella-Shaw, Harrison, Colon-Semenza, and Turvey (2006) reported effects of age, illumination, and the stationary structure of the visible environment on the time-varying net center of pressure—COPnet(t)—derived from dual force plates (see Winter, 1995). In the present study, we reexamined the effects of the aforementioned manipulations in terms of the coordination of the legs as revealed in the fluctuating mechanical interactions of the left and right feet with their respective force plates. We refer to this interleg coordination during quiet standing in the context of our experiment as axial postural control: the coordination of the lower limbs such that the body preserves a relatively invariant orientation to the visible environment. Geschwind (1975) and Waxman (1988) have pointed to the bilateral innervation of proximal musculature by an axial (nonpyramidal) motor system and highlighted its potential contribution to postural, orienting, and steering movements. We questioned, therefore, how age, illumination, and the stationary structure of the visible environment would affect this axial system as it subserves stable standing.

The mechanical interactions of limb and surface entailed in axial postural control under the upright standing conditions depicted in Figure 1 are summarized in Figure 2A. For each limb they comprise (following the analysis of Winter et al., 1996): mediolateral center of pressure (ML-COP), anteroposterior COP (AP-COP), and vertically oriented ground reactive force (z-GRF). They are modulated by the reciprocal actions of the ankle evertors and invertors, the ankle plantar- and dorsiflexors, and the hip abductor and adductor muscle groups (in conjunction with the obliques and quadratus lumborum of the abdomen), respectively. Note that when the body’s weight is shifted mediolaterally, the hip abductors on the side receiving the increased loading contribute to pelvic elevation on the opposite side, altering ground reaction forces. Each leg generates, therefore, three different time series: COP, COP, and GRF.

Anticipating the data analysis, inspection of Figure 2A indicates that determining the dual-plate dynamical structure of quiet standing involves 15 nonredundant pairings (signified by dotted lines) of the left and right time series relative to x, y, and z. Figure 2B isolates the nine pairings (linkages, couplings) of relevance to the present goal of evaluating the interlimb dynamics defining axial postural control. In contrast, the six pairings isolated in Figure 2C bear on the separate issue of the individual within-limb dynamics of quiet standing. The pairings in Figure 2B are of two kinds, which may be termed parallel and nonparallel, depicted by the gray and white arrows, respectively.

A method that can be applied to the pairings of Figure 2B is Cross-recurrence Quantification (CRQ) analysis, as schematized in Figure 3 and developed in Appendix A and the Method section. This analysis delivers two measures of particular relevance to the axial dynamics: the percentage of cross-recurrence (%Cross RECUR) and %Cross MAXLINE. If X(t) and X(t) in Figure 3 are considered as the idealized time series of Z(t) and Z(t), respectively, in

Correspondence address: Jeffrey M. Kinsella-Shaw, Department of Kinesiology, University of Connecticut, 406 Babbidge Rd., U-1020, Storrs, CT 06250, USA. e-mail: jeffrey.kinsella-shaw@uconn.edu
FIGURE 1. The two conditions of stationary environmental structure, more (left) and less (right), and the participant’s orientation to them during quiet standing on dual force plates.

Figure 2B, then following a suitable subsequent embedding of both time series in a reconstructed phase space, the amount of shared activity (inverse of %Cross RECUR) and the dynamical stability of any shared activity (%Cross MAXLINE) can be determined. The former can be taken as indexing variability or noise in axial dynamics and the latter as indexing the stability of axial dynamics. For the nine pairings identified in Figure 2B, it is possible to therefore inquire into how the noise and stability of each was affected by the age of the participants, the level of illumination, and the degree of stationary environmental structure.

FIGURE 2. Assessing interlimb coordination using cross-recurrence quantification (CRQ) of multiple time-series pairs (output variable pairs). (A) Measures derived from dual force plates of the mechanical interaction between each limb and the surface of support (COP and GRF) were analyzed by pairing all possible outputs. All of the potential time series pairs are shown as dashed lines connecting nodes in a graph. Each node in the graph represents an output of either the left (L) or right (R) limb. Each arrow represents a time-series pairing used to form part of a given analytic variable. (B) Axial coordination was assessed through an analytic variable formed from pairings of outputs across the limbs. Gray arrows capture pairings of parallel outputs and white arrows capture pairings from nonparallel or orthogonal outputs. (C) The six pairings isolated bear on the separate issue of the individual within-limb dynamics of quiet standing.

