

Postural Disequilibrium Quantification In Children with Chronic Lead Exposure: A Pilot Study

A. BHATTACHARYA¹, R. SHUKLA¹, R. BORNSCHEIN¹, K. DIETRICH¹
AND J. E. KOPKE²

¹Department of Environmental Health, University of Cincinnati, Medical School, Cincinnati, Ohio 45267 and ²Medical Computer Services, University of Cincinnati, Cincinnati, Ohio 45267

ABSTRACT: Previous studies reported that some children who survive acute lead encephalopathy suffer from ataxia and have difficulties maintaining postural equilibrium. More recent studies have failed to quantify postural imbalance in association with lower levels of lead exposures, perhaps due to the insensitivity of the clinical measure. In our study, we noninvasively measured postural disequilibrium with a microprocessor-based force platform. The test provides a real time quantification of the body's center of gravity movement pattern. Measurements were made in a cohort of 33 inner city children (mean age: six years \pm 0.4 SD) with well documented blood lead histories. The average maximum blood lead of these children during their first six years of life was 23.5 μ g/dl (range = 8.5 to 49.4). The children performed four postural tests [i.e., standing eyes open (EO) and closed (EC), on firm surface and standing on a compliant foam surface with eyes open (FO) and closed (FC)]. The results indicated that the maximum blood lead incurred during the second year of life was significantly positively related to postural sway, and the body balance was most affected in the EC test where visual cues were eliminated and proprioceptive feedback was not modified. Fetal Pb exposure levels as well as Pb exposures during the first year of life were not correlated with postural sway of six year olds. However, the maximum blood lead concentration beyond two years of life was significantly associated with the postural sway at six years of age.

Key Words: Postural Sway, Force Platform, Lead Exposure, Quantitative Stabilography, Noninvasive Measurement, Children

INTRODUCTION

Previous studies suggest that deficits in the central nervous system (CNS) function (particularly as measured by IQ tests) are present in children with blood lead over 40 μ g/dl. Pueschel *et al.*, (1972) found mild CNS effects such as clumsiness and irritability at

blood lead levels over 50 μ g/dl. Minor neurological dysfunction and various forms of motor impairment were found by elaborate motor testing in about 25% of the 59 children tested. In addition, de la Burde and Choate (1975) showed that a group of 70 selected four year old children, asymptomatic for lead poisoning but with elevated blood lead level

(mean value 58 $\mu\text{g}/\text{dl}$) or a lead level of at least 30 $\mu\text{g}/\text{dl}$ with positive radiographic findings of lead lines in long bones, had deficits in fine motor function and behavior. Follow up of most of these children at age 7 years showed persistent impairment in behavior and fine motor coordination as well as deficits in global IQ. These studies implied that, at blood levels higher than 40 $\mu\text{g}/\text{dl}$, adverse health effects may occur, but no correlation was found between minimal motor effects for a particular level of blood lead concentration. Recent studies by Hawk *et al.*, (1986) have shown a significant inverse relationship between lower lead levels (mean: 20.8 $\mu\text{g}/\text{dl}$) and Stanford-Binet IQ in a group of 80 three to seven year old children. In summary, while these studies imply an association between lead exposure and neuro-cognitive development, we lack quantitative data on the relationship between lead exposure and neuromotor development.

In the present study, we investigated the association of the neuromotor developmental status and blood lead of lead-exposed children with a new technique. This technique measures human body sway associated with upright posture which is the most common neuromotor function a person has to perform on a daily basis. The control of body balance requires processing of afferent signals from various receptor organs (proprioceptors, vision, cutaneous and vestibular apparatus), both at spinal and supraspinal levels, the resulting efferents having influence from higher level cortical centers. Since previous studies (Goyer *et al.*, 1982) have shown that lead can affect both peripheral and central nervous systems (including direct loss of neurons), it is postulated that lead-exposed children will show modified postural balance characteristics, and, therefore, the measurement of body sway would provide insight into the developmental status of a child's CNS. The proposed technique utilizes a microprocessor-based Biomechanics Force Platform for the quantification of human body sway, i.e., movement pattern of center of gravity of the body. We have found this technique to be effective in identifying subtle (or low dose) changes in body sway under exposure to low levels of a reference CNS perturber such as ethanol in adult subjects (Bhattacharya *et al.*, 1987). The technique is simple, rapid (testing period is 2 min.), noninvasive, objective and

provides a hard copy of the quantitative "picture" of the movement pattern of the subjects' center of gravity. Unlike many other established techniques for neuromotor evaluation, the force platform test can be administered without much prior training of the subject, and the results are independent of the tester's subjective scoring capability.

The primary focii of this study were to evaluate the use of the force platform technique (Bhattacharya *et al.*, 1987) for quantifying postural equilibrium in the Cincinnati Lead Program Project cohort children, aged five to six years, and to explore if an association exists between postural sway and children's blood lead levels. Furthermore, this test was also conducted to determine whether or not children as young as five years of age can be effectively instructed to perform the task and to examine the reliability of the scores via the repeated test experience.

METHODS

Subject

The subjects for the present study were obtained from the Cincinnati Lead Program Project cohort children. For this pilot study, a total of 33 children with a mean age of 6.0 ± 0.4 SD were tested. Two of the 33 children tested were clinically diagnosed at birth as exhibiting fetal alcohol syndrome. Data from these children were used only as a positive control. For the remaining analyses, data from these children were excluded. The mothers of the Cincinnati Lead Study subjects were recruited prenatally from the local prenatal clinics which serve the recruitment area (a large portion of Cincinnati's urban center where elevated blood lead levels in children have been historically common according to the Cincinnati Lead Registry data). Mothers who were diabetic, alcoholic, confirmed drug users, psychotic or mentally retarded were excluded from the study. Also, neonates with genetic syndromes or serious medical conditions were excluded. The follow-up studies included frequent complete medical checkups, blood lead levels (every three months), standardized neurocognitive and neuromotor test batteries, etc. For comparison of sway data with those obtained from standardized neuromotor and

neurocognitive tests, the data from the Bruininks-Oseretsky Test of Motor Proficiency and the Kaufman Assessment Battery, respectively, were used.

