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Specificity of postural sway to the demands of a precision task

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Abstract

We examined a precision aiming task in which a handheld laser pointer was controlled by the postural system. The task was performed in two orientations of the body's coronal plane to the target. In the parallel orientation medio-lateral (ML) sway had to be minimized, in the perpendicular orientation antero-posterior (AP) sway had to be minimized. In the parallel orientation ML sway decreased and AP sway increased with target distance and size. The pattern reversed in the perpendicular orientation. Nonlinear measures found independence of the two directions of sway and differences in their deterministic structure. Apparently a postural organization for upright standing and aiming (as in archery) entails two independent postural subsystems with different but reciprocally related dynamics. Furthermore, it seems as if some amount of postural variability is needed to ensure stability in quiet standing; if postural activity is reduced in one direction it is compensated for in the other direction.

Keywords: Posture control; Recurrence quantification analysis; Average mutual information; Human

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1. Introduction

How is postural sway constrained in the performance of a precision aiming task, such as archery or rifle shooting? Investigations of the postural adjustments to satisfy precision requirements have, to date, been limited to questions of whether postural sway is a function of expertise [1–3] and whether postural variability changes immediately prior to the act (e.g. pulling the trigger in sharpshooting) [3]. More often the focus of investigations into precision aiming tasks has been the aiming itself, e.g. how the variability of the aim declines with practice [4,5]. Absent from the investigations to date are questions of how postural sway meets the dual challenges of precision aiming and standing upright and how the meeting of these challenges varies with degrees of precision.

In archery, for example, once the archer has taken aim and fixed the posture of the arms, the fluctuations of the body must be such as to preserve: (a) the alignment of the arrow with the target, and (b) the center of gravity within the base of support. As target distance is increased preserving the arrow–target alignment becomes more challenging and a magnitude of postural sway that was tolerable at a closer distance becomes intolerable at a further distance. An obvious response to the increased demand on precision, therefore, is to reduce the magnitude of postural sway.

Satisfying requirement (a) by reducing the overall magnitude of postural sway might not be so easy to do, however, given requirement (b). Both anterior-posterior (AP) sway and medio-lateral (ML) sway increase with increasing distance and/or decreasing size of a fixated target [6]. Visual stabilization of posture in the AP and ML directions seems to depend on how effectively oscillations of the body can be detected relative to stationary environmental surfaces. A standard argument is that with increasing distance or decreasing size of a fixated target, the magnitude of the retinal displacement caused by head sway during fixation of the target declines, with a resultant deterioration of visual stabilization [6]. For the archer, therefore, the precision requirements (contingent upon target distance) that dictate reduction in body sway are possibly requirements

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that render the detection of body sway and, therefore, the control of body sway, more difficult. The implication is that an archer using a strategy limited to adjusting the general level of postural sway would be challenged to satisfy simultaneously the opposing demands of precision and stability.

The possibility of a different strategy that is more adaptable to the archer's task is suggested by the finding that, for a person standing with the feet side-by-side, AP fluctuations are independent of ML fluctuations [7–9]. Consider an archer who adopts the square sideways stance. Precision would be compromised primarily by sway in the AP direction. This sway occurs in the plane parallel to the plane of the target and displaces the arrow rightward and leftward of the target. Clearly, the archer needs to reduce AP sway but the archer does not necessarily need to reduce ML sway (at least, not to the same degree). Could the archer take advantage of the factorization of postural fluctuations, controlling precision primarily through AP sway and controlling stability primarily through ML sway? There are obvious benefits to such a strategy, in particular the potential for reconciling the opposing demands of precision and stability.

A separation of the precision and stability functions of the archer's postural system should show up in the patterning of AP and ML fluctuations. To the extent that AP sway is dedicated to precision, it is less available for purposes of postural stability. Simply, an increase in precision means a decrease in the availability of AP sway for stability control. It also means, presumably, that postural stability is increasingly the responsibility of ML sway. An archer's AP and ML fluctuations may, therefore, vary in magnitude in different ways as a function of target distance. For example, as AP sway gets smaller, ML sway may remain steady in magnitude or even increase. That is, the patterning of AP and ML sway as a function of target distance should be very different in a precision aiming task from the patterning of AP and ML sway that is evident when one has to merely look at the target. In the latter situation, as noted above, AP and ML sway increase at the same rate with target distance [6].

An additional expectation about an archer's AP and ML fluctuations is that they may differ in composition, given their distinct roles. The possible difference in composition can be pursued through nonlinear variables that quantify recurring patterns (hidden rhythms) and nonstationarities (drifts) in experimental time series [10–12]. The recurrence plots from which these variables are derived are well-suited to exposing subtle dynamical processes in time series with inconstant statistical properties [13]. The mean, variance and higher moments of postural sway are known to vary in time [14,15]. Prior research has confirmed subtle recurrences in center-of-pressure (COP) time series [10]. They are detectable in higher dimensions and affected systematically by a manipulation of major relevance to postural stability, namely, vision (eyes open versus eyes closed). Returning to the archer, if precision and stability are met by devolving responsibility across AP and ML fluctuations, then recurrence analysis should be up to the task of exposing the determinism that characterizes and distinguishes these orthogonally-directed fluctuations.

In the present article the question of how the postural system is organized to perform a precision task was evaluated in two experiments in which participants stood with the right hand holding a laser pointer to the side of the upright body with the arm parallel to the body's longitudinal axis and the hand immobile against the thigh. Maintenance of the pointer on a target was to be achieved by 'keeping the body still'. The primary expectations were that ML and AP sway would be: (a) independent, and (b) respond differently to precision demands in both magnitude and deterministic structure.

2. Experiment 1

The participant's task in experiment 1 was to maintain a laser light beam on a target positioned at a distance of 1.1, 2.2, or 3.3 m from the participant. The coronal plane of the participant's body was parallel with the plane of the target. The target was of fixed size. Accordingly, the target distance could be equated with the task difficulty. Successful performance of the task, therefore, required reducing the fluctuations in the ML direction.

2.1. Method

2.1.1. Subjects

Twelve graduate students from the University of Connecticut served as participants. Six of the subjects were male and six were female. Their ages ranged from 22 to 39 years, with a mean of 25.8 years. Their body weights ranged from 42.2 to 81 kg, with a mean of 64.2 kg. Their heights ranged from 154 to 186 cm, with a mean of 168 cm. None of the subjects reported recent injuries at the time of the experiment. All 12 subjects had normal or corrected to normal vision. All subjects were right handed.

2.1.2. Apparatus, data collection, and reduction

Center of pressure (COP) data were collected using a Kistler force platform (type 9281B) and a Kistler charge amplifier (type 9865) set to 10 000 pC. The AP and ML fluctuations were sampled at a rate of 100 Hz, yielding a total of 3000 data points per 30 s trial. Data were collected on an microcomputer using the force analysis software system (FASS) digitizer software (ESI Technologies, OH).