FIGURE 3. The phase-space reconstruction of a sample data set is shown. The series $X_1(t)$ (black dashed lines) and $X_2(t)$ (solid gray lines) are embedded in a reconstructed phase space. Time-delayed copies of $X(t)$ are used as surrogate dimensions $X(t + \tau)$ and $X(t + 2\tau)$ for a 3-dimensional embedding (as simply an example). Cross-recurrence quantification (CRQ) of two embedded time series is shown with intersecting trajectories counted as recurrent points for %Cross RECUR calculations and the longest parallel trajectory of $X_1(t)$ and $X_2(t)$ defines %Cross MAXLINE. Adapted with permission from Pellecchia, G., Shockley, K., & Turvey, M. T. (2005). Concurrent cognitive task modulates coordination dynamics. Cognitive Science, 29, 531–557 (Figure A1), Wiley-Blackwell Publishers.

Method

Participants

There were two groups of 12 participants, distinguished by age. A total of 7 men and 5 women constituted the group of younger adults ($M_{age} = 22.8 \pm 0.83$ years) and 6 men and 6 women constituted the group of older adults ($M_{age} = 72.2 \pm 4.9$ years). All participants were living independently in the community, and driving. All participants gave their consent in accordance with the University of Connecticut Institutional Review Board’s regulations for studies with human participants. None of the participants used any kind of assistive devices, orthoses, or prostheses for ambulation or maintenance of upright stance. All had normal or corrected-to-normal visual acuity. Cutaneous sensation of the feet was assessed by a licensed physical therapist using Semmes–Weinstein monofilaments and was intact for all participants. A history of falls over the previous 6 months, medical procedures, and medication use was obtained from each participant. None of the younger adults had a history of falls. Of the older adults, 7 had zero falls, 2 had one fall, and 3 had two falls. All reported falls were noninjurious and self-corrected. None of the participants had a history of use of any medication known to compromise balance. Height of the younger adults
ranged from 155 to 188 cm, with a mean height of 163 cm ($SD = 10$). Weight for this group ranged from 46.34 to 92.10 kg, with a mean weight of 67.62 kg ($SD = 6.3$). For the older adults, height ranged from 152 to 191 cm, with a mean height of 171 cm ($SD = 4.4$). Weight for the older group ranged from 56.22 to 95.78 kg, with a mean weight of 73.93 kg ($SD = 3.1$). Each person in each group was paid $10 for participating.

**Apparatus and Data Collection**

COP and GRF data were obtained at a sampling rate of 100 Hz using two Advanced Mechanical Technology, Inc. (Watertown, MA) force platforms and a 64-Channel Run Technologies (Laguna Hills, CA) Datapac 2000 Analog-to-Digital Collection System. A Peak Performance Technologies (Alpharetta, GA) Synchronization Trigger System synchronized data collection across the force plates networked with a dedicated Dell Optiplex GX300 workstation. In each trial, participants stood barefoot on the platforms, arms relaxed at their sides, legs abducted 10–12°, with heels 12 cm apart, and one foot on each platform. The platforms were embedded in the floor and separated by a 4 mm gap. Participants were instructed to stand still and relaxed, and to look at the depth-grating (more structure) array or at the white planar (less structure) array, depending on the experimental condition. COP under each foot was obtained independently from the two force plates.

Four 100 W work lamps controlled from a central, custom-built rheostat were the source used in the low illumination (3 lx), mesopic vision condition. The overhead fluorescent lights were the source for the high illumination (440 lx), photopic vision condition. Ambient illumination levels were verified with an Extech Instruments (Waltham, MA) Heavy Duty Light Meter (Model 407026) for each experimental condition for every subject. The light meter was calibrated at the beginning of each data collection session. The Extech Instruments light meter was used because of its compensatory circuits that ensure accuracy under incandescent and fluorescent light sources.

The depth grating apparatus consisted of nine rows of 1.8 cm diameter aluminum rods (conduits) arrayed three deep, for a total of 27 potentially visible rods. The rods in each row were placed 8 cm apart, with successive rows separated by a distance of 18 cm. Participants stood on the platforms at a distance of 122 cm from the nearest row of the display, positioned such that their eyes were directed roughly at its center (Figure 1). As a whole, the depth-grating assemblage measured 92 cm wide and 105.6 cm high. Consequently, the first row subtended a visual horizontal angle of 41.32° and a visual vertical angle of 46.8°.