Maternal (prenatal) blood samples were collected by venipuncture at the first prenatal clinic visit. Quarterly postnatal blood samples were also obtained via venipuncture except in young infants, where fingersticks or heel sticks were more frequently used. Prenatal blood samples were analyzed using an ESA Model 2014 Anodic Stripping Voltammeter, while a Model 3010 was used for postnatal blood samples. Details of the micro-analytic procedures as well as the laboratory's quality control and quality assurance program have been described previously (Roda *et al.*, 1987).

The Kaufman Assessment Battery for Children (Kaufman and Kaufman, 1983) was administered to 29 of the 33 children in this study when they were five years of age, while the Bruininks-Oseretsky Test of Motor Performance (Bruininks, 1978) was administered to 22 of these children at six years of age.

The Bruininks-Oseretsky Test of Motor Proficiency is an exhaustive neuromotor examination which includes subtests of balance bilateral coordination, upper-limb coordination,

strength, visual-motor control, upper-limb speed and dexterity, and fine-motor coordination. This assessment is scheduled to take place when Cincinnati Lead Study children are six years of age, so only a small number of subjects ($n = 22$) have been examined thus far.

The Kaufman Assessment is based on theories of cognitive performance posed by cognitive developmental researchers and neuropsychologists (e.g., Luria, 1973; Das *et al.*, 1975; Das, 1984; Kaufman *et al.*, 1982). The test consists of a Sequential Processing Scale (problems must be solved by mentally arranging input in a sequential or temporal order), Simultaneous Processing Scale (problems must be solved using holistic or gestalt-like approaches to integrate many separate stimuli), Mental Processing Composite (a combination of sequential and simultaneous processing scales), and an Achievement Scale (acquired facts and academic skills).

Instrumentation

For the measurement of postural sway, a strain gauge-type, high frequency response (400 Hz), six-component force platform was utilized (Model OR6-3, Advanced Mechanical

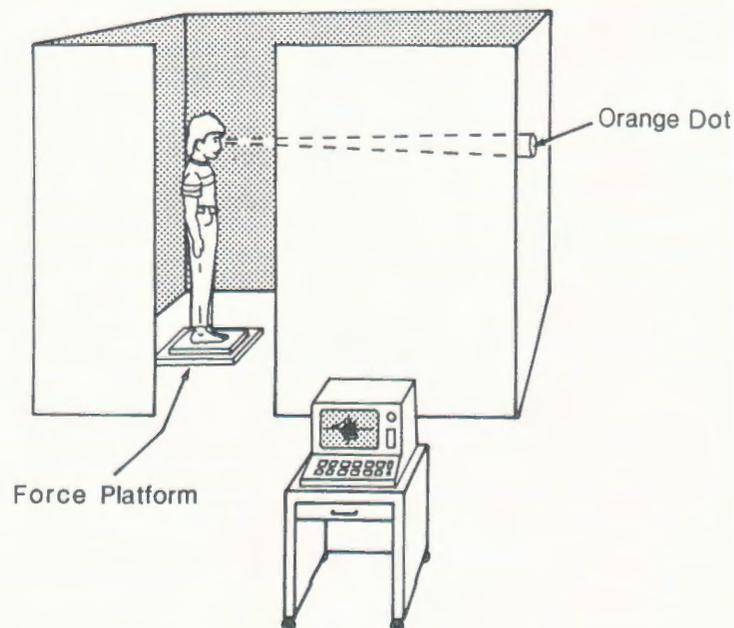


FIG. 1. Schematic of postural sway test on a child.

Technology, Inc., Newton, MA). This platform has the capability of measuring forces in three orthogonal axes (F_x , F_y and F_z) as well as moments (M_x , M_y and M_z) around them. The force platform was calibrated as per our previous work (Bhattacharya *et al.*, 1987). The outputs from F_x , F_y , F_z , M_x , M_y and M_z channels of the force platform recorded were used for the calculation of location (x_p , y_p) of the center of pressure (CP) of the subject on the horizontal plane. Appropriate equations developed in Bhattacharya *et al.*, (1987) were used for this calculation. Our analysis for the calculation of x_p and y_p does not neglect the effect of horizontal forces which are significant in children.

In our previous publication (Bhattacharya *et al.*, 1987), we have established the validity and measurement accuracy of the force platform technique. The measurement error for x_p and y_p were 2.3% and 4.4%, respectively, and the corresponding error for the radius of sway R ($=\sqrt{x_p^2 + y_p^2}$) was 2.1%.

Protocol

All subjects' parents/guardians provided a signed informed consent before initiating the test protocol. On the day of the test, each subject's middle ear pressure was measured with a standard tympanometry method, and a health history was also taken. This information allowed us to rule out possible presence of acute ear infection which might affect sway data. For the postural sway measurements, the subjects stood in the middle of the force platform without shoes and with their heels together. They were asked to stand relaxed without moving their feet and head and to concentrate on an orange dot placed on the facing wall (see Fig. 1). The following four postural tasks were recorded for analysis.

EO: Eyes open on force platform for 30 seconds.

EC: Eyes closed on force platform for 30 seconds.

FO: Eyes open on foam placed on force platform for 30 seconds.

