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NONSTATIONARY PROPERTIES OF POSTURAL SWAY

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Abstract—Postural sway during quiet stance is usually assumed to be a stationary stochastic process. We tested this assumption by investigating the time invariance of the average value and variance of the postural sway of three subjects. The sway was measured with a force plate under three conditions: subject standing on two feet with eyes open; subject standing on two feet with eyes closed; and subject standing on one foot with eyes open. Data were collected in 1 min runs. More than 50 min of data were collected for each subject under each test condition. The data were averaged across all runs for each subject and condition. Trends were found to be present in the data. In addition, there were initial transient increases in the second-order moments about the trends. The transient changes in first- and second-order moments usually disappeared during the first 20 s. In light of these findings, we can reject the hypothesis that postural sway is a stationary process. The results imply that the usual methods to parameterize postural sway have to be either changed or reinterpreted.

INTRODUCTION

Postural sway is measured in order to determine a person's ability to maintain upright stance. Often, the control of posture is tested by challenging the postural systems with perturbations of various kinds. However, in many clinical applications such as testing of elderly or neurologically impaired people, postural control is measured during quiet stance.

Quiet, bipedal stance requires active control of the body. The efficacy of the control is often monitored by measuring the center of pressure of the body acting on a substrate. One way to accomplish this is with a force plate on which the subject stands. The plate is instrumented with force transducers which are used to determine the point of contact under the feet through which the ground reaction force may be considered to be acting.

It is almost always implicitly assumed that postural sway is a stationary process; that is, its statistics are invariant over time. On occasion (Maki *et al.*, 1987; Werness and Anderson, 1984), trends have been found in initial portions of some data. But if obvious trends can occur on occasion, then perhaps less obvious trends are also present. By definition, trends are time-dependent first-order moments. If trends exist, then there must be a difference between the average initial orientation of the body and its average final orientation.

If trends for postural sway exist, then it seems appropriate to ask whether the second-order moments contain transients. For example, does the variance in postural sway about the trend vary with time? If this does happen, it may be due to the variability in the way in which the subject begins the measurement process or, more importantly, it may indicate that the ability of the postural system to regulate balance changes with time. If the latter possibility is true, then the postural control system is much more complicated than what the current models of the system would indicate.

If postural sway is not stationary, then more than just the models of this system would have to be changed. Almost all current methods of analyzing postural sway data rely in one way or another on a time average of the data. Transients can distort the result of a time average. For example, the value of root-mean-squared deviation, which is commonly used to characterize postural sway data, will be increased if it is based on data which contain a transient. In order to interpret any parameter based on a time average of postural sway data, it is critical to determine if transients exist in the data.

In this work, we will examine the time invariance of the first- and second-order moments of postural sway and discuss the implications of the measurements and the interpretation of postural sway data.

METHODS

Postural sway was measured with the subject quietly standing on a strain gauge instrumented force plate. Experimental control and collection of displacements of the center of foot pressure data in the anterior–posterior and lateral directions were accomplished using a PDP 11/10 laboratory computer. The equipment was always allowed to temperature-stabilize for at least one half hour before any data were collected in order to minimize any electronic drifts.

Data were collected on three subjects under three different conditions. The subjects were healthy males (age range 25–52) without a history of vestibular,

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visual, proprioceptive or postural problems. In the first two conditions, the subjects stood on two feet with the feet brought together and toes pointed straight ahead. In the first condition (EO2F) the eyes were open; in the second (EC2F) they were closed. In the third condition (EO1F) the subject stood on his left foot with toes pointed approximately ahead; the right foot rested on top of the left one and the subject's eyes were open. These three common test conditions were chosen to present the subjects with postural tasks providing increased levels of instability from EO2F through EO1F (Werness and Anderson, 1984; Johanson *et al.*, 1988).

In all three conditions, the subjects folded their arms against their chest and looked straight ahead. Before the beginning of each measurement trial, the subject stepped onto the force plate from the rear. Measurements began when the subject said he was ready, i.e. with feet, arms and eyes in the proper position.