For the low visual structure condition, the planar array consisted of a rectangular section of 5 mm thickness white foamcore board of the same vertical and horizontal dimensions as the depth-grating apparatus. The planar array was presented at the same location relative to the participants’ vantage point as the depth-grating array, thereby preserving all the same visual angle relationships. The foam core board surface had a flat white homogeneous finish with no detectable texture or other surface features. An identical section of white foamcore board provided a backdrop for the depth-grating apparatus and was affixed flush to the posterior surfaces of the most distant (third) row of rods.

In either condition participants were instructed to simply look at the array and were not instructed to focus specifically on the rods or the white screen (see Figure 1). Data collection was initiated once the participant was in position and indicated that they were comfortable and that their breathing was regular.

**Procedure**

There were eight trials in each of the five experimental conditions: (a) eyes closed; (b) eyes open, 3 lx, planar array; (c) eyes open, 3 lx, depth-grating array; (d) eyes open, 440 lx, planar array; and (e) eyes open, 440 lx, depth-grating array. Conditions 2–5 were collected as blocks of eight trials with 5 min separating data collection in each block to allow for full, stable levels of adaptation to the level of available illumination. This method of presentation is consistent with the recommended protocol for testing contrast sensitivity and assures that all the participants had the same opportunity for light-dark adaptation (see McMurdo & Gaskell, 1991). The order of presentation of Conditions 2–5 (the conditions analyzed in this report) was randomized for each participant. The eyes-closed condition was used to establish a baseline for postural variability in the total absence of visual support and data in this condition was collected in two four-trial blocks. The first block preceded data collection in all other conditions; the second block of eyes-closed trials was the final episode of data collection. The subsequent analysis of variance (ANOVA) conducted on all of the obtained measures of COP and GRF variability revealed no significant differences among the trials collected in the two eyes-closed blocks for any of the participants. Trials lasted 35 s each, with the initial 5 s excluded from the analysis to eliminate any possible transients that could bias the analysis of the steady-state trajectories. The analyzed portion of each trial yielded 3,000 data points. Participants were allowed to rest as needed. As in Blaszczyk et al. (2000), participants were allowed to freely select a limb load distribution strategy.

**Data Analysis**

Data analysis took advantage of the provision, by the dual force plates in Kinsella-Shaw et al. (2006), of simultaneous and independent recordings of COP$_x(t)$, COP$_y(t)$, and GRF$_x(t)$ generated under each foot (see Figure 2A). These data were submitted to CRQ analysis.

**Method of CRQ**

Amplifying our remarks in the introduction and Appendix A, %Cross RECUR in Figure 3 is the percentage of states
relative to all the states sampled that are returned to (are proximate to each other in phase space under a preestablished distance criterion during the period of observation) by the systems or subsystems under investigation. \( \% \text{Cross MAXLINE} \) expresses the maximum number of states that remain close (satisfy the preestablished distance criterion) over time, forming a line of recurrent states arrayed diagonally in phase space, relative to the longest possible line (the line of symmetry), indicative of complete between-systems state-transition congruence (Marwan, Romano, Thiel, & Kurths, 2007). Diagonal lines of this kind are present in the common phase space when stable, deterministic, dynamical coordination exists between systems’ trajectories.

In CRQ, independently generated time series, such as \( \text{COP}_L(t) \), \( \text{COP}_R(t) \), and \( \text{GRF}(t) \), are embedded in their respective phase spaces and then used to compute a \( \% \text{Cross-recurrence plot} \), providing a graphical representation of:

\[
C R_{m,i,j} = \frac{1}{N^2} \sum_{i,j=1}^{N} C R_{i,j}.
\]