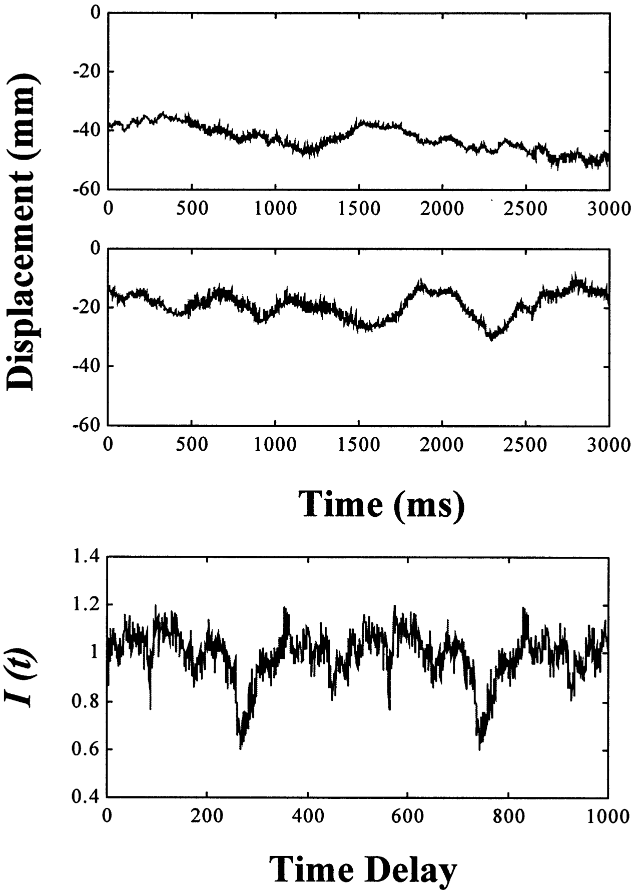

Fig. 1. The upper panel shows representative time series data of AP and ML fluctuations respectively. The bottom panel shows the average mutual information $I(t)$ shared between the AP and ML time series over 900 time lags.

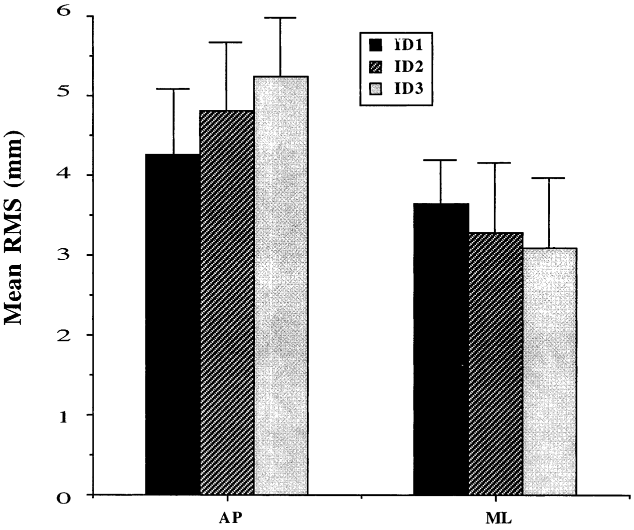

Fig. 2. Mean RMS variability (mm) of AP and ML sway in Experiment 1 as a function of task distance, with each distance equated with an ID as defined by target size/target distance. The error bars indicate S.E.s.

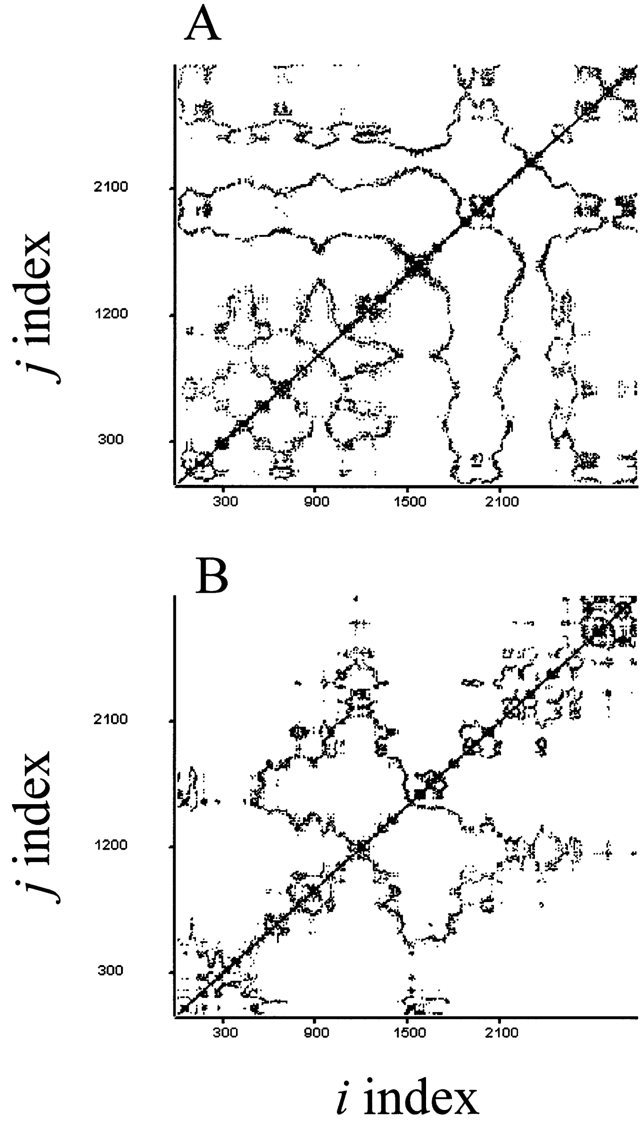

Fig. 3. Recurrence plots derived from AP (A) and ML (B) fluctuations shown in Fig. 1. Recurrent points are designated as blackened pixels that form distinct patterns that are symmetrical across the central diagonal (line of identity). Recurrence plots reveal qualitative differences between AP (more complex) and ML (less complex) fluctuations. Computations were performed using the following parameter settings: lag, 4 cycles; embedding dimension, 10; cut-off, 10% of the mean distance; and minimum line length, 2 points and mean distance rescaling. Four quantitative measures were calculated from each of the recurrence plots, percent recurrence, percent determinism, entropy and trend. See text for further details.

2.1.3. Stimuli

The target was a white square of 36 cm^2 at the center of four equal black squares each of area 9 cm^2 on a sheet of paper 21.6 × 27.9 cm, each black square was separated by 6 cm. The target was affixed to a plane surface located at a distance of 1.1, 2.2, or 3.3 m from the participant. At these distances the square target region subtended vertical/horizontal visual angles of 1.56, 0.78, and 0.52°, respectively.