FC: Eyes closed on foam placed on force platform for 30 seconds.

The foam height was 7.3 cm. All four postural tasks (EO, EC, FO and FC) were then repeated in the reverse order (FC, FO, EC and

EO) for each subject. The four postural tasks are designed to provide an indirect challenge to some of the afferents pertinent to the maintenance of upright balance (Bhattacharya *et al.*, 1987). Fourteen out of 33 children were retested after a six-month period in order to determine the stability and reproducibility of postural sway over a prolonged period.

The postural sway data were sampled at 30 Hz by a Zenith 241 microcomputer connected to the force platform via a analog-to-digital converter board (DASH-16 Model, Metrabyte, Inc.). Immediately after the test, the raw data from the force platform were presented as a graph on the computer screen. This feature allowed the investigator to instantly review the raw data to identify any extraneous body movements (e.g., head movement, head scratching, foot stomping, etc.) which might affect the sway data analysis. The experimenter was also able to view the subject continuously during test intervals. If voluntary movements were excessive, the trial was repeated. This was a very infrequent incident. The collected data were recalled later for offline processing using our custom-developed software package (written in the fourth generation ASYST™ language) for characterizing the postural sway patterns. These parameters were then automatically stored in a new processed file on the computer hard drive. The investigator was blind to the lead exposure status of the subjects. During the processing of the raw data from the sway test, the investigator was given the opportunity to analyze any part of the 30-second data segment or the entire 30-second segment of the collected data. Furthermore, at appropriate stages of the processing, the operator could also request printer or plotter output of stabilographs (for example, see Figs. 2 and 3). After all the files are processed, the operator directly uploaded the processed data (i.e., all calculated sway parameters) via modem to the University of Cincinnati's AMDAHL main frame computer for future statistical analysis. Such an automation allowed elimination of key punching thousands of data points and the possibility of human error.

The location of the CP for each subject was first calculated with respect to the center of the platform. Next, a mean value of location of CP was calculated for each test period. This

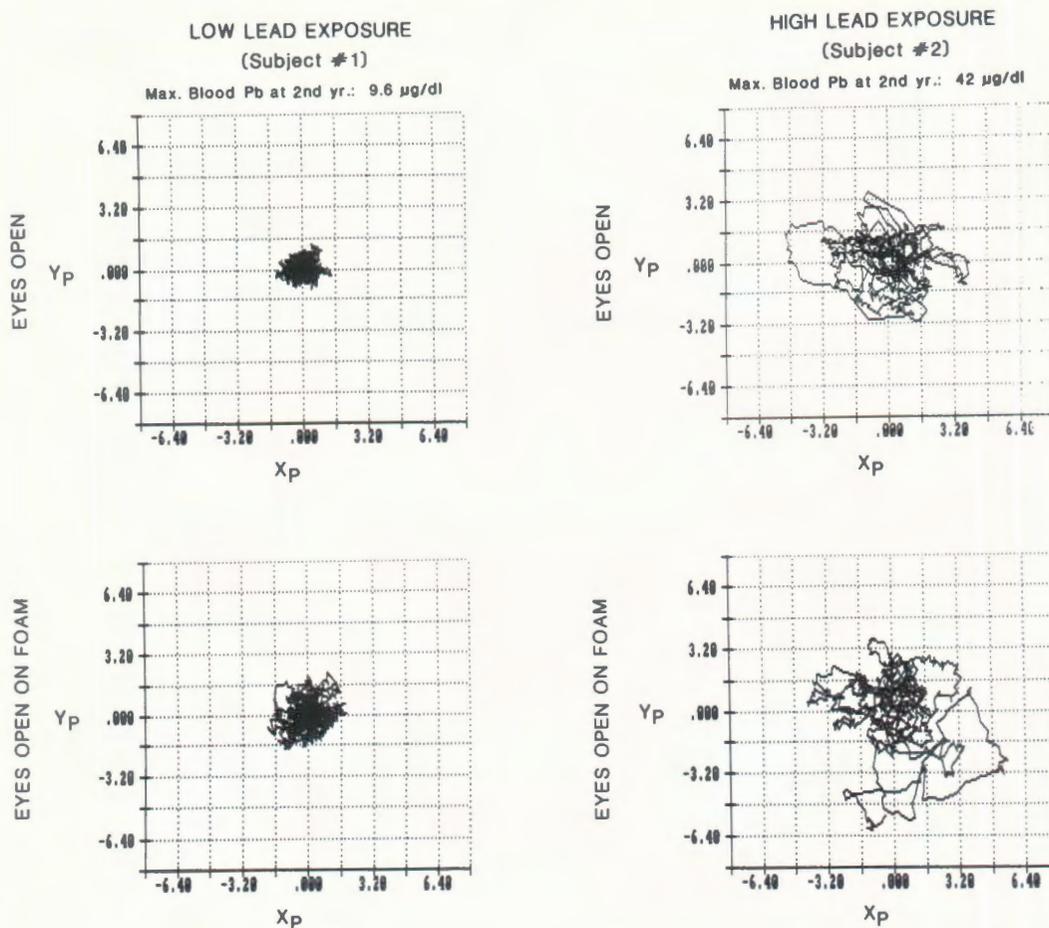


FIG. 2. Stabilograms obtained during postural sway tests of eyes open on firm and compliant surfaces.

mean value was then used as the new origin or reference for the calculation of mean radius of sway and maximum radius of sway. Such analysis procedure was used to overcome the effect of change in feet location with respect to the platform center from test to test on the location of the CP.

