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Functional Implications of Postural Disequilibrium Due to Lead Exposure

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Abstract: AMIT BHATTACHARYA, RAKESH SHUKLA, KIM N. DIETRICH, JOEL MILLER, ANGSHUMAN BAGCHEE, ROBERT L. BORNSCHEIN, CYNDY COX AND TERRY MITCHELL. Functional Implications of Postural Disequilibrium Due to Lead Exposure. *Neurotoxicology* **14**(2-3):179-190, 1993. *Measurement of postural equilibrium has been employed as an indirect indicator of functional status of the nervous systems of 109 children (mean age: 5.8 ± 0.78 years) from the Cincinnati Lead Program Project. The geometric mean blood lead for the first five years of life (PbB05) was 11.9 ± 1.5 μg/dL. Postural sway associated with upright balance was noninvasively quantitated with a microprocessor-based force platform and four tasks performed for 30 sec each by the subjects. A covariate-adjusted multiple regression analysis showed statistically significant associations between PbB05 and the postural sway for the task requiring primarily vestibular and/or proprioceptive systems input, implying potential functional impairment. These findings raised several new issues which are addressed here: (1) A dynamic task has been developed to further test the effect of perturbing those afferents' functional capabilities. (2) A method has been developed to quantitate the stability boundary of each subject to better characterize the limits of functionally-safe postural sway. (3) There is a need to perform the postural sway in a shorter duration than 30 sec so that children younger than five years of age can be tested for early identification of Pb-induced functional impairment of postural equilibrium.* © 1993 Intox Press, Inc.

Key Words: Postural Balance, Stability Boundary, Force Platform, Lead Exposure, Children

INTRODUCTION

There is sufficient evidence in the literature that early childhood exposure to environmental lead (Pb) causes modifications in both cognitive and neuromotor systems (Needleman *et al.*, 1990; Benetou-Marantidou *et al.*, 1988; Roberts *et al.*, 1979; Bellinger *et al.*, 1987). However, issues related to level of impairment, threshold values of blood lead (PbB) levels at which such impairments might begin and reversibility of impairments are still being debated. The need to further address these issues is heightened by the announcement of the new PbB "level of concern" of 10 μg/dL by the Centers for Disease Control (CDC, 1991). In order to better understand the significance of early childhood Pb exposure, one needs to know not only the PbB level and its effect in reducing IQ or motor function, but how much reductions in these variables can impair functional behavior and performance of the child's daily tasks of living. For example, Needleman *et al.*, (1990) have reported that children with high early childhood Pb exposure show poor academic performance in high school.

The long-term effect of Pb on neuromotor function has been studied showing detrimental effects at PbB levels of > 40 μg/dL (Benetou-Marantidou *et al.*, 1988). In our laboratory, measurement of postural equilibrium has been employed as an indirect indicator of functional status of the nervous system of 109 children [mean age (± SD): 5.8 ± 0.78 years] from the Cincinnati Lead Program Project. The geometric mean PbB for their first five years of life (PbB05) was 11.9 ± 1.5 μg/dL. Postural sway associated with upright balance was noninvasively quantitat-

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ed with a microprocessor-based force platform and four tasks performed for 30 sec each by the subjects. A covariate-adjusted multiple regression analysis showed a statistically significant association between PbB05 and postural sway performance for the task requiring primarily vestibular and/or proprioceptive system input, implying potential functional impairment. This relationship was also significant for the Maximum PbB values at two years of life (MaxPbB2) after adjusting for covariates. These results are consistent with our previous study with a smaller group of children (Bhattacharya *et al.*, 1990)

The data from Pb-exposed children also show that postural tests requiring processing of inter-sensory conflicting signals (such as standing on a compliant surface with and without vision) produced significantly greater sway than in adults (Bhattacharya *et al.*, 1988, 1990). However, what remains to be determined is whether Pb-exposed children will develop the ability to appropriately resolve such inter-sensory conflicts and acquire adult-like postural sway response. Furthermore, if this cohort is suffering from maturational delay, there is a need to determine the extent, time course, and mechanism of recovery. Can impairments be identified at early stages so that remedial actions can be implemented to minimize long-term damage (which may be permanent) to the functionality of the systems affected?