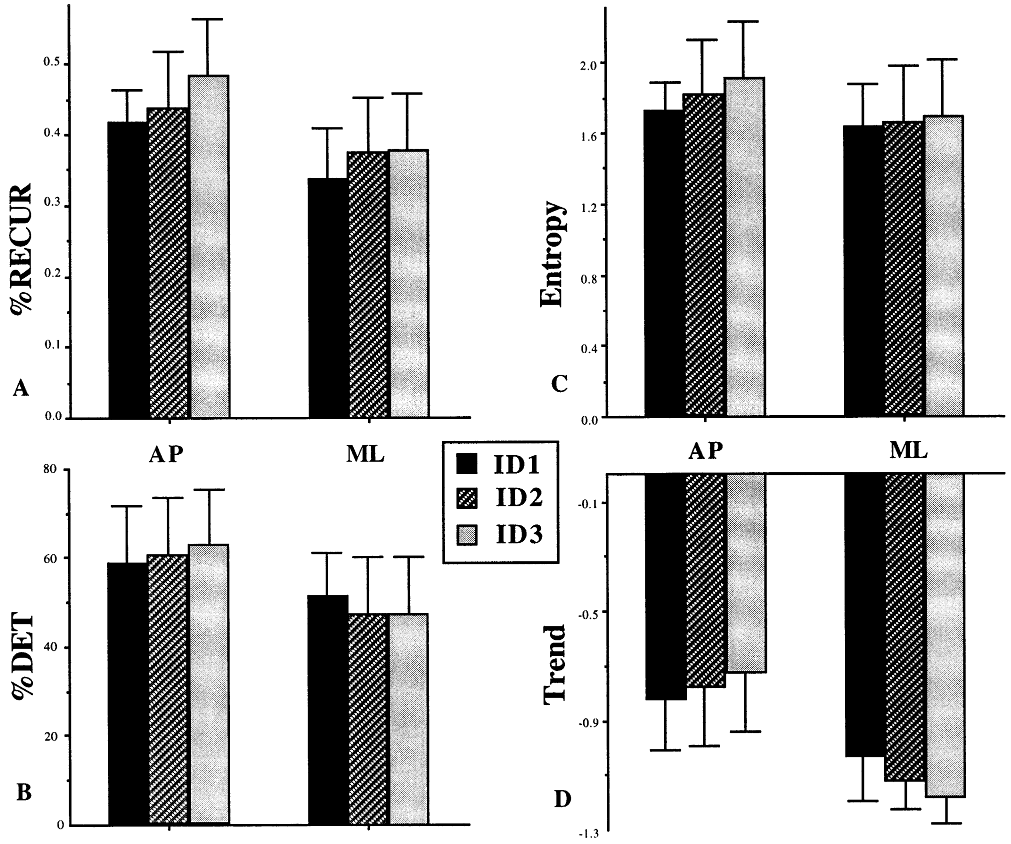

Fig. 4. (A) Mean percent recurrence for AP and ML sway. (B) Mean percent determinism for AP and ML. (C) Mean entropy for AP and ML (in bits). (D) Mean trend for AP and ML sway, across levels of task difficulty. The error bars indicate S.E.s. Data are from Experiment 1.

A handheld laser pointer was used to project a horizontal arrow onto the target. The area covered by the horizontal arrow increased with target distance — approximately 6, 12 and 18 cm^2 at 1.1, 2.2, and 3.3 m, respectively. The vertical and horizontal visual angles subtended by the arrow at these distances were 0.78 and 0.52°, 0.52 and 0.39°, and 0.39 and 0.35°, respectively.

2.1.4. Procedure

Participants stood on the force platform in a dimly lit room with all surrounds visible. They stood with arms by the side holding a laser pointer in the right hand. The right hand was held against the thigh. Each trial began with the participant aligning the laser pointer with the target which was oriented in a plane parallel to the coronal plane of the body and displaced off-center to be approximately in line with the participant's right hand. To achieve the required alignment the participant merely had to adjust the hand position to orient the laser beam. Once the beam and target were aligned, the hand was to be kept immobile. Participants were instructed to keep the laser arrow on target by simply 'standing still'.

We opted for voluntary immobility of the hand rather than affixing the hand to the thigh by tape (for example) in order to: (a) facilitate the comfort of the participants, and (b) allow a simple means (namely, hand rotation) by which any participant, regardless of his or her height relative to the fixed target height, could direct the laser beam onto the target. Any tendency for participants to control the laser pointer by hand motions rather than by postural motion would produce results counter to the present hypothesis. The experimenter did keep a visual check on the arrow's location and on the hand holding the laser beam with the charge of reminding participants of what their goal was if the arrow strayed out of the target region or if the hand moved. Importantly, the need to remind participants of the two task requirements never arose beyond the few practice trials used to acquaint the participants with the task.

There were 30 randomized trials of 30 s duration each, 10 trials per target distance. Data collection began when the participant indicated that the stance was stable and comfortable and that he or she was able to maintain the arrow on target. The interval between trials was at the participant's discretion. It was approximately 1 min on average.

2.2. Results

The subjects were requested only to keep the laser arrow within the boundaries of the white square defining the target. The variability in the arrow's behavior beyond the preceding requirement was not at issue. Importantly, the sizes of the target regions were chosen such that, for each distance, once the laser arrow was positioned inside a target region it was a simple matter to keep it there. Although the arrow would fluctuate within the boundaries of a target region there were no instances when the arrow strayed outside the boundaries once a trial began. In short, as defined, the precision task was satisfied equally in all conditions by all subjects.

Typical COP time series for sway in the AP direction (top panel) and ML direction (middle panel) on a given trial are shown in Fig. 1. Inspection of the upper panel in Fig. 1 suggests differences between the two time series in degree of variation and temporal structure.