The parameters used to characterize the postural sway were: (1) the area of the projection of the body's CP on the xy plane due to sway (A); (2) the mean radial deflection of sway with respect to the mean value of xy coordinates of the CP for the test period (R_{mean}); (3) the maximum radial deflection of sway (R_{max}), (4) directions of R_{mean} and R_{max} ; (5) total length of sway; (6) mean velocity of sway; (7) maximum velocity of sway; and (8) parameters of frequency analysis of anterior-posterior (y_p) sway and lateral sway

(x_p).

The customized software developed by us calculated these values and provided us with a hard copy. In the present study, only the results of the sway area are presented as an indicator of postural balance performance. From our previous study (Bhattacharya *et al.*, 1987), it was determined that the sway area is one of the more reliable parameters for characterizing the postural sway. For analysis purposes, the total area was transformed to natural logarithmic units. The sensitivity of other sway parameters is currently being evaluated and will require further testing with a larger subject population. Standard statistical techniques such as Pearson Bivariate Correlation, Regression Analysis and Analysis of Covariance (ANCOVA) were used for analyzing the collected data.

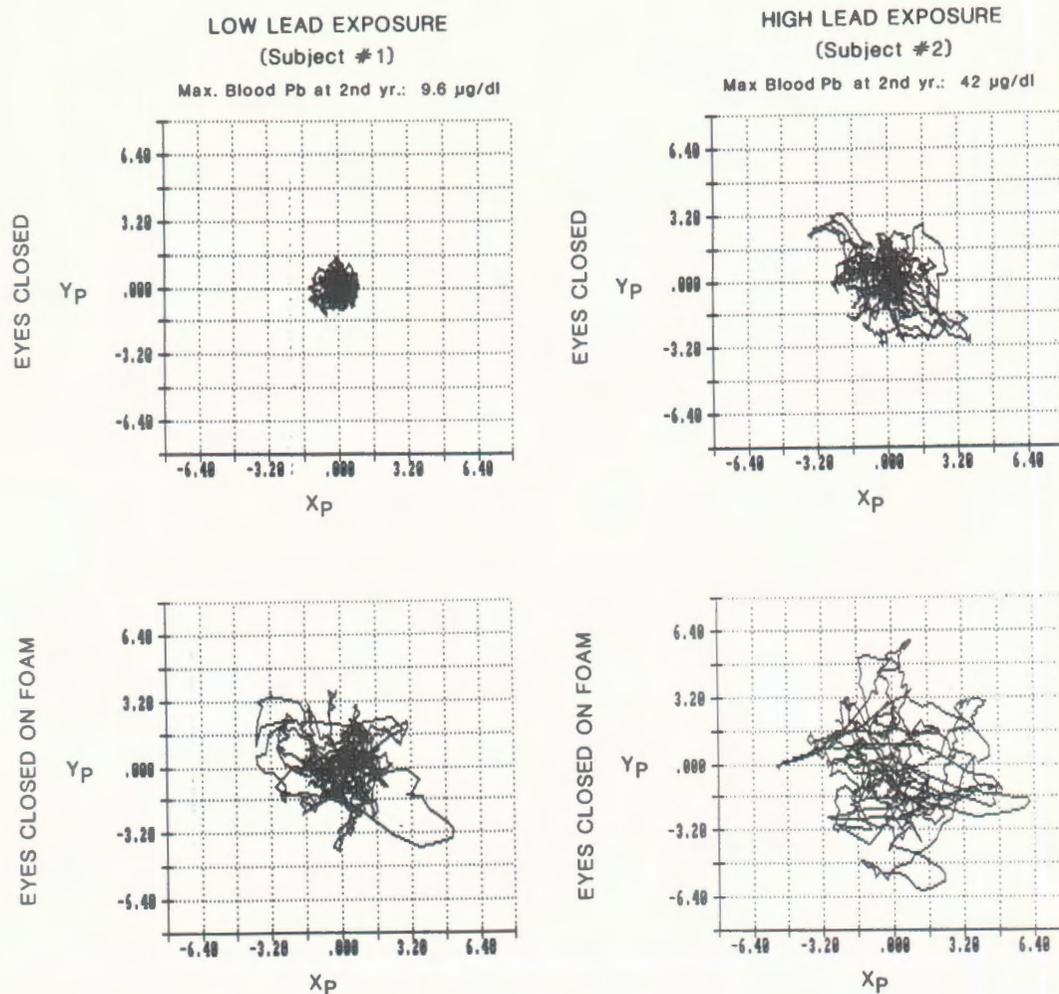


FIG. 3. Stabilograms obtained during postural sway tests of eyes closed on firm and compliant surfaces.

RESULTS

Table 1 gives the descriptive statistics for the demographic data and maximum blood lead history. The results from this study indicated that the force platform technique developed for the adults (Bhattacharya *et al.*, 1987) can also produce significant graded levels of challenge to various afferents in a population of children by exposing them to four postural tasks via EO, EC, FO, and FC. This is illustrated in Figs. 2 and 3 where the stabilograms (x - y plots of the center of pressure) from two children [one (Subject #2) with a higher level of blood lead than Subject #1] are presented.

The results from Subject #3 (Table 2) illustrate the combined effect of lead exposure

and residual effect of fetal alcohol toxicity on postural disequilibrium. In these three subjects as the vision and proprioception were removed and modified in the EC, FO and FC tasks, respectively, the body balancing task became gradually more difficult as depicted in an increase in the postural sway area parameter. The most challenging task was the FC condition when the vision was removed and the standing support system was compliant. For this condition, the vestibular system was most challenged and primarily responsible for postural control. A qualitative comparison of stabilograms between a high lead and a low lead exposed child clearly illustrates that for four postural tasks, the high lead child's (Subject #2) sway was larger and more erratic

TABLE 1a. Descriptive Statistics: Demographic Data.