The center of foot pressure was measured for both the anterior–posterior and lateral directions at the rate of 100 samples per second for a duration of 60 s. The 60 s trials for each test condition were performed with the subjects alternating turns, i.e. one trial for each subject with condition EO2F, followed by a trial for each subject with condition EC2F, etc. Measurements were made on 10 different occasions which spanned a period of 5 months. For each of the three subjects, a total of 51 min data was collected for conditions EO2F and EC2F while 71 min data were obtained for condition EO1F. More data were obtained for condition EO1F because one session was completely devoted to collecting data under this condition.

The data collected from the force plate sensors were modified by multiplying the data array by the calibration matrix. The calibration parameters were obtained by placing a 50 lb weight (through point contact) at the four corners and at the center of the force plate. Calibration data at each point were collected in 30 s trials at the beginning and end of every data collection session in order to adjust for any electronic drift which may have occurred during a testing session.

The average position of the feet varied somewhat from trial to trial because the subject stepped off the force plate to rest between each 1 min trial. To eliminate this contaminant, the center of pressure data over the last 40 s were averaged and the result subtracted from all the data of that trial. Explicitly, let $y_i(n)$ represent the center of foot pressure data collected at the ith sample time during the nth trial for a particular subject. The data variable, $x_i(n)$, is related to the measurements as follows:

$$x_i(n) = y_i(n) - \sum_j y_j(n)/I, \qquad (1)$$

where the sum is over the index j for all times greater than 20 s and I represents the number of samples in the sum. The first 20 s of data were not used to find the mean value of x_i since initial transients, if they existed, could occur during that phase.

The ensemble average of the data, $x_i(n)$, was estimated by averaging the data across all runs at each sample time for each experimental condition and subject. The data were assumed to be from trials which were statistically independent in order to determine the standard errors.

The ensemble average variance was estimated by subtracting from each data point its previously estimated ensemble average, squaring the result, and averaging across all runs. The estimate of the ensemble average, EA, at the ith sample time is

$$\mathrm{EA}_i = \sum_n (x_i(n) - \sum_n x_i(n)/N)^2/N, \qquad (2)$$

where both sums are over all values of the trial number index n, and N represents the total number of trials.

An estimate of the time-averaged variance was found by computing the variance in the data for the last 40 s of every trial and then by averaging the results across all trials for each subject and condition. The time-averaged estimate of variance, TA, of the center of pressure data is

$$\mathrm{TA} = \sum_{in} (x_i(n))^2/IN, \qquad (3)$$

where the sum is over both the trial number index n and the point index i and the value x_i is the data point minus the mean value. The index i is summed over the last 40 s of data for each trial. The first 20 s of data were not used to estimate the time average because, as will be shown, there often are trends in that time interval.

The standard errors for the estimates of variance, which were needed for statistical tests, were computed by assuming that the process was Gaussian, by using the null hypothesis that the process was stationary and then by inserting standard time-averaged estimates of the second-order moments into the resulting theoretical expressions for the errors (Anderson, 1971).

In order to investigate further the properties of the transients in the second-order moments, each 60 s trial was divided into 24 intervals, each 2.5 s long. It was assumed that the trend in each interval could be adequately approximated by a linear function and to check this assumption, the data were fit with quadratic functions. The coefficients for each interval during each trial were estimated by a least-squares procedure and the sum of the squares about the regression were determined. The sums of squares were averaged over all trials for each interval, experimental condition, and subject.

Strictly speaking, in equation (1), the average value is not subtracted from the data, but rather an estimate of the average value. This produces an error which in turn causes a relative bias, δ^2, in the estimate of the time-averaged variance given by the following expression:

$$\delta^2 = \sum_T (1 - |T|/I)c(T)/I, \qquad (4)$$

where $c(T)$ is the correlation coefficient (Anderson, 1971, p. 463). The correlation coefficient was estimated, for each subject and each condition, using the data gathered over the last 40 s of each run. In this interval, the process was assumed to be stationary. Then using equation (4), the relative bias was calculated in order to determine if this source of error could possibly influence any of the analysis.