2.2.1. Independence of ML and AP sway

Following the results of Winter and coworkers [8,9] and Rosenblum et al. [7], it was expected that fluctuations in the AP and ML directions would be independent. Rosenblum et al. [7] had reached their conclusion by application of: (a) the coherence function which quantifies linear correlations in the frequency domain, and (b) the more powerful measure of average mutual information (AMI) or Kolmogorov–Sinai entropy which quantifies both linear and nonlinear correlational structure [16]. AMI indicates how much information (in bits) about one time series at time t can be learned from the measurement of the other time series at time t. More specifically, given a series of AP measurements $\mathrm{ap}_1, \mathrm{ap}_2, \ldots, \mathrm{ap}_m, \ldots, \mathrm{ap}_M$, and a series of ML measurements $\mathrm{ml}_1, \mathrm{ml}_2, \ldots, \mathrm{ml}_n, \ldots, \mathrm{ml}_N$:

$$I_{\mathrm{AP\,ML}} = \sum_{\mathrm{ap}_m,\,\mathrm{ml}_n} P_{\mathrm{AP\,ML}} \log_2\{[P_{\mathrm{AP\,ML}}(\mathrm{ap}_m, \mathrm{ml}_n)] /[P_{\mathrm{AP}}(\mathrm{ap}_m) P_{\mathrm{ML}}(\mathrm{ml}_n)]\} \qquad (1)$$

where I is the average mutual information between all measurements of AP and ML, and $P_{\mathrm{AP\,ML}}(\mathrm{ap}_m, \mathrm{ml}_n)$ is the joint probability density for AP and ML and $P_{\mathrm{AP}}(\mathrm{ap}_m)$ and $P_{\mathrm{ML}}(\mathrm{ml}_n)$ are the individual probability densities for AP and ML. The above equation answers the question of "how much can be learned about the measurement ap_m from the measurement ml_n?" For independence of AP and ML, Eq. (1) should not differ significantly from 1 (i.e. 0 bits).

The AMI function for the two time series in the upper panels of Fig. 1 is given in the lower panel of Fig. 1. As can be seen, the value of Eq. (1) at each of 900 lag times between ap_m and ml_n, that is, the function $I(t)$, remained reasonably constant around 1, that is, zero bits. The implication is that no information (in bits) can be learned about the measurement of AP at time t by the measurement of ML at time t and vice versa.

AMI was computed between the AP and ML time series of each trial for each subject under each condition. The AMI measures calculated for each subject in the 10 trials of each condition did not depart significantly from 0 bits ($P > 0.05$). The average values of AMI at the three target distances were the same, namely, 0.02 bits. As a check, the particular variant of AMI used by Rosenblum et al. [7] and referred to as the general mutual information (GMI) measure was also computed for the present data. The outcome of the GMI analysis replicated that of the AMI analysis.

2.2.2. RMS as a function of sway direction

For all reported data analyses, a repeated-measures analysis of variance (ANOVA) was used given a positive check for homogeneity of AP and ML variance and the similarity of their respective covariances.

For each participant the mean RMS of the COP for the 10 trials in each condition was computed. Fig. 2 summarizes the overall means as a function of sway axis and an index of difficulty (ID) defined by the ratio of twice the target size to target distance. Inspection of Fig. 2 reveals that AP fluctuations increased, and ML fluctuations decreased, with task difficulty. A 2 (directions of sway) × 3 (target distance) ANOVA verified the interaction, $F(2,11) = 277.35$, $P < 0.0001$. There were also significant main effects of direction ($\mathrm{AP} = 4.77$ versus $\mathrm{ML} = 3.33$ mm), $F(1,11) = 450.93$, $P < 0.0001$, and task difficulty (3.95 mm for the 1.1 m target distance, 4.04 mm, for the 2.2 m target distance, and 4.16 mm for the 3.3 m target distance), $F(2,11) = 9.23$, $P < 0.001$.

2.2.3. Recurrence quantification analysis (RQA)

Fig. 3 shows recurrence plots for the two time series of Fig. 1. In a plot of time against time, a point (i, j) is recurrent if the COP value at time i and the COP value at time j are sufficiently similar. Consideration of all possible i, j coordinates, and darkening all pixels satisfying the similarity criterion, produces a recurrent plot with a strong upward diagonal corresponding to the points $i = j$ and distinct patterns that are symmetrical about the diagonal. In practise the recurrent plot is produced by embedding the COP in higher dimensional N-space and carefully setting criteria for suitably similar vectors [10]. The latter strategy follows from the embedding theorem [17,18]. By this theorem a measured scalar time series such as COP(t) in the ML direction can be embedded in a space of vectors $\boldsymbol{y}(t)$ whose coordinates are $[\mathrm{COP}(t), \mathrm{COP}(t + T\tau), \mathrm{COP}(t + 2T\tau), \ldots]$, where T is some integer multiple of the sampling period , and τ is an appropriate time delay. It is this embedding that gives rise to the detection, in higher dimensions, of subtle recurrences invisible in the original time series [12].

Given recurrence plots of AP and ML fluctuations, quantitative comparisons can be made between them in terms of degree of recurrence in the embedded space (tendency of vector string patterns to repeat themselves), determinism, complexity, and stationarity [10–12]. Recurrence in the embedded space is quantified by the percentage of the recurrence plot occupied by recurrent points. For the erratic variations in COP, this percentage will not be large. The vast majority of vector strings do not repeat. As it appears to the naked eye, COP behavior is largely stochastic. Nonetheless, within this noisy environment structure lies. Piecewise determinism (trajectories) is interposed with periods of stochasticity (pauses) [10–12]. Using Fig. 3 as reference, the determinism is quantified by the percentage of recurrent points that form trajectories in the sense of upward diagonal lines. The complexity of the determinism (the complexity of the dynamical rule) is quantified by the Shannon entropy defined over the independent probabilities of finding diagonal lines formed by two or more recurrent points. The stationarity of the dynamics shaped by the determinism is quantified by the rate at which the percentage of recurrence points changes with increasing perpendicular distance from the central diagonal (line of identity). (For a more detailed description and discussion of these quantities see Ref. [19]; for details of their specific application to postural control see Ref. [10]).

Inspection of Fig. 3 suggests that the two time series differed in the structure of their time correlations. The four primary quantifiers of the AP and ML recurrence plots were computed on each trial of each condition for each subject. Details of the computational procedures and parameter selections are given in [11,12], and the software package provided by Webber [20]. The values used in the following 2 × 3 ANOVAs of sway direction by target distance were the means of the 10 trials per subject per target distance. Fig. 4 shows the mean values of each of the four quantifiers as a function of sway direction and ID.

2.2.4. Percent recurrence

AP sway was more recurrent than ML sway in the reconstructed 10-dimensional space, $F(1,11) = 34.75$, $P < 0.001$. The total number of points in a triangular area of a given trial's recurrence plot was approximately 4 500 000. For the AP direction, approximately 20 250 of these points were recurrent on average (0.45%). In comparison, for the ML direction the number of recurrent points was approximately 15 300 on average (0.34%). Recurrence increased with task difficulty (target distance), $F(2,11) = 47.02$, $P < 0.001$, with the rate of increase greater for AP sway than for ML sway, $F(2,11) = 7.30$, $P < 0.001$.