Parameters	Value (X ± SD)
Age (years)	6 ± 0.4
Birth weight (gm)	3030.9 ± 547
Birth length (cm)	48.4 ± 3.0
Sex	46% males
Number of subjects	31
Middle ear pressure (mm H ₂ O)	-75.0 ± 92.0*

* Anything less than -150 mm H₂O is considered indicative of eustachian tube dysfunction.

TABLE 1b. Descriptive Statistics: Maximum Blood Lead Values.

Time of Blood Lead Measurement	Mean ± SD* µg/dl	Minimum Value µg/dl	Maximum Value µg/dl
Prenatal	9.92 ± 3.9	5.6	22.1
1st year of life	21.3 ± 8.2	9.0	39.0
2nd year of life	25.6 ± 12.2	9.3	49.4
3rd year of life	22.2 ± 9.7	9.7	47.4
4th year of life	20.4 ± 9.0	8.6	42.6
5th year of life	17.9 ± 7.4	8.5	36.4

*Average across subjects of the maximum lead recorded for each child in each of the five years (four measures per child per year).

than that observed for the child with lower lead levels (Subject #1) (see Figs. 2 and 3). A quantitative comparison of sway between Subjects #1 and #2 as depicted by one of the sway parameters (e.g., sway area) indicates substantial increases in body sway areas for all tasks (see Table 2).

The stabilograms of the fetal alcohol syndrome child (Subject #3) were also very erratic in nature for all the tests. However, a point of interest in this subject's data is the fact that he repeatedly failed to stand upright during the FC test when the vision was removed while standing on a compliant surface (foam). During this test, the subject needed

help to prevent a fall. In Fig. 4, the stabilogram obtained with the help of our customized software from the fetal alcohol syndrome child is presented. On the right-hand side of the stabilogram in Fig. 4, various parameters are listed which are designed to quantitate a stabilogram. A tightly enclosed sway pattern is indicative of a stable postural stabilogram.

Fig. 5 shows the response of sway area of the children to the four postural tasks and how they compare to those obtained from a nonexposed adult study performed earlier by us (Bhattacharya *et al.*, 1987). For all postural test conditions, the mean values of sway areas

TABLE 2. Illustrative Examples of Children's Postural Sway Area Values.

Subject	Postural Sway Area (cm ²)			
	Firm Surface (No Foam)		Compliant Surface (On Foam)	
	Eyes Open	Eyes Closed	Eyes Open	Eyes Closed
1	3.27	3.86	8.80	26.20
2	22.70	23.30	40.60	47.60
3	6.0	10.00	24.40	49.65*

* Lost balance (likely to be an underestimate of true sway area).

of the children (mean age: six years) were significantly higher than those of adults (mean age: 26 years), although some low lead exposed children approached adult levels of sway performance.

Effect of Test and Retest

The four postural tasks (EO, EC, FO and FC) were repeated once for each child during a testing session. The first sequence of four postural tasks were termed Trial 1 and the repeat test which was conducted in the reverse order (FC, FO, EC and EO) was termed Trial 2. Most of the sway parameters showed good

reproducibility. The bivariate correlation coefficients (r) between Trial 1 and Trial 2 were 0.50, 0.70, 0.72, 0.78 for EO, EC, FO and FC, respectively. The mean difference (0.02) between Trial 1 and Trial 2 was not different than zero ($p = 0.80$). The average score obtained on both trials was used to provide a more reliable estimate.

In addition to retesting within a test session, 14 subjects were retested six months later. This retesting was conducted to determine the stability and reproducibility of postural sway over a more extended interval. Both bivariate correlations and regression analysis were used to investigate this issue. The results show that the correlations between

STABILOGRAMS OBTAINED DURING POSTURAL EQUILIBRIUM TEST

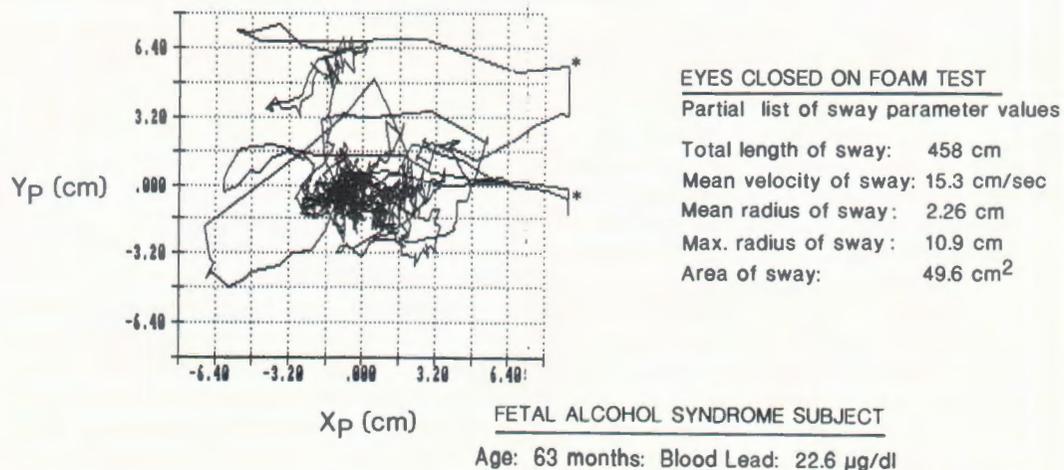


FIG. 4. Stabilogram obtained from a child fetal alcohol syndrome subject. *(Subject needed help to prevent a fall).