This is the equation for the \( \% \text{Cross-recurrence matrix} \), \( CR_{m,i,j} \), where \( N \) is the number of considered (sampled) states, \( x_i \) (from the first time series) and \( y_j \) (from the second time series), so that any point \( x_i \) and \( y_j \) is said to be \( \% \text{Cross-recurrent} \) (an element of the matrix) if the Euclidean distance between the two normalized vectors is less than or equal to the threshold radius \( r \). This is equivalent to \( \epsilon_i \), the cutoff distance in simple recurrence quantification analysis (RQA). This threshold distance provides the radius for the sphere (see Figure 3) defined with \( x_i \) at its center, such that any \( y_j \) falling within the sphere represents a recurrent state in the shared state space and is plotted as a point. Therefore, the percentage of points that are \( \% \text{Cross-recurrent} \) is given by the following:

\[
\% \text{Cross RECUR} = \frac{1}{N^2} \sum_{i,j=1}^{N} C R_{i,j}.
\]

The \( \% \text{Cross RECUR} \) measure derived in this manner has been shown to be highly sensitive to even small amounts of stochastic (random) noise. Thus, \( \% \text{Cross RECUR} \) provides a measure of the density of \( \% \text{Cross-recurrent} \) points within the CRQ plot and corresponds to the probability of identifying truly recurrent points as such (Thiel et al., 2002; Marwan, 2003). Because this measure captures the proportion of points that are recurrent relative to the total number of points, its inverse can be interpreted as analogous to \( Q \), the index of system noise measurable in bidirectional, coupled-pendulum systems (Kudo, Park, Kay, & Turvey, 2006; Richardson, Schmidt, & Kay, 2007; see Appendix A).

In CRQ, \( \% \text{Cross MAXLINE} \) is the longest shared trajectory (see Figure 3) and is a measure of the shared activity of the two observed processes: for example, \( \text{COP}_L(t) \) of left limb and \( \text{COP}_R(t) \) of right limb. More specifically, if the two processes have the same or similar time evolution, parts of the two trajectories in phase space occupy the same region of phase space and do so for a certain length of time. The longer the time, the longer the shared trajectory or, equivalently, the longer is the line that represents it. The maximum length of the diagonal lines in the \( \% \text{Cross-recurrence plot} \) excluding the line \( i = j \) is given by the following:

\[
\% \text{Cross MAXLINE} = \max_{i=1}^{N_l} \text{length}(i; i = 1, \ldots, N_i).
\]

where \( N_i \) is a diagonal sequence of recurrent points and \( \lambda \) is the Lyapunov exponent, providing a measure of local attraction, \( \% \text{Cross MAXLINE} \) can be interpreted as a measure of entrainment (Marwan, 2003; Richardson et al., 2007). Under this interpretation, \( \% \text{Cross MAXLINE} \) quantifies mutual convergence of state dynamics at a local space-time scale, comparable to \( \lambda \) (Lyapunov exponent), providing a measure of local attractor strength for interlimb coordination (Kudo et al., 2006; Richardson et al., 2007).

### Parameters for CRQ

Before performing phase-space reconstruction, all output variables were rescaled (normalized) on a unit interval (0–1). Consistent with our previous analysis (Kinsella-Shaw et al., 2006), phase-space reconstruction was performed using nine embedding dimensions and a time lag of 0.1 s. Criterion for recurrence was set at 5% of the maximum distance between points in the distance matrix.

### Results

To reiterate, where Kinsella-Shaw et al. (2006) evaluated the effects of age, illumination, and environmental structure on net measures, the present evaluation was in respect to the time series \( \text{COP}_L(t) \), \( \text{COP}_R(t) \), and \( \text{GRF}(t) \) at each of the two force plates. The focus of the present evaluation were the nine couplings identified in Figure 2B and the potential interlimb relations determining axial dynamics. To this end, the left and right time series were subjected to \( \% \text{Cross RECUR} \) and \( \% \text{Cross MAXLINE} \) measures. The two measures were calculated for each of the older and younger participants for all 32 trials (eight trials for each of the four experimental conditions). Figure 4 summarizes the data: A and B show \( \% \text{Cross RECUR} \) under manipulations of illumination and structure, respectively; C and D show \( \% \text{Cross MAXLINE} \) under manipulations of illumination and structure, respectively. In all four, the measures are shown in respect to each of the nine paired time series depicted in Figure 2B.
FIGURE 4. %Cross RECUR and %Cross MAXLINE as a function of age group and the nine pairings (see Figure 2). First row: lower illumination (black), higher illumination (white). Second row: less structure (white), more structure (crosshatched). Third row: lower illumination (black), higher illumination (white). Fourth row: less structure (white), more structure (crosshatched).
Pairings: Parallel Versus Nonparallel

The initial issue was with respect to the nine pairings: Were they equivalent in respect to their CRQ measures? We conducted a mixed design 2 (age) × 2 (illumination) × 2 (environmental structure) × 9 (pairing) ANOVA. The ANOVA found the effect of pairing to be highly significant for both %Cross RECUR, $F(8, 176) = 62.46, p < .0001, \eta_p^2 = 1$, and %Cross MAXLINE, $F(8, 176) = 65.83, p < .0001, \eta_p^2 = 1$.