2.2.5. Percent determinism

Both AP and ML sway exhibited deterministic dynamics, with AP more deterministic than ML. The mean percentage of upward diagonal lines resulting from multiple repetitions of strings of vectors was 62.33% for AP and 58.27% for ML, $F(1,11) = 64.96$, $P < 0.001$. That is, 12 622 of the 20 250 recurrent points in AP sway and 8915 of the 15 300 recurrent points in ML sway were organized, on average, into strings of length 2 or greater. Such strings of vectors would not be present if the recurrent points were randomly chosen rather than coming from a dynamical system [11,13]. Despite the suggestion of Fig. 4b, sway direction and task difficulty did not interact in determining the number of recurrence points organized by dynamical rule, $P > 0.05$.

2.2.6. Entropy

The deterministic structure of the recurrences in the embedding space was more complex for AP sway than for ML sway. The mean number of bits required to describe the determinism (to express the underlying rule) was 1.77 for AP and 1.65 for ML, $F(1,11) = 6.78$, $P < 0.05$. The complexity of the determinism for both directions of sway did not change with task difficulty (target distance), $P > 0.05$.

2.2.7. Trend

Both AP and ML sway exhibited progressive decorrelation or drift at larger time intervals, with the degree of drift less for AP sway than for ML sway. The mean rate at which the percentage of recurrent points declined with perpendicular distance from the identity line (the diagonal, see Fig. 3), as defined by the mean coefficient of the linear regressions, was -0.77 for AP sway and -1.26 for ML sway, $F(1,11) = 97.56$, $P < 0.001$. This rate of decorrelation decreased with task difficulty (target distance) for AP sway but increased with task difficulty for ML sway, $F(2,11) = 4.471$, $P < 0.05$.

2.3. Discussion

The observed independence between ML and AP sway for a side-by-side arrangement of the feet confirms the biomechanical analysis of Winter and coworkers [8,9] and the mutual information analysis of Rosenblum et al. [7]. Use of two force platforms, in contrast to the typical single force platform (as used here), allowed Winter et al. [8] to recognize two separate mechanisms in quiet standing with the feet side-by-side. The anatomical focus of one mechanism is the ankle; the anatomical focus of the other is the hip. In side-by-side standing, an ankle strategy involving plantar flexor and dorsiflexor activity is responsible for AP fluctuations and a hip strategy involving abductor and adductor activity is responsible for ML fluctuations. With different stances (e.g. right foot directly in front of the left, right foot partially ahead and to the side of the left) the two separate mechanisms combine in different ways and may use different muscular configurations (e.g. the ankles' invertors and evertors rather than their plantar flexors and dorsiflexors) in generating the AP and ML fluctuations [10]. The independence of AP and ML fluctuations evident in the present experiment, with the standard side-by-side stance, should be interpreted, therefore, as reflecting the relatively pure contributions of the ankle strategy to AP motions and the hip strategy to ML motions. Said differently, AP and ML fluctuations are themselves not necessarily independent; the independence is of the underlying mechanisms.

Rosenblum et al. [7] applied the AMI measure in its generalized form to quiet standing. They reported AMI values in the range 0–0.25 bits for the AP–ML relationship. These values indicate a very weak interdependency at most, and their range encompasses the mean value of the present data. The importance of the AMI measure is that it detects any correlation, linear or nonlinear, between two time series. Rosenblum et al. [7] also reported the results of a standard technique used to detect strictly linear relationships between two signals, namely, the coherence function $\gamma^2(f)$. This proved to be less than unity throughout the whole frequency range, confirming the absence of linear correlations between AP and ML sway as revealed by the AMI analysis.

A particularly significant finding was that the RMS variability of AP and ML sway changed in different ways with target distance. We hypothesized that in satisfying the demands of precision aiming, fluctuations in the plane parallel to the target, that is ML fluctuations, would have to be reduced as target distance and, thereby, aiming difficulty, increased. In confirmation ML sway decreased with increasing task ID. Our expectations for AP sway, however, were much less definite. With increasing target distance AP sway could have: (a) decreased, (b) increased, or (c) stayed at the same level. The observation was that AP sway increased.

This patterning of the two directions of sway shown in Fig. 2 may be compared with the patterning of AP and ML sway shown in Fig. 4 and 7 of Paulus et al. [6]. The latter figures reveal that, when participants simply fixate a target binocularly, both AP and ML sway increase with target distance. The strong implication is that keeping the hand-held laser pointer on target in the present experiment engaged vision differently from, and in a role additional to, its role in stabilizing posture.

The opposite trends of AP and ML sway raise the possibility that a threshold level of activity in postural subsystems might have to be surpassed in order to ensure stability. Consequently, curtailed activity in the ML direction would have to be compensated, wholly, or in significant part, by activity in the AP direction. That some amount of sway is needed to maintain balance during quiet standing has been suggested by Schieppati et al. [20]. Relatedly, Riccio [21], Riccio and Stoffregen [22], and Riley et al. [23] have proposed that postural fluctuations in quiet stance serve two essential functions, exploratory (obtaining information about current postural dynamics) and performatory (making corrections and adjustments to those dynamics on the basis of the obtained information). Parkinson's patients exhibit impaired movement in the AP direction possibly due to amplified ankle muscle stiffness. Their response to this reduction in AP sway is an elevated degree of ML sway [24]. Arguably, the increased ML activity reflects an attempt by Parkinson's patients to achieve the needed level of postural stabilizing activity in the face of the reduced contribution of AP activity [24].

An alternative speculation on the amplification of AP fluctuations in the present experiment attributes it to the decreasing degree of optical change caused by head sway as target distance increases. Fluctuations in the direction perpendicular to the target's plane may grow, reflecting weaker visual control of posture, as fluctuations parallel to the target's plane shrink to enhance precision aiming. It is noteworthy that recurrence analysis of COP data from quiet standing (with no explicitly identified supra-postural task) has found that determinism and complexity tend to be higher for eyes closed than eyes open [10]. Inspection of Fig. 4 suggests that task difficulty in the present experiment may have had a similar effect on the recurrence structure of posturally-relevant fluctuations such as closing the eyes [10].

The conjecture that ML and AP sway might differ in their deterministic structure due to the differences in their roles was confirmed by RQA. Sway in the AP direction was more recurrent, more deterministic, more complex and more stationary than in the ML direction. The approximate reciprocity of AP and ML variability as a function of task difficulty shown in Fig. 2 reflects, to some degree, the deterministic structure of the dynamics shown in Fig. 4. The recurrence quantifications in the AP and ML directions do not vary with task difficulty in the same way. Whereas the nonlinear measures of AP sway tended to increase systematically with task difficulty, those for ML sway were affected by task difficulty in a less consistent manner. The overall implication is that postural control in the present task (achieved through AP sway) required a dynamics that was: (a) more deterministic than that of precision control (achieved through ML sway), and (b) tied more systematically to task difficulty.