RESULTS

There were trends in the postural sway data for all subjects under most conditions. The ensemble-averaged data, shown in Figs 1 and 2, would be zero at all times for all subjects under all conditions if there were no trends. For anterior–posterior sway, the initial values of center of foot pressure (Fig. 1, at $t = 0$) for all subjects and all conditions are statistically different from zero (t-test, $p < 0.05$). For lateral sway (Fig. 2, at $t = 0$), only a few of the initial positions are statistically different from zero (subject A condition EO1F, and subject C condition EC2F). After the first 20 s (except the data of EC2F for subject A), the data points do not differ statistically from zero (Hotelling's T^2 test, $p < 0.05$; Afifi and Azen, 1979). These findings indicate that there are transients in the first-order moments, particularly in the anterior–posterior direction, and that these transients usually die off in the first 20 s. The ensemble-averaged variance and the time-averaged variance were, in general, not the same during the first 20 s of each run. The differences between these quantities are shown in Figs 3 and 4. If the postural sway were stationary, these two estimates of the variance should be the same. At $t = 0$, the ensemble-averaged variance is larger than the time-averaged variance for all subjects, all experimental conditions, and both directions of sway with only two exceptions: subject B, anterior–posterior sway under condition EC2F and subject A, lateral sway, condition EO1F. For the time interval 20–60 s, the hypothesis that the difference between the time average and the ensemble average was zero was investigated by a goodness-of fit test. No evidence was found for any difference between the two averages over the interval for all subjects and all conditions.

When the effects of trends were removed from the data by the regression procedure described earlier, the sum of the squared error about the regressions (Figs 5 and 6) showed the same transient effects which were found in the variance. The sum of squares of the errors were averaged over the interval 20–60 s and compared with the average of the sum of the squares determined for time $t = 0$. A statistically significant difference was found in all the same cases where, previously, time-dependent, ensemble-averaged variances had been seen.

The bias error in the estimate of the variance, which is given by equation (4), did not influence any of our conclusions. Its largest value was 10%, and it was almost always less than 5%. The source of this error is the fact that the subject stepped off the force plate between runs. Consequently, this procedure had no statistically significant effect in our analysis.

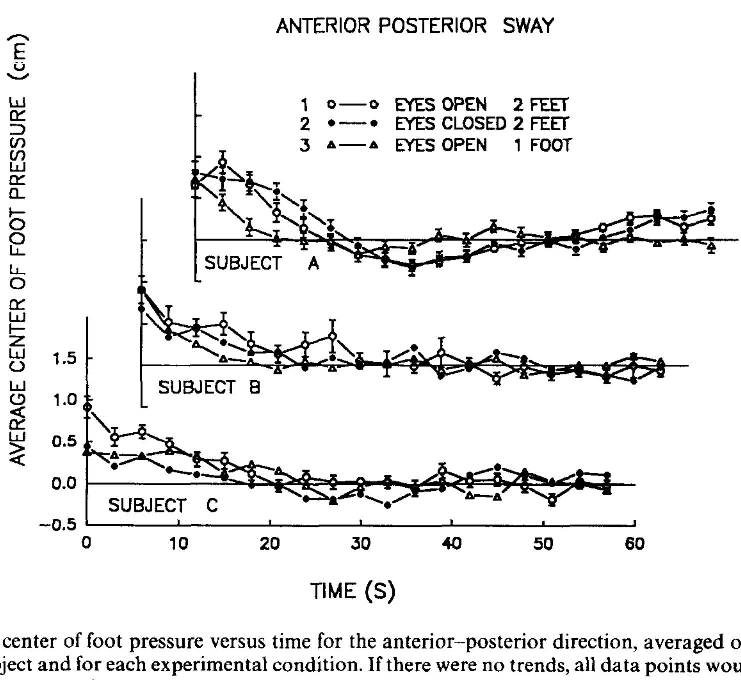

Fig. 1. The center of foot pressure versus time for the anterior–posterior direction, averaged over all runs, for each subject and for each experimental condition. If there were no trends, all data points would be within statistical variation of zero as seen e.g. in subject B after 30 s. The ordinates are the same for all graphs.