An inspection of Figure 4 suggests that the effect for %Cross RECUR and %Cross MAXLINE was carried by the parallel (e.g., $X_L(t), X_R(t)$)-nonparallel (e.g., $X_L(t), Z_R(t)$) contrast. A direct comparison of the means (Bonferroni-adjusted for multiple comparisons, $p < .05$) confirmed that for both CRQ measures the three parallel cases exceeded the magnitudes of the six nonparallel cases, with the $Y_L(t), Y_R(t)$ pairing significantly greater than all other pairings. In the following ANOVAs the factor of Pairings is restricted to the three parallel pairings.

% Cross RECUR

As is evident from inspection of Figure 4, the three parallel pairings differed in %Cross RECUR, with $Y_L(t), Y_R(t)$ ($M = 1.20, SD = .73$) greater than $X_L(t), X_R(t)$ ($M = 0.48, SD = .34$) and $Z_L(t), Z_R(t)$ ($M = 0.44, SD = .21$), $F(2, 21) = 35.78, p < .001, \eta_p^2 = 1$. Older and younger participants did not differ in overall magnitude of %Cross RECUR (for older adults, $M = 0.64, SD = .42$; for younger adults, $M = 0.78, SD = .47$). However, the effect of structure on %Cross RECUR depended on age (for younger adults, less 0.83, more 0.73; for older adults, less 0.54, more 0.73), $F(1, 22) = 7.31, p = .013, \eta_p^2 = 0.733$ (Figure 5A), and illumination’s effect on %Cross RECUR depended on age and pairing, $F(2, 21) = 4.74, p = .02, \eta_p^2 = 0.728$ (Figure 5B). Illumination had an overall effect, with %Cross RECUR greater under higher (0.76) than lower (0.66) illumination, $F(1, 22) = 5.85, p = .024, \eta_p^2 = 0.638$.

% Cross MAXLINE

As can be inferred from inspection of Figure 4, the results for %Cross MAXLINE followed closely those for %Cross RECUR. The type of parallel pairing was significant, with $Y_L(t), Y_R(t)$ ($M = 7.08, SD = 2.84$) greater than $X_L(t), X_R(t)$ ($M = 2.40, SD = 1.71$) and $Z_L(t), Z_R(t)$ ($M = 2.56, SD = 1.16$), $F(2, 21) = 69.76, p < .001, \eta_p^2 = 1$. There was no main effect of age (for older adults, $M = 4.27, SD = 3.18$; for younger adults, $M = 3.76, SD = 3.40$). The effect of structure depended on age (for younger adults, less 3.96, more 3.56; for older adults, less 4.04, more 4.50), $F(1, 22) = 5.27, p = .032, \eta_p^2 = 0.593$ (Figure 5C), and the effect of illumination depended on age and pairing, $F(2, 21) = 5.12, p = .02, \eta_p^2 = 0.763$. The %Cross MAXLINE values for the three parallel pairings depended marginally on age, $F(2, 21) = 3.11, p = .07, \eta_p^2 = 0.535$.

% Cross RECUR and % Cross MAXLINE for $Y_L(t), Y_R(t)$

The preceding analyses and inspection of Figures 5A and 5B invite a further analysis restricted to $Y_L(t), Y_R(t)$, one that includes measure as a factor. Ideally, such an analysis should accentuate the difference in the axial dynamics of the younger and older participants.

For the structure manipulation, the significant interaction of measure and age, $F(1, 46) = 5.27, p = .026, \eta_p^2 = 0.613$, affirmed that %Cross RECUR (for younger adults: $1.34 \pm 0.79$; for older adults: $1.06 \pm 0.64$) and %Cross MAXLINE (for younger adults: $6.16 \pm 2.26$; for older adults: $7.88 \pm 3.38$) patterned oppositely for participants.