3. Experiment 2

Given the results of experiment 1 a precision aiming task that requires minimizing AP sway rather than ML sway should increase RMS in the ML direction, and decrease RMS in the AP direction as task difficulty increases. Furthermore, with respect to recurrence the reversal of roles should result in more recurrence, determinism, complexity, and stationarity in the ML fluctuations rather than in the AP fluctuations.

In experiment 2 the participant's coronal plane was oriented either parallel with the plane of the target (as in experiment 1) or perpendicular to the plane of the target. In the perpendicular orientation the participant stood sideways relative to the target with the right side of the body facing the target and the laser pointer in the right hand turned toward the target. In a further extension of experiment 1 both target size and target distance were manipulated. There are indications that AP and ML sway are similarly affected by visually fixating targets of different sizes at the same distance [7]. In the present experiment, with vision involved in the guidance of precision aiming in addition to stabilizing posture, we would expect target size to affect AP and ML sway differently.

Three major predictions can be made, therefore, for experiment 2 given the results of experiment 1. First, that the AMI measure quantifying the mutual predictability of the AP and ML time series should not differ significantly from zero bits in either the parallel or perpendicular orientation. Second, that the recurrence plot measures of recurrence, determinism, complexity and stationarity should favor AP in the parallel orientation and ML in the perpendicular orientation. And third, that RMS variabilities in the ML and AP directions should vary systematically with task difficulty, with ML decreasing and AP increasing in the parallel orientation and ML increasing and AP decreasing in the perpendicular orientation.

Finally, it should be noted that an added benefit of experiment 2 is to provide confirmation that the relatively novel application of the RQA analysis to posture is reliable. At issue is whether the similar manipulations in Experiment 2 reproduce the RQA pattern of Experiment 1.

3.1. Method

3.1.1. Subjects

Eight graduate students (five females) from the University of Connecticut served as participants. Their ages ranged from 22 to 27 years, with a mean of 24.7 years. Their body weights ranged from 41.3 to 95 kg, with a mean of 69.71 kg. Their heights ranged from 157 to 178 cm, with a mean of 164 cm. None of the participants reported recent injuries at the time of the experiment. All participants had normal or corrected to normal vision and all were right handed.

3.1.2. Apparatus, data collection, and reduction

The apparatus, data collection and collation procedures were identical to experiment 1 with the exception that the target was of two sizes, the size used in experiment 1 and a smaller size in which the white square within the four black squares (each of 9 cm^2 as before) was 24 cm^2. In this smaller target size each of the squares was separated by 4.89 cm. The corresponding visual angles for the smaller target square at the three distances were 1.30, 0.65, and 0.43°, respectively. The projected arrow sizes and visual angles subtended by the arrow were identical to experiment 1.

3.1.3. Procedure

Participants stood with arms relaxed holding a laser pointer in their right hand and were asked to point to the target oriented either parallel to or perpendicular to the participant's coronal plane. Whereas the participant looked at the target from a straight ahead position in the parallel orientation, he or she looked at the target from a sideways position in the perpendicular orientation. The procedure was identical in all other respects to that of experiment 1.

3.1.4. Design

Participants were presented with 10 randomized trials in each combination of three distance conditions (1.1, 2.2, and 3.3 m) two orientation conditions (parallel and perpendicular) and two target sizes (24 and 36 cm^2). The combinations of distance and size yielded six values of ID.

3.2. Results

As in experiment 1 all subjects satisfied the precision requirements as defined. Comparisons of time series for AP and ML sway suggested the same role-dependent contrasts as observed in experiment 1. That is, RMS variability was less for ML than AP when the orientation was parallel and less for AP than ML when the orientation was perpendicular.

3.2.1. Independence of ML and AP sway

Analyses of the two time series (AP and ML) across participants and conditions confirmed the observation of experiment 1 that the AMI was approximately 0 bits. In the parallel orientation, for ID 1–6 the mean values of AMI were 0.01, 0.01, 0.21, 0.11, 0.12, and 0.01 bits, respectively, and in the perpendicular condition they were 0.02, 0.01, 0.21, 0.17, 0.13, and 0.01 bits, respectively. AP and ML sway were independent. A $6 \times 2 \times 2$ ANOVA performed on the subjects' mean AMI values for the factors task difficulty, sway axis and orientation yielded no significant effects ($F < 1$).

3.2.2. RMS analysis

The mean values per condition are summarized in Fig. 5A (the parallel orientation) and Fig. 5B (the perpendicular orientation). Inspection of Fig. 5A and B reveals that: (a) the results of experiment 1 for the parallel orientation were replicated, (b) the patterns of increasing and decreasing RMS variability as a function of sway direction found in the parallel orientation were reversed in the perpendicular orientation, and (c) RMS was affected systematically by task difficulty.

A 6 × 2 × 2 ANOVA was conducted on the subjects' means with factors of task difficulty, axis of sway and orientation. The theoretically significant three-way interaction suggested in Fig. 5 was corroborated, $F(3,7) = 27.89$, $P < 0.01$. Overall, AP sway (mean of 4.66 mm) was greater than ML sway (mean of 3.45 mm) in the parallel condition, ($P < 0.0001$), and conversely, ML sway (mean of 4.25 mm) was greater than AP sway (mean of 3.59 mm) in the perpendicular condition ($P < 0.0001$). Comparisons of means within an orientation condition revealed that for a given task difficulty (e.g. small target at 2.2 m), there was, for most comparisons, a significant effect (minimally, $P < 0.05$) due to direction of sway (e.g. in the perpendicular orientation ML was greater than AP). The only main effect was of task difficulty, $F(2,7) = 176.05$, $P < 0.001$.

3.2.3. RQA

The four primary quantifiers of the AP and ML recurrence plots were computed for each trial under each condition for each subject. ANOVAS (6 × 2 × 2) were conducted on the subjects' means. The most important issue is whether, for a given measure, the relationship between task difficulty and sway depended on orientation.

3.2.4. Percent recurrence

In the parallel condition AP was more recurrent than ML in that 0.56% of the vectors in the N-dimensional embedding space of AP recurred compared to 0.46% of the vectors in the N-dimensional embedding space of ML. In the perpendicular orientation ML was more recurrent than AP (0.57 versus 0.37%). The dependence on orientation of task difficulty × axis of sway was significant, $F(5,35) = 4.171$, $P < 0.01$.

3.2.5. Percent determinism

In the parallel orientation AP was more deterministic (66 versus 57%); in the perpendicular orientation ML was more deterministic (64 versus 53%). The dependence on orientation of task difficulty × axis of sway was significant, $F(5,35) = 18.68$, $P < 0.001$.

3.2.6. Entropy

In the parallel orientation AP was more complex (1.82 versus 1.53 bits); in the perpendicular orientation ML was more complex (2.04 versus 1.83 bits). The dependence on orientation of task difficulty × axis of sway was significant, $F(5,35) = 11.03$, $P < 0.01$.