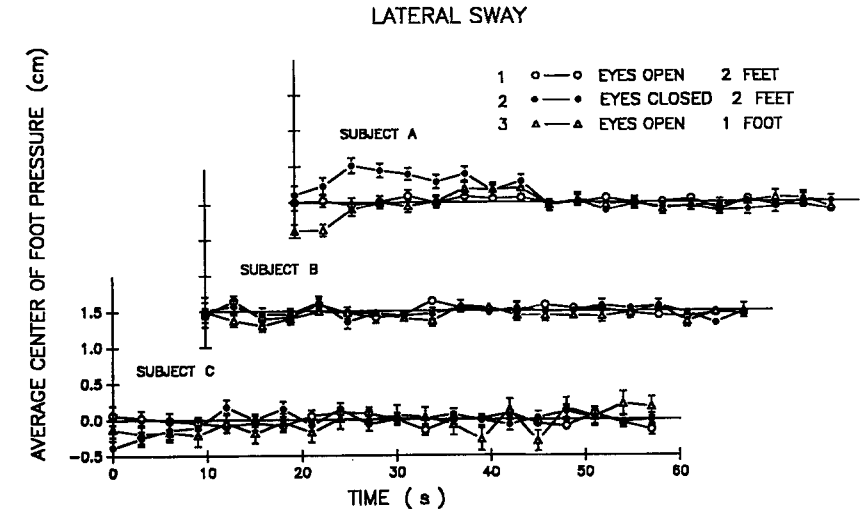

Fig. 2. The center of foot pressure for the lateral direction. The interpretation of the graphs is the same as in Fig. 1.

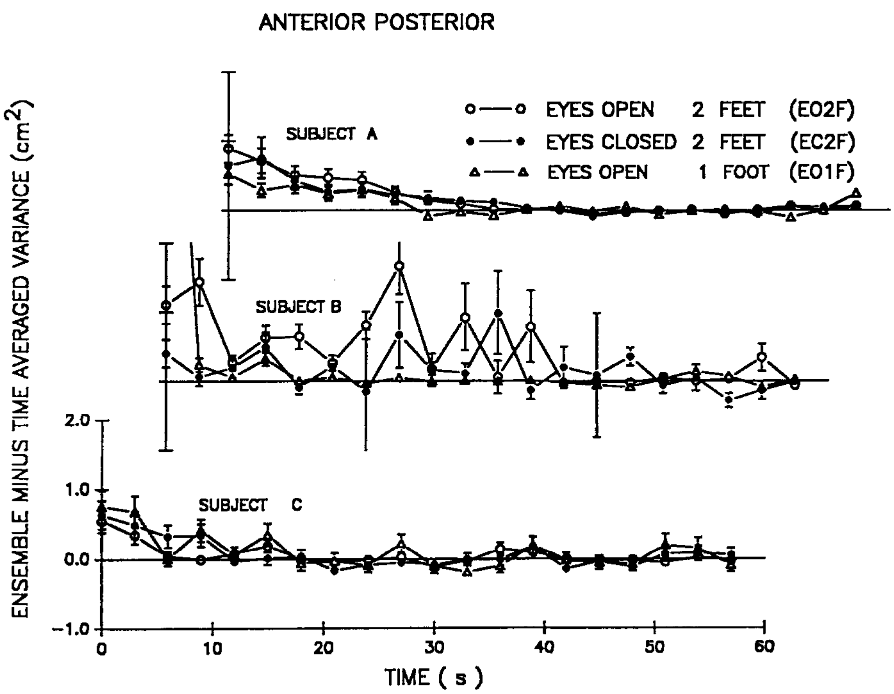

Fig. 3. The difference between the ensemble-averaged variance and the time-averaged variance for anterior–posterior sway for each subject under each experimental condition. If the second-order moments of postural sway were time-invariant, the difference would be zero for all times. Early transients can be seen for each of the subject's data by referring to the nonzero values at $t = 0$. The error bars shown indicate ± 1 S.E., where standard error is computed as the square root of the postural sway variance divided by the (degrees of freedom $- 1$). Note that the ordinates are the same for all graphs, which causes the value at $t = 0$ for subject B to be off scale for tests performed during one-foot stance.

Finally, we found no evidence that the transient effects changed over the time period of the experiment. The data collected over the first 2.5 months of experiments were compared with the data from the last 2.5 months. Each group of data was analyzed separately with the transients found to be present in each set. In addition, the data collected under condition EO1F was divided into two groups. In the first group, the 20 min of data for each subject collected during a single testing session were analyzed. The remaining