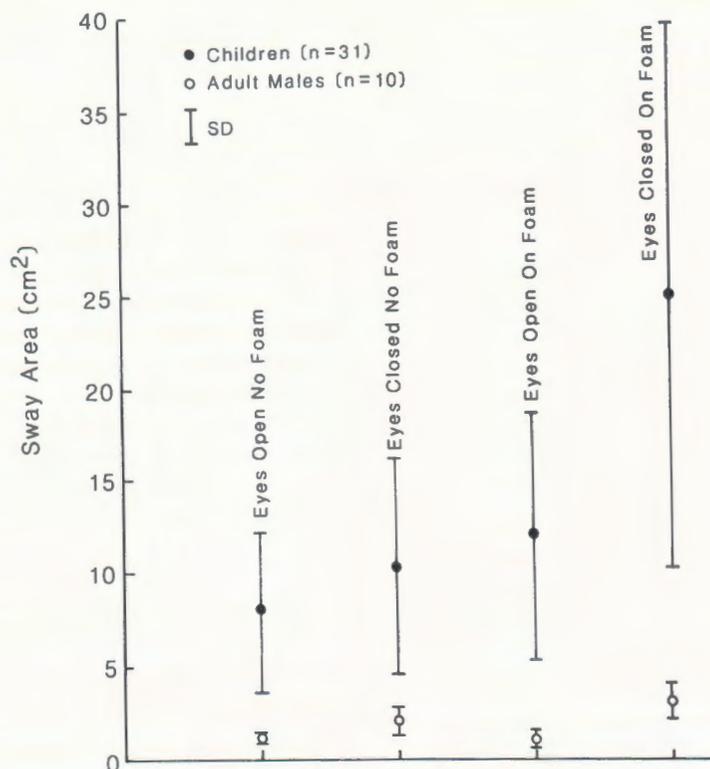


FIG. 5. Postural sway area of children in the present study compared to those from adult subjects.

Test 1 and Test 2 (performed six months later) were generally good. For example, the bivariate correlation coefficients (r) were 0.78 ($p = 0.0008$), 0.58 (0.03), 0.69 (0.006) and 0.72 (0.004) for EO, EC, FO and FC test conditions, respectively.

Bivariate Relationship Between Sway and Maximum Blood Lead

A Pearson bivariate correlation analysis was performed to determine the relationship between sway parameters and maximum blood lead for prenatal, first year, second year, third year, fourth year and fifth year of life. This analysis was performed for all the postural tasks (i.e., EO, EC, FO and FC). The eyes closed, no foam task (EC) produced most of the significant ($P < 0.05$) correlations (Table 3). Other parameters such as age, sex, height and body weight did not show any significant correlations with sway parameters. The middle ear pressure was not correlated with sway area

and maximum blood lead. For the eyes closed - on foam condition, the sway area was marginally correlated ($r = 0.32$; $p = 0.08$) with middle ear pressure. In Table 3, it can be observed that most of the significant correlations were obtained with maximum second year blood lead and maximum fifth year blood lead. These correlations were highest for the maximum second year blood lead. It is to be noted here that the blood lead usually attains its maximum value during the second year of life (see Table I), and there was a correlation between the second year blood lead and the fifth year blood lead.

Regression Analysis of Sway Area Response and Maximum Blood Lead

The objective of this analysis was to investigate the effect of maximum blood lead on sway after adjusting for the maximum blood lead during the previous year and the middle ear pressure. The model used was:

We determined the effect of task conditions using analysis of covariance (ANCOVA), with a pair-wise multiple comparison of least squares means between the tasks. The model used for ANCOVA was:

Postural Sway (e.g., sway area) = max blood lead + postural task condition

The objective of this analysis was to determine if various postural task conditions or afferents when modified produced significant changes in body sway after adjusting for the effect of the covariate, i.e., maximum blood lead. Other covariates such as age, sex, body weight, height and middle ear pressure were not found to correlate with body sway although this could be due to the small sample size in this pilot study. The homogeneity of "slopes" or estimates between maximum blood lead levels and sway area was assessed by interaction between blood lead levels and postural task conditions; no significant interaction was found. This justified the use of ANCOVA.

It was found that the sway area in the FC condition was significantly higher ($p = 0.0001$) than that obtained for the FO test condition. On the other hand, the sway area values were not significantly different ($p = 0.27$) between EO and EC conditions. Furthermore, the sway responses were also not different between EO and FO conditions ($p = 0.08$), while significant differences existed when comparisons were made between FC and EC ($p = 0.0001$) and between EO and FC ($p = 0.0001$).

Comparison Between Postural Sway and Standard Measures of Neurocognitive and Neuromotor Functions

The Bruininks-Oseretsky Balance Subtest was significantly ($p < 0.05$) and inversely correlated with the sway area (Table 4) as well as other sway parameters such as maximum velocity, mean radius, and direction of mean radius under the EO, FO and FC conditions. Bilateral coordination, strength, upper-limb coordination were also inversely associated with sway parameters, although at a somewhat lower significance level.

The Kaufman Mental Processing Composite was significantly ($p < 0.05$) and inversely correlated with a variety of sway

TABLE 4. Bivariate Correlation Between Sway Parameters and the Bruininks-Oseretsky Balance Subtest. Bruininks-Oseretsky Balance Subtest Versus Sway Area.

Test Condition	Correlation Coefficient (p value)
Eyes Open, No Foam	-0.56 (0.003)
Eyes Closed, No Foam	-0.16 (0.23)
Eyes Open, On Foam	-0.44 (0.02)
Eyes Closed, On Foam	-0.5 (0.005)

parameters (e.g., total length, mean velocity, etc.; r values ranged between -0.34 and -0.53) under all test conditions (EO, EC, FO and FC). However, no significant correlation with sway area was found. Further, Kaufman Achievement Scale scores were significantly and inversely correlated (r ranged between -0.34 and -0.49) with a variety of sway parameters of interest under all testing conditions except sway area which showed correlations for the EO condition only.