3.2.7. Trend

In the parallel condition AP was more stationary (-0.83 versus -1.24); in the perpendicular condition ML was more stationary (-0.92 versus -1.19). The dependence on orientation of task difficulty × axis of sway was significant, $F(5,35) = 12.32$, $P < 0.001$.

Fig. 6 summarizes the patternings of the recurrence measures for experiment 2. There is reasonable similarity between the patterns shown in Fig. 6 and those shown in Fig. 4 depicting the results of experiment 1. In both experiments, percent recurrence, percent determinism, and entropy tended to change more pronouncedly with task difficulty in the sway direction relevant to posture. Furthermore, in both experiments trend tended to change more pronouncedly with task difficulty in the sway direction of relevance to precision.

3.3. Discussion

The main result of experiment 2 was that the two subsystems of postural balance in quiet standing exchanged roles in the parallel and perpendicular orientation conditions. When the precision task required minimizing fluctuations in the ML direction (the parallel orientation) fluctuations in the AP direction became correspondingly magnified with task difficulty. In contrast, when the precision task required minimizing fluctuations in the AP direction (the perpendicular orientation) fluctuations in the ML direction became correspondingly magnified with task difficulty.

It is typically the case (for healthy participants) that AP sway exceeds ML sway [25,26]. This difference has been attributed to the geometry of the lower limb, in particular the simple-hinge design of the ankle joint that permits rotation in the sagittal plane [25]. From a purely passive mechanical perspective, upright bipedal stance ought to be less stable in the AP than ML direction. The present finding of a reversal in the magnitudes of AP and ML sway in the perpendicularly oriented precision task, with ML sway greater, opens up the possibility that the ordering of AP and ML sway magnitudes may be as much functional as biomechanical in origin. This possibility is consistent with the hypothesis, identified above, that the opposite trends of AP and ML sway suggest that some amount of postural activity is needed to maintain balance [20,21]. If the contribution of postural activity in one direction is restricted because of suprapostural demands, then postural activity in the other direction will be increased to compensate.

An extension of the interpretation of elevated ML sway in Parkinsonian patients [24] bears on the present

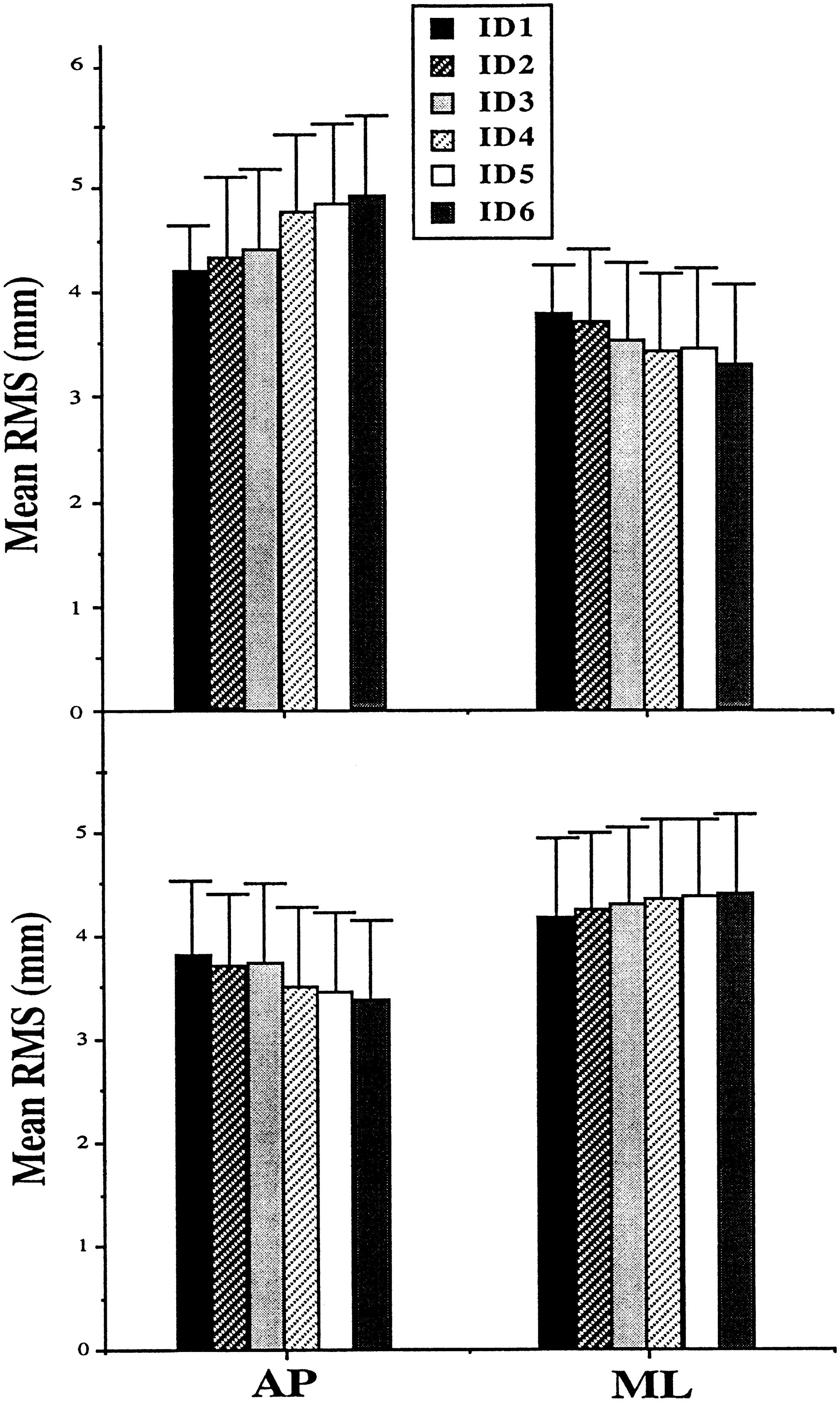

Fig. 5. (A) Mean RMS variability of AP and ML sway of the participant as a function of task difficulty in the parallel condition of Experiment 2. (B) Mean RMS variability of AP and ML sway as a function of task difficulty in the perpendicular condition of Experiment 2. The error bars indicate S.E.s.