For the illumination manipulation, the significant interaction of measure, illumination, and age, $F(1, 46) = 5.77, p = .020, \eta_p^2 = 0.653$, affirmed that %Cross RECUR (for younger adults: low $= 1.32 \pm 0.72$, high $= 1.35 \pm 0.86$; for older adults: low $= 0.88 \pm 0.54$, high $= 1.25 \pm 0.72$) and %Cross MAXLINE (for younger adults: low $= 6.29 \pm 2.33$, high $= 6.04 \pm 2.18$; for older adults: low $= 7.21 \pm 2.82$, high $= 8.55 \pm 3.92$) patterned oppositely participants.

Discussion

We questioned how age, illumination, and the stationary structure of the visible environment would affect axial
postural control as it serves stable orientation to the visual environment. Examining \( \text{COP}_t(t) \), \( \text{COP}_p(t) \), and \( \text{GRF}_t(t) \) from each force plate allowed us to augment the analysis of Kinsella-Shaw et al. (2006). It gave access to information about axial dynamics that was not available in the previously measured \( \text{COP}_\text{net}(t) \). Specifically, we evaluated, for the first time, the relative contributions of the coordination between displacements and force modulations generated by each leg. In essence our analysis decomposes the commonly reported \( \text{COP}_\text{net}(t) \) to reveal interleg organization.

**How Is Interleg Coordination Organized in the Service of Axial Postural Control?**

Participants were instructed to maintain a stable axial alignment relative to the environment (Figure 1). In the context of this task, the modulation of fluctuations along the line of sight—the parallel pairing \( Y_L(t) \), \( Y_R(t) \)—showed the greatest attractor strength. Interleg coordination was assembled such that it was least noisy (highest %Cross RECUR) and most dynamically stable (highest %Cross MAXLINE) in this direction. Consistent with the biomechanical analysis of Winter et al. (1996), the parallel pairings, \( X_L(t) \), \( X_R(t) \) and \( Z_L(t) \), \( Z_R(t) \), were the next most stably coordinated pairs of outputs between the two legs. This was required if fluctuations in the frontal plane were to be appropriately modulated to preserve axial orientation to the visible environment. Said differently, participants were required to minimize torques and lateral flexion moments (corresponding to the nonparallel pairings) in an appropriate manner to prevent being turned away from the visual arrays by postural fluctuations. Analogous \( \text{COP}_\text{net}(t) \) fluctuation dynamics have been reported when either aiming or visual search required a particular rectilinear orientation to the visual environment (Balasubramaniam, Riley, & Turvey, 2000; Bonnet et al., 2010).

**How Does the Visual Environment Influence the Noise and Dynamical Stability of Interleg Coordination During Stable Standing?**

Older participants’ interleg coordination was influenced more by our manipulations of illumination and stationary environmental structure. Less structure resulted in lower %Cross RECUR for older participants. The level of structure did not exert comparable influence on the %Cross RECUR of younger participants. When required to maintain a stable orientation, older adults’ axial control benefited from an increase in structure. Reduced illumination similarly reduced %Cross RECUR of the older adults, distinguishing them from the younger adults, but was specific to the parallel pairing \( Y_L(t) \), \( Y_R(t) \). Reducing illumination resulted in more noise being associated with postural fluctuations along the line of sight for the older adults. The axial control required for stable orientation to the visible environment was facilitated by higher illumination, especially for older adults.

The dowel array and the higher level of illumination made changes in orientation to the visual environment more readily detectable. That older adults benefited more than the younger adults from higher levels of the visual variables suggests that there may have been an underlying difference in the axial control dynamics of the two age cohorts. Our analysis revealed this to be the case for the parallel pairing, \( Y_L(t) \), \( Y_R(t) \), of greatest salience to the orientation required by the experiment. %Cross RECUR and %Cross MAXLINE patterned oppositely for younger and older adults under our manipulations of illumination and structure. Specifically, %Cross MAXLINE was higher and %Cross RECUR was lower for the older adults; the inverse relationship held between these measures for the younger adults. Under the constraints of this experiment, the postural fluctuations of the older adults in the direction of the visual arrays exhibited greater dynamical stability against a backdrop of greater intrinsic noise.