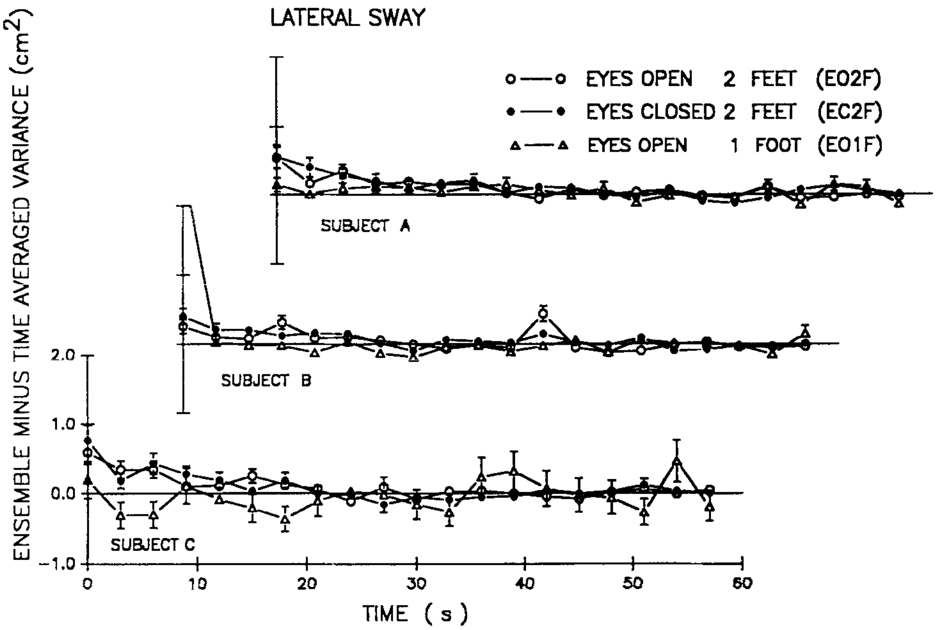

Fig. 4. The difference between the ensemble-averaged variance and the time-averaged variance for lateral sway for each subject under each experimental condition. The interpretation is the same as for Fig. 3.

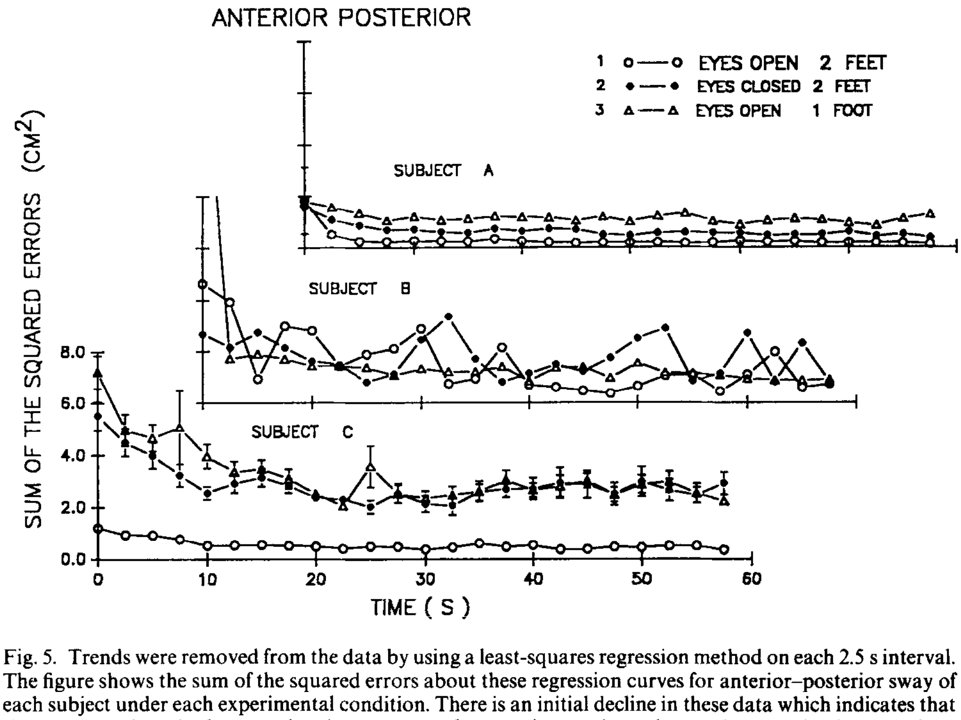

Fig. 5. Trends were removed from the data by using a least-squares regression method on each 2.5 s interval. The figure shows the sum of the squared errors about these regression curves for anterior–posterior sway of each subject under each experimental condition. There is an initial decline in these data which indicates that there are transients in the second-order moments of postural sway about the trends. Note that because these are plots of squared error, the curves do not tend to go to the abscissa as the time progresses.