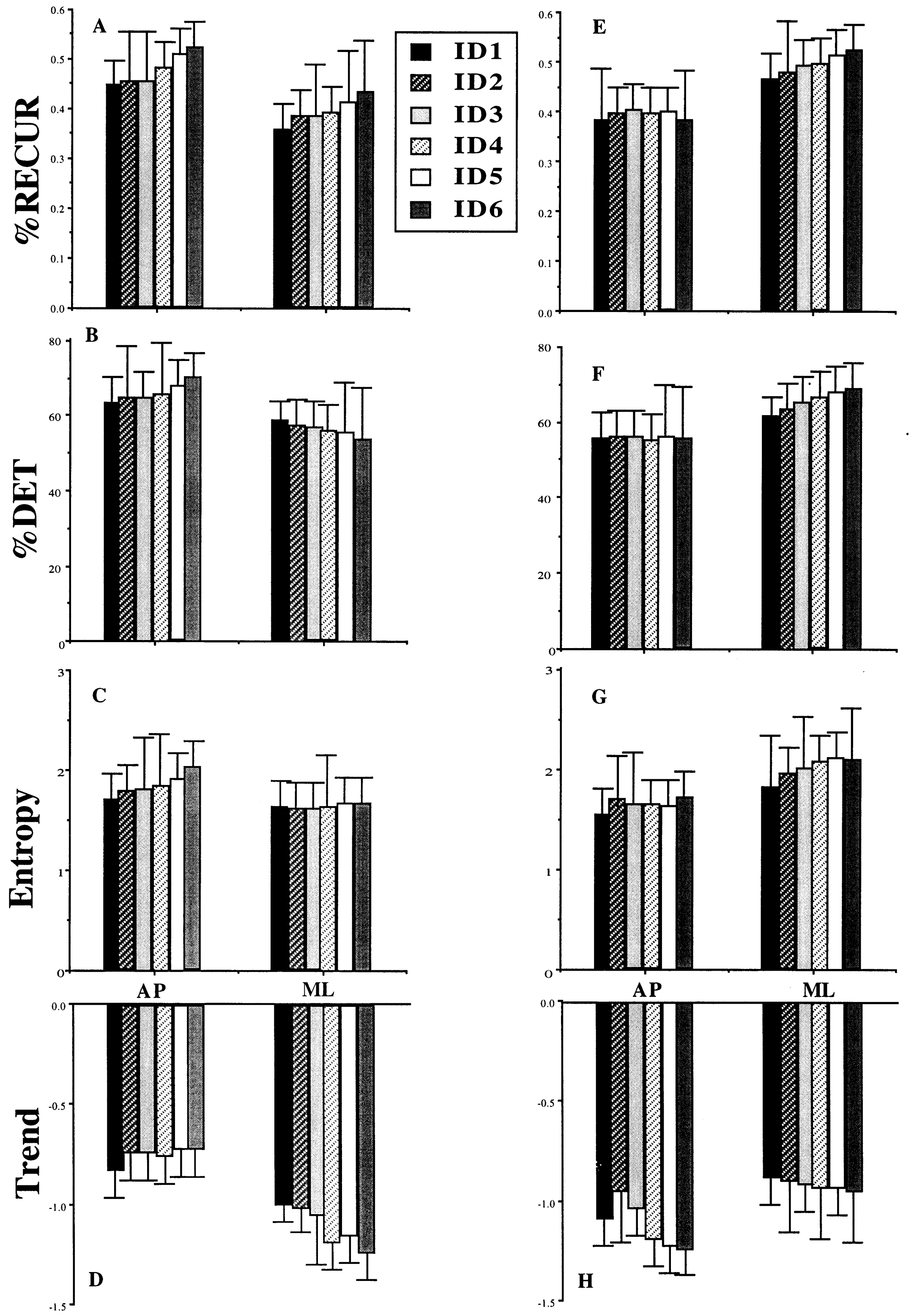

Fig. 6. (A) Mean percent recurrence for AP and ML sway. (B) Mean percent determinism for AP and ML. (C) Mean entropy for AP and ML (in bits). (D) Mean trend for AP and ML in the parallel condition. (E) Mean percent recurrence for AP and ML sway. (F) Mean percent determinism for AP and ML. (G) Mean entropy for AP and ML (in bits). (H) Mean trend for AP and ML in the perpendicular condition (all as functions of task difficulty). The error bars indicate S.E.s. The data are from Experiment 2.

results. How does a healthy person perform the precision aiming task in the parallel orientation? The formula might be: stiffen the hip muscles in direct relation to the required precision and elevate postural activity in the AP direction to ensure a sufficient level of postural activity for stability. How does a healthy person perform the precision aiming task in the perpendicular orientation? The formula might be: stiffen the ankle muscles in direct relation to the required precision and elevate postural activity in the ML direction to ensure stability. The pattern of data in Fig. 5 indicates an ability to modulate selectively the directions of postural activity in response to the demands of suprapostural tasks.

The preceding ideas receive additional support from the RQA analysis. Whereas AP was more recurrent, deterministic, complex and stationary in the parallel orientation (confirming experiment 1), ML was more recurrent, deterministic, complex and stationary in the perpendicular orientation.

4. General discussion

The present results provide insight into suprapostural, precision aiming tasks [1,4,5] and suggest how the hypothesis of two independent postural subsystems [9] can be usefully extended. The broad theoretical lesson of experiments 1 and 2 is that the assembly of a postural organization for upright standing and aiming (as in, for example, the square sideways stance in archery) entails two negatively correlated but distinct dynamics.

The negative correlation was evident in RMS variability. As task difficulty increased the fluctuations of the subsystem of primary relevance to posture increased, whereas those of the subsystem primarily responsible for precision decreased. The distinctiveness was evident in the nonlinear measures of AMI and recurrence quantification. The AMI value of 0 bits, obtained for both experiments, revealed that the two subsystems were independent. The recurrence quantification revealed, furthermore, that the two subsystems were distinguished in the fine structure of their time correlations. Although both exhibited subtle periodicities (recurrence) in higher dimensions, the subsystem primarily responsible for postural control tended to be more recurrent, deterministic, complex and stationary. Importantly, there were indications that the influence of task difficulty on the fine structure of the time correlations was roughly similar to its influence on the mean level of postural fluctuations. Future experiments and theory development can be expected to clarify the relation between average measures of postural fluctuations such as RMS of COP variability and measures conducted at finer time scales such as AMI and recurrence quantification.

With respect to the measures, it should be underscored that the present research provides important support for the application of recurrence plot methodologies [11,12]. These methodologies are intended to make evident the dynamical processes that are not obvious in the fundamental time series and difficult to detect by standard linear techniques [12]. In the present research we have identified that recurrence measures can reveal determinism in behavioral and physiological signals that appear to lack such structure (such as the COP signal) and, furthermore, that recurrence measures, despite their extreme subtlety, can be shown to vary systematically as a function of experimental manipulations.

In sum, it seems apparent that the independence discovered by Winter et al. [9] is expressible as two postural subsystems that can manifest two very different but interacting dynamics befitting the contrasting but parallel requirements of suprapostural tasks (e.g. maintaining stance and aiming). Identifying these different task-specific and negatively correlated dynamics is an important direction for future research on adaptive postural control.

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