DISCUSSION

This study demonstrated that the measurement of postural sway with a force platform technique can be effectively made in children five to six years of age. The test-retest evaluations, both during the test day (Trial 1 and Trial 2) and after a six-month period (Test 1 and Test 2), produced quite stable sway data. The results from six months of retesting in our small population indicated that individual differences in sway performance was relatively stable over this period of time. Additional testing with more subjects will allow us to determine the extent of developmental change in postural control in this cohort.

While the data from retesting showed acceptable results for EO, EC and FO, the task of eyes closed on foam (FC) produced somewhat poorer reproducibility, implying

that this condition is probably too difficult and less reliable with children of this age. It is possible that 7.3 cm high foam might be producing both the intended modification of proprioception as well as pure mechanical instability of the standing surface. We are currently exploring some other heights of foam which we believe will help improve the test-retest reproducibility of the FC test.

In Fig. 5, it can be seen that the variation in the children's sway area was quite large. The coefficient of variation ranged between 54.2% and 58.8% for all test conditions. In comparison, the coefficient of variation in our previous adult study ranged between 25.7% and 38.6%. The finding of the large between-subject variability in our study substantiates the results of Riach and Hayes (1987). They reported that these large variations were not readily explainable by differences in physical stature, sex and body weight. Also, in our analysis, there were no significant effect of the covariates, such as sex, body weight and stature on sway. This variability could very well be associated with individual differences in maturation of components of postural control processes. For example, Ornitz et al. (1979) have indicated that even though the vestibular system is both anatomically and functionally responsive at or before birth, the most significant maturational changes occur in pre-school age children.

There was a significant relationship between the maximum blood lead at the second year of life and the sway area. This suggests that either the timing of the exposure and/or the level of exposure are critical determinants of impaired postural stability. Since we measured sway at five years of age (not two years of age), the correlation analysis was redone after controlling for the effect of first year blood lead as well as for the fifth year blood lead. Even after controlling for these factors, a significant correlation still existed. Therefore, the results suggest a residual detrimental effect from the second year carried into the fifth year. The only other factor which could have affected this correlation would be the effect of the aging process from two years to five years. Since the aging process (especially up to the age of 25 years) in the absence of any neurotoxins should have reduced the sway area size (Woollacott et al., 1982), it is logical to assume that we are able

to detect, with the force platform technique, the residual effect of lead-induced damage about three years after the blood lead values had declined from peak values attained in the second year of life (Table I). In order to further test this finding and actually document the time course of sway response changes, we plan to start testing these children as young as possible and monitor their sway as blood lead levels begin to decline. With more subjects, it will be possible to provide better statistical control for covariates and confounders, and thus test more informative multivariate models of the lead-sway relationship.

Figs. 2 and 3 illustrate how various postural tasks affected the postural stability. These tasks were designed to indirectly challenge the four major afferents, relevant for the maintenance of upright posture. These afferents, when individually or collectively challenged, elicit postural reflexes. The validity of using these four postural tasks for producing relative challenge to various afferents have been provided elsewhere (Bhattacharya et al., 1987; Sahlstrand et al., 1978).

In our study, it was found that the eyes closed condition (versus EO) alone failed to elicit a significant sway response. This finding is comparable to those of others (Njiokiktjien, 1976; Odenrick and Sandstedt, 1984; Riach and Hays, 1987). However, both our studies, as well as those by Riach and Hays (1987), indicate that, unlike children, normal adults show significant increase in sway (Bhattacharya et al., 1987; Dichigans et al., 1976) with eye closure. This difference in response might be attributable to a difference in how adults and children process visual information. Previous studies with pre-ambulatory (Butterworth and Hichs, 1977) and ambulatory infants (Lee and Aronson, 1974) have shown that in the presence of incongruent information from visual, cutaneous, proprioceptive and vestibular inputs, the integrating and processing of these signals are not as well handled by children as by adults. This was also found in our study. For example, it was found that in the absence of a firm standing surface, vision played a strong stabilizing role for maintaining postural balance. In the eyes open condition, the modification of proprioception alone did not affect postural balance; however, these

childrens' sway showed the significant influence of proprioception modification when the vision was blocked. In general, the results imply that in the absence of vision, the availability of proper proprioception input is critical for postural control in children, or more importantly, the congruency of afferent inputs is a critical factor for postural stability.

Results of this study provided the basis for the construct validity of the force platform technique by comparing results with established methods of evaluating neuromotor functions. In addition, the association of sway with standardized measures of cognitive development was examined. The associations between the Bruininks-Oseretsky Balance Subtest and postural sway area were striking. In addition to sway area, other sway parameters (mean radius, maximum velocity, etc., not presented here) also showed strong correlations with the Bruininks-Oseretsky Balance Subtest. In other words, children who display poorer neuromotor development on this comprehensive and well-validated test also appeared to have poorer vestibular-proprioceptive control when assessed with the postural sway method.