51 min of data were analyzed separately and, once again, similar transients were found for each grouping of data.

DISCUSSION

The center of foot pressure (COP) is used in clinical and research settings as a measure of a person's ability to maintain upright posture. In the analysis of these measurements, postural sway is inevitably assumed to be a stationary, stochastic process. We have shown that this is not true, in general, by demonstrating that there were initial transients in the first- and second-order moments of the postural sway of three subjects. Of course, this does not imply that similar transients exist in all measurements of postural sway, but it does

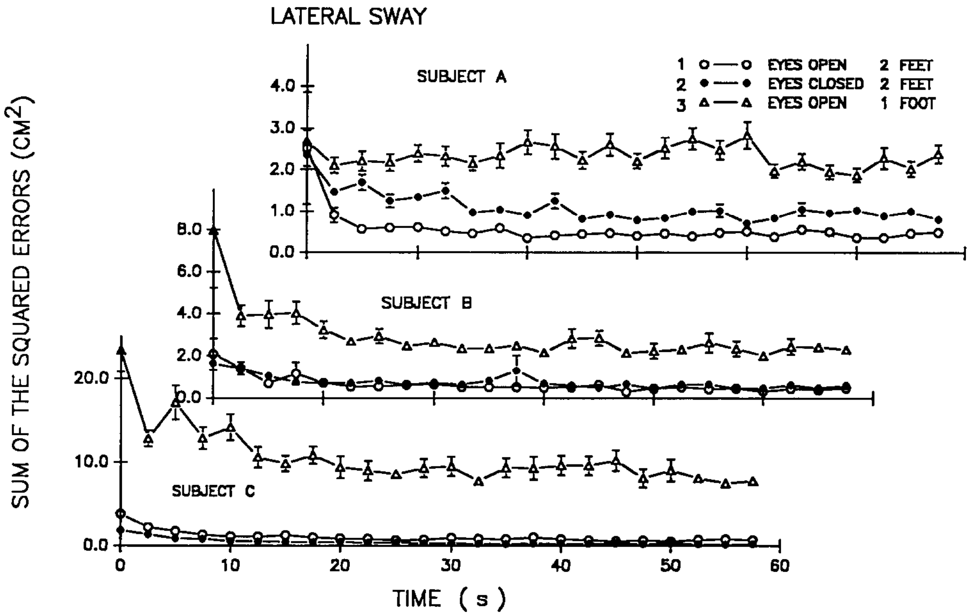

Fig. 6. The sum of the squared errors about the regressions for lateral sway. The interpretation of the data is the same as in Fig. 5.

imply that the interpretation of postural sway data must be done with greater care because of the potential of transients.

There is a wide variety of methods used in the literature (Association Francais de Posturologie, 1986; Hufschmidt *et al.*, 1980) to parameterize postural sway data. Some are straightforward, such as root-mean-square value of the calculated center of foot pressure (Paulus *et al.* 1984). Other statistics appear to be unique to this application, such as path length, i. e. arc length of the locus of center of foot pressure over time (Diener *et al.*, 1984 ; Norre *et al.*, 1987a, b) or sway area, i. e. area swept out by a line joining the origin to the center of foot pressure. Also, postural sway has been analyzed using parametric (Amblard *et al.*, 1985; Anderson *et al.*, 1986; Brauer and Seidel, 1978; Brauer and Seidel 1979 Dichgans *et al.*, 1976; Kodde *et al.*, 1982; Nashner 1970; Peters *et al.*, 1985; Seidel *et al.*, 1978) and nonparametric procedures (Brauer and Seidel, 1980; Ishida and Imai, 1980; Johanson *et al.*, 1988; Maki *et al.*, 1987; Werness and Anderson, 1984).

For each of these approaches, the potential for transients presents a serious problem. Statistics, such as variance or path length, measured during the first 20 s may be very different from the same parameters determined from the data measured during the second 20 s. The definition of the power spectrum assumes that the process is stationary. Similarly, autoregressive techniques are based on the assumption of a stationary process (Kay, 1988, p. 3).