**How Might the Visual Influences Be Understood?**

As argued in detail in Kinsella-Shaw et al. (2006), there is a strong, but not monolithic, influence of visual contrast sensitivity (VCS) on the postural dynamics of quiet standing. The VCS of the older participants was substantially less than that of the younger participants, especially at lower levels of illumination and higher spatial frequencies (see Figure 6 in Kinsella-Shaw et al.). On the VCS measure alone, age-related effects of illumination and environmental structure should have been expected.

It is of value to note that VCS is advanced as a measure of the nervous system’s developmental age (e.g., Anstey, Lord, & Williams, 1997; Baltes & Lindenberger, 1997) and can be put into contrast with chronological age. Bonnet et al. (2010) found that COP stability in the mediolateral direction increased with VCS magnitude within a group of older adults of similar mean age to the present group of older adults, and Kinsella-Shaw et al. (2006) found that VCS, not age, was the best predictor of MAXLINE when standing with eyes closed. If VCS is a general index of the aging CNS, then an effect of VCS on standing should be expected in not only the presence but also absence of vision.

The larger point made by Kinsella-Shaw et al. (2006) needs to be repeated here: The minimal variant of upright postural activity referred to as quiet standing can only be fully understood as an embedded, embodied action. In the present study, the observed stability and variability in \( Y_L(t) \), \( Y_R(t) \) were dependent on the embedding environmental variables (light intensity, surface structure) and the embodied organismic variables (age, VCS).

**Postscript**

The relative differences between dynamical stability and noise for older and younger adults appear analogous to reports of age- and disease-related changes in postural task performance. Studies comparing younger adults to older adults (with and without Parkinson’s disease) found that under many circumstances older adults generate more variable sway fluctuations against a backdrop of elevated muscle...
cocontraction. It has been suggested that the older adult strategy is to elevate muscle tone around joint axes to limit segmental excursion, referred to as a stiffening strategy. Consequently, control is improved at the cost of decreased adaptability and increased metabolic demand. (Benjuya, Melzer, & Kaplanski, 2004; Hortaeghi & DeVita, 2000; Melzer, Benjuya, & Kaplanski, 2001; Termoz et al., 2008). Similarly, studies employing RQA or conventional variability measures of \( \text{COP}_{\text{sw}}(t) \) (e.g., path length, standard deviation, root mean square) suggest that older adults and adults with Parkinson’s disease seek to increase control at the expense of flexibility (Lauk, Chow, Lipsitz, Mitchell, & Collins, 1999; Dimitrova, Horak, & Nutt, 2004; Dimitrova, Nutt, & Horak, 2004; Horak, Dimitrova, & Nutt, 2005; Schmit et al., 2006). In agreement with our results, this trade-off was most evident in the anteroposterior fluctuations, the parallel pairing, \( Y_L(t) \) and \( Y_R(t) \), in the present study (Dimitrova, Horak, & Nutt, 2004; Horak et al., 2005; Schmit et al., 2006). The trade-off between increased control and reduced adaptability may contribute to the well-documented, delayed responses to mechanical perturbations that elevate fall risk for these populations (Bosek, Grzegorzewski, Kowalczyk, & Lubinski, 2005; Dimitrova, Horak, & Nutt, 2004; Horak, Nutt, & Nashner, 1992; Smithson, Morris, & Iansek, 1998).

ACKNOWLEDGMENTS

A grant (Collaboratory for Rehabilitation Research) awarded by the Provost’s Office of the University of Connecticut supported this research.