The finding of postural impairment due to Pb exposure raises the following new issues: (1) The need to perform the postural sway test in a shorter duration than 30 sec so that children younger than five years of age can be tested for early identification of Pb-induced functional impairment of postural equilibrium. This will also help determine, in future studies, the time course of development of postural disequilibrium due to Pb exposure. (2) There is a need to better characterize the limits of functionally-safe postural sway. (3) There is a need to employ a dynamic postural test which will further test the effect of perturbing those afferents' functional capabilities which have been, so far, found to be influenced by Pb.

TESTING OF POSTURAL BALANCE IN YOUNGER CHILDREN (< 5 YEARS OF AGE)

The test of postural balance can be performed on any child as long as s/he can stand without support on the force platform quietly for 30 sec. The choice of this particular length of testing period has been primarily based on studies performed by previous investigators and the ability of a subject to stand upright without making any intentional movements or developing postural muscle fatigue. In children, these issues are very critical for getting artifact-free data. Because the attention span is short in younger children, it is important that this test be accomplished in the shortest possible time. In order to address this issue further, we studied postural sway data collected from 30 sec test period in 109 children to answer the following questions: (1) Are there differences among postural sway characteristics obtained during the first, second and third 10 sec intervals of a 30 sec test? (2) Is the relationship between postural sway and PbB influenced by the duration of the test period?

The Cincinnati Lead Program Project is a prospective study addressing issues of Pb-induced health effects in young children. Mothers were recruited at the time of pregnancy based on criteria described in Dietrich *et al.*, (1991). The health status of children has been monitored carefully every three mon from birth. Postural balance was assessed at the age of approximately five years. On the day of testing, subjects' middle ear pressures (MEP) were assessed with a standard tympanometry technique. Subjects with MEP values less than -150 mm H_2O were not included in the analysis. MEP less than -150 mm H_2O is considered indicative of eustachian tube dysfunction (which might affect postural balance). Height, weight, foot length and width were also measured. The details of the postural balance methodology are described in our earlier studies (Bhattacharya *et al.*, 1987, 1988, 1990). The experimental protocol was approved by the University of Cincinnati Institutional Review Board and informed consent was obtained from all participants (and/or their guardians) following a full explanation of procedures. The postural sway was measured with a microprocessor based force platform system and custom software (All rights reserved, University of Cincinnati, 1991). This system provided a quantitative description of postural sway by measuring the movement pattern of body's center of pressure (CP) during the test. Details of this methodology are given in Bhattacharya *et al.*, (1987). Briefly, each subject performed four tests twice while standing on the force platform with his/her feet in a standardized position (heels at 30 degrees) for a period of 30 sec each. These were: (1) stand on force platform with eyes open without foam (EO); (2) stand on force platform with eyes closed without foam (EC); (3) stand on foam pad (three inches high) placed on the force platform with eyes open (FO); and (4) stand on foam pad (three inches high) placed on the force platform with eyes closed (FC). Each of these tests are designed to indirectly challenge, minimize and/or enhance sensitivity of various afferents (vision, proprioception and vestibular system) relevant for postural control (Bhattacharya *et al.*, 1987, 1988, 1990; Sahlstrand, 1978). The mean age (± SD) of children was 5.8 ± 0.78 years and their PbB05 (approximately 20 measurements per child) was 11.9 ± 1.5 μg/dL (range: 5.1 - 28.2 μg/dL). MaxPbB2 value was 20.3 ± 1.5 μg/dL (range: 8.5 - 53.5 μg/dL). The mean height (± SD) was 114.4 ± 6.6 cm and the mean body mass (± SD) was 21.2 ± 5.9 kg.

Data were analyzed to determine postural sway characteristics during the 0 - 10 sec, 10 - 20 sec, and 20 - 30 sec periods. In addition, sway patterns were also analyzed for the 0 - 20 sec and 0 - 30 sec periods. The parameters used for characterizing the postural sway were sway length [SWL, (cm)], sway radius [SWR, (cm)], and the sway area [SWA, (cm^2)]. The SWL measured the distance travelled by the body's CP during the test period. The SWR provided the mean value of radial vectors of all the locations of body's CP assumed during the test period. The SWA was the area of the region contained within the outer envelope of x-y plot of the movement pattern of the body's CP (also known as a stabilogram). Intercorrelations among these variables were also obtained. SWA and the SWR were highly correlated for all four test conditions (correlation coefficient r, range: 0.91 to 0.96) while the correlations between SWL and SWA were relatively low (r, range: 0.28 to 0.42). Therefore, subsequent data analyses employed only two variables (*i.e.*, SWA and SWL).