There are several possible solutions to these problems. Investigators could continue to analyze postural sway data with standard statistical parameters provided they modify slightly the interpretation of the results. For example, they can always apply the standard formula for the estimator of variance to the data, even during the first 20 s of measurement. If transients are present, this statistic is not a good estimator of variance but, nevertheless, it is still an estimator of some statistical property of postural sway. In some applications, this may be good enough. However, there are several significant drawbacks of this approach. First, the statistic will depend on the duration of measurement even if all other variables are held constant. Second, if transients are included in the data analysis, the initial conditions must be controlled so that the results can be made as reproducible as possible. Unfortunately, the procedure to accomplish this is not apparent; it will require further study of the transients. Third, because there are so many factors which can potentially influence the transients, a comparison of results between different experimental paradigms may be very difficult. Fourth, the standard estimators used in the analysis of postural sway have simple interpretations when the process is stationary, but when transients occur, their interpretations become complex. These complications may obscure simple relationships.

Another method of analyzing postural sway data, in view of the results, is to ignore the first 20 s of data. After this period of time, any transients should have died out, and the process should then be stationary. The usual statistical procedures are then applicable. While this approach is conceptually straightforward, it does have its share of difficulties. First, we have not established that all transients die out after 20 s; we have only shown that it is approximately true in three normal subjects. In fact, for one subject, we did find small, but, nevertheless, statistically significant, trends beyond 20 s (W-F, Fig. 1). Second, the first 20 s of data contain valuable information which would be lost with this procedure. Third, even if we ignored the first 20 s of data, there still may be subtle but important biases in the statistical estimators. For example, we have already discussed the error in estimating the average center of foot pressure and the effect of this error on the estimate of variance. For the data presented, in which we sampled for 60 s during each trial, this error was small. However, if data are sampled for 30 s in each trial, which is frequently done for postural sway measurements, the bias error due to foot placement would become very large if the first 20 s of data were dropped.

Another possible alternative would be to remove the trends from the data by methods such as those of Box and Jenkins (1976). However, by doing this, important information about postural sway may be ignored. But more importantly, we have shown earlier that when the trends are removed from the data, there are still transients in the second-order moments. Consequently, stationary methods of analysis still cannot be used.

The methods for analyzing postural sway data discussed so far are not completely satisfactory because each one attempts to hide or ignore the effects of the transients which we have found. To find an appropriate method of analysis, the transients must be incorporated into the data analysis. Because only three subjects were used in this experiment, we cannot draw any conclusions about the frequency or nature of these transients in the general population. However, we did find a remarkably similar pattern in the transients for all three of our subjects, which does provide some clues to the nature of these transients.

For the subjects in this experiment, there was a tendency for the average center of foot pressure to move slightly forward over the first 20 s of a trial. This may be due to the fact that our subjects mounted the force platform from the rear. Or perhaps there was a strategy involved in which it was easier to position the body for standing if more of the body weight was supported by the heel rather than the ball of the foot. And after the initial period, it may have become more efficient for the postural system to support the weight more anteriorly. Since we used only three subjects and since each of our subjects always mounted the force plate from the rear, we cannot conclude that this anteriorly directed transient is at all common. However, our data do raise the possibility that there are transient, systematic changes in body orientation at the beginning of a period of standing which are part of a strategy of the postural system for the transition from movement to standing.

There was also a significant reduction in the ensemble-averaged variance over the first 20 s (Figs 3 and 4). This may be due to the variability in the initial conditions. From an analysis of the trends, we have already suggested that the subjects initially positioned their weight towards their heels. Most likely, the subjects will not initially position their bodies in exactly the same way before each run. This variability in the initial position will produce a transient in the ensembled-averaged variance, as we found in the data. However, this cannot account for the complete effect. We determined the trends for each individual trial by regression analysis. Variations in the initial conditions can account for differences in regression curves from one trial to the next, but they will have no effect on the variation of data about each individual regression curve. We found transients in the residual error of these regression curves. This result shows that the postural system of our subjects is not as effective at stabilizing postural position initially as it is 20 s later. The explanation for this transient is not obvious. It may indicate delays in the feedback loops controlling posture, or it may just indicate that the initial position of the body, with the COP shifted posteriorly, is inherently more unstable than the final body position.

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