NOTES

1. In simplest terms, the \%Cross RECUR measure provides an estimate of the prevalence of noise in the time series. Consider that what the measure does is evaluate the number of times a system revisits the same states during a given interval. The fewer returns to previously visited states that are observed, the more states the system must have occupied over the interval of observation and the more random or noisy is its behavior. The recurrence-derived measure on Shannon entropy provides an allied index on this version of noise. In the extreme case of white noise, all possible states would be represented in the interval evaluated with an equal probability of occurrence at any time. In the context of postural control and other voluntary actions, noise of this kind can be conceived of as any trajectories observed that are not congruent with those required by the behavioral goal. In physical systems, the origins of noise are thermal. For living systems the origins of this noise ultimately resides in the metabolic processes that liberate biochemical energy sufficient to maintain viability. As these underlying processes are cyclical and operating at multiple time scales, they are correlated at multiple time scales and display fractality. In the context of movement trajectory generation, this plays out in the motor system in the interaction of baseline physiological tremor, the tonic contractile states required for dealing with gravity, and the phasic contractile states required for torque generation around joint axes that result in voluntary movement. Additionally, to the extent that information can change the scaling relations across these levels of the motor system, changes in the sensitivity of sensory detection (e.g., visual, proprioceptive, vestibular) can serve to increase the noise associated with movement generation. Shaw and Kinsella-Shaw (1988) provided formal grounds for this in the context of an analysis of goal-directed behaviors. Briefly, some degree of movement trajectory overshoot and undershoot is always observable as the different levels of the sensory and motor systems differ in their resolving power or availability. For these reasons, the well-documented changes in sensory detection capacity that accompany aging should be accompanied by corresponding changes in noise, as evaluated under cross-recurrence quantification analysis.

2. In the present context, the cross-recurrence measures are most usefully (and conservatively) viewed as providing information about the recorded movements’ dynamics, originating in a three-way interaction among the task constraints, the mechanical properties of the body, and the contribution of the neural substrate as it supports information detection and action. RQA methods have been applied to postural fluctuation data collected from individuals with Parkinson’s disease, diabetic peripheral neuropathy, and clinically significant age-related changes in sensory and motor capacities (Bonnet, Carello, & Turvey, 2009; Kinsella-Shaw et al., 2006). In the broader neurological domain, RQA has also been applied to data collected from normally developing infants, as well as individuals with cortical disease, cardiac arrhythmia, and epilepsy (Altmann, Romano, Thiel, & Niemitz, 2007; Babloyantz, 1991; Bianciardi et al., 2007; Censi et al., 2000; Harrison, Frei, & Osorio, 2008). These studies suggest that recurrence quantification measures are sensitive to changes in the functional connectivity of the nervous system. Furthermore, studies of Parkinsonian postural control and work with multiple electrode array chips (designed to provide simple simulations of cerebellar circuits) suggest that RQA measures may be particularly responsive to changes in the modulatory contributions of subcortical structures (i.e., basal ganglia and cerebellum) to postural control (Gour et al., 2007; Novellino, & Zaldívar, 2010).

REFERENCES


Influence of Age and Visual Environment on Posture


Submitted June 30, 2010
Revised November 20, 2010
Second revision February 18, 2011
Accepted March 28, 2011
APPENDIX

Cross-recurrence Analysis

The nonlinear technique of cross-recurrence analysis (CRQ) has been demonstrated to be of particular value in the pairwise analysis of the dynamics of independently controlled systems (e.g., speakers cooperatively coordinated in a conversational dyad; Shockley, Baker, Richardson, & Fowler, 2007) and independently controllable subsystems (e.g., the upper limbs engaged in rhythmic behavior; Kudo et al., 2006; Pellecchia, Shockley, & Turvey, 2005; Richardson et al., 2005; Richardson et al., 2007; Shockley & Turvey, 2005). For each pair in Figure 1B, CRQ provides indices of the amount of shared activity (inverse of %Cross RECUR) and the dynamical stability of any shared activity (%Cross MAX-LINE). CRQ provides these measures of the dynamic similarity of system trajectories without making assumptions about the data size, underlying distribution, or stationarity. Thus, CRQ is particularly appropriate for evaluating COP displacement data, as this has been demonstrated to be statistically nonstationary over a bounded range prescribed by the base of support (Newell, Slobounov, Slobounova, & Molenaar, 1997; Slobounov & Newell, 1994). CRQ is known to be highly sensitive to subtle space–time correlations that can occur between two motion trajectories, identifying recurrent states (episodes of shared activity) in reconstructed phase space (see Marwan, 2003; Shockley, Butwill, Zbilut, & Webber, 2002; Zbilut, Giuliani, & Webber, 1998; for tutorials, see Shockley, 2005; Webber & Zbilut, 2005). This sensitivity, in combination with the lack of restrictive computational requirements, makes CRQ ideally suited for the analysis of the time series of the potentially coordinated outputs generated during stable standing. It is important to note that recurrence of states, in the sense of a system being arbitrarily close at a later point in time to a state it was in at an earlier point in time, is a basic property of deterministic dynamical systems and typifies nonlinear systems (Marwan, 2003).