The scores from the Kaufman Mental Processing Composite showed inverse correlations with sway parameters (total length, mean velocity, etc.) other than sway area. Sway area, however, showed significant correlations with scores from the Kaufman Achievement Scale for the EO condition only. The reason behind the sensitivity of one sway variable over the other is not clear yet. Future studies on subjects with known CNS disorders may allow us to identify sway parameters which could serve as better descriptors of certain types of disorders. Nevertheless, the finding of inverse correlations between sway variables and scores from established neurocognitive tests suggests that the postural sway assessment method is sensitive to the developmental maturity of higher-level cortical centers. Such a relationship is possible since the literature (Vander, 1970) indicates that the postural control is also influenced by direct cortico-spinal pathways. The direct cortico-spinal efferents have been reported to also influence the afferent inputs at synaptic points coming from the various receptor organs relevant for postural control (Vander, 1970). Also, in 1976 Njiokiktjien *et al.*, found in

learning disabled children that their equilibrium problems were correlated with hyperkinesia and choreiform motor unrest. The present study, as well as studies cited above, suggests that postural sway might be a good quantitative indicator of higher level CNS functional status.

Impaired postural regulation which leads to postural disequilibrium can have significant developmental consequences for the young school age child. If the impairment of motor coordination results in the child being labeled "clumsy", the subsequent social development of the child is in jeopardy. The lack of coordinated body control may lead to the exclusion of the child from normal games children play. This ostracism can, in turn, result in personality changes and behavioral changes in peer relationships.

The results of this study, although based on a small subject population, have significance for furthering our understanding of the many manifestations of low level lead toxicity, the mechanisms of impaired nervous system function, and the social/developmental consequences of such toxicity in children.

ACKNOWLEDGMENTS

The authors appreciate and thank the families and the children for their participation and cooperation. The authors also wish to thank Dr. George Robinson for conducting the tympanometry and Dr. Kathleen Krafft for assisting in the development of the questionnaire used for the pre-testing interview. Thanks are also due Ms. JoAnn Grote, Ms. Terry Mitchell, Ms. Ronnie Ratliff, Ms. Mary Bier, Ms. Susan Naraine and Ms. Suzanne Liebee of the Lead Program Project. This project was partially supported by the Lead Program Project, NIEHS Grant ES-01566-09 and the NIEHS Center Grant #P30 ES-00159.

REFERENCES

- Bhattacharya A, Morgan R, Shukla R, Ramakrishnan HK, Wang L. Noninvasive estimation of afferent inputs for postural stability under low levels of alcohol. *Annals of Biomedical Engineering* 1987; 15 (6):533-550

- Bruininks, RH. *Bruininks-Oseretsky Test of Motor Proficiency*. Minnesota, Circle Pines, American Guidance Service, 1978
- Butterworth G, Hicks L. Visual proprioception and postural stability in infancy - A developmental study. *Perception* 1977; 6:255-262.
- Das JP, Kirby J, Jarman RF. Simultaneous and successive synthesis: An alternative model for cognitive abilities. *Psychological Bulletin* 1975; 82:87-103
- Das JP. Functional lateralization of the brain. *J Special Education* 1984; 18 (3):229-238
- de la Burde B, Choate MS. Does asymptomatic lead exposure in children have latent sequelae? *J Pediatr* 1975; 81:1088-1091
- Dichgans J, Mauritz KH, Allum JHJ, Brandt TH. Postural sway in normals and ataxic patients: Analysis of the stabilizing and destabilizing effects of vision. *Agressologie* 1976; 17C: 15-24.
- Goyer RA. Lead toxicity. In: *Absorption in Children*, Chisolm JJ, Jr., and O'Hara DM, eds. Baltimore, MD, Urban and Schwarzenberg, 1982
- Hawk BA, Schroeder SR, Robinson G, Otto D, Mushak P, Kleinbaum D, Dawson G. Relationship of lead and social factors to IQ of low SES children: A partial replication. *Amer J Mental Deficiency* 1986; 91: 178-183.
- Kaufman, AS, Kaufman NL. Kaufman assessment battery for children--Administration and scoring manual. Minnesota, American Guidance Service, Circle Pines Publishing, 1983
- Kaufman AS, Kaufman NL, Kamphaus RW, Naglieri JA. Sequential and simultaneous factors at ages 3-12 1/2: Developmental changes in neuropsychology dimensions. *Clin Neuropsychology* 1982; 4:74-81.
- Lee, DN, Aronson E. Visual proprioceptive control of standing in human infants. *Perception and Psychophysics* 1974; 15:529-532
- Luria AR. *The Working Brain: An Introduction to Neuropsychology*. London, Penguin Books, 1973
- Njiokikjien CH, DeRijke W, Dieker-Van Ophem A, Voorhoeve O. Stabilography as a diagnostic tool in child neurology. *Agressologie* 1976; 17D:41-48
- Odendrick P, Sandstedt P. Development of postural sway in the normal child. *Human Neurobiology* 1984; 3:241-244
- Ornitz EM, Atwell CW, Walter DO, Hartmann EE, Kaplan AR. The maturation of vestibular nystagmus in infancy and childhood *Acta Oto-Laryngol* 1979; 88:244-256
- Pueschel SM, Kopito L, Schwachman H. A screening and follow-up study of children with an increased lead burden. *JAMA* 1972; 222:462-466
- Riach CL, Hayes KC. Maturation of postural sway in young children. *Developmental Medicine and Child Neurology* 1987; 29:650-658
- Roda SM, Greenland R, Bornschein RL, Hammond PB. Modification of an anodic stripping voltammetry procedure for improved accuracy of blood lead analysis. *Clin Chem* 1988, 34:563-567
- Sahlstrand T, Ortengren R, Nachemson A. Postural equilibrium in adolescent idiopathic scoliosis. *Acta Orthop Scand* 1978; 49:354-365
- Vander AJ, Sherman JH, Luciano DS. *Human Physiology: The Mechanisms of Body Functions*, New York, McGraw-Hill, 1970
- Woollacott MH, Shumway-Cook A, Nashner L. Postural reflexes and aging. In: *The Aging Motor System*, Vol. 3, Mortimer, J, ed. Praeger Publishing, 1982