For each experimental condition, an analysis of variance (ANOVA) was performed to assess if the mean values for each of the sway variables differed between 10 sec intervals. The model used was SWAY Variable = Subject + Time Interval. The only significant ($p = 0.05$) difference found was SWA in the EC condition. This finding should be viewed cautiously because of multiple test conditions. Fig. 1 shows SWA response to time interval on platform for all four test conditions.

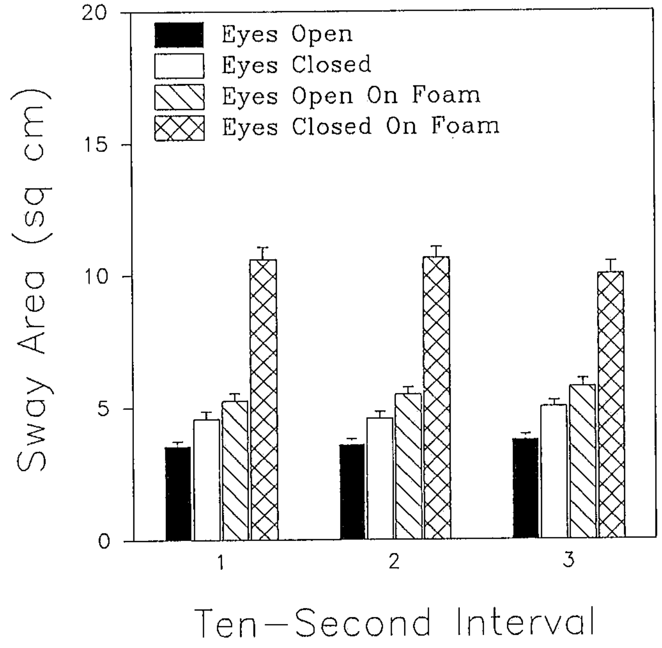

FIG. 1. Sway Area vs. Time Interval on Platform.

Pearson's bivariate correlations between SWA and SWL and PbB05 were obtained for the 0 - 10 sec, 0 - 20 sec, and 0 - 30 sec periods. Results are shown in Tables 1 and 2. SWA and SWL were not correlated with subject's gender for any test condition or for any time interval. SWA was uncorrelated with age except for EO. SWL was uncorrelated with age for all test conditions as well as for all time intervals. SWL was correlated with body mass for all test conditions as well as for all time intervals. On the other hand, SWA was uncorrelated with body mass. There were no significant correlations between sway variables and the subject's race and socioeconomic status. The relationship between SWL and birth weight and birth length were not significant for all test conditions. For the SWA, there were no significant correlations with birth weight for all test conditions. However, there were significant relationships between SWA and birth length only for the 0 - 10 sec ($r = -0.21$; $p = 0.03$) and the 0 - 20 sec ($r = -0.19$; $p = 0.05$) periods for the EO test and for the 0 - 10 sec period ($r = -0.21$; $p = 0.03$) for the FO test. The relationship between SWL and current height was significant for all test conditions as well as all time intervals (range of r: -0.23 to -0.28). The SWA was not correlated with current height.

In Table 1, SWA is significantly ($p < 0.05$) correlated with PbB05 for all time intervals for EC and FC tests. However, this relationship was not significant for any of the time intervals for the EO test. For the FO test, this relationship was significant for the 0 - 30 sec time interval only. As the EC and FC tests rely more on the use of vestibular and proprioception systems, it is likely that Pb-induced sway impairment might be related to modifications of the functions of these two afferents. This finding was further confirmed when a multiple regression analysis was performed on SWA with PbB variables and covariates of age, MEP, body mass and height for the EC test. The only significant regression parameters were for PbB05 ($p = 0.0001$) and for age ($p = 0.007$). Similar results were obtained when this analysis was repeated with MaxPbB2 and covariates, including Maximum 1st year PbB (MaxPbB1). This finding is consistent with our previous results (Bhattacharya *et al.*, 1990).

On the other hand, SWL was significantly correlated with PbB05 for all test intervals as well as all test conditions. A multiple regression analysis was also performed on SWL with PbB and the covariates of age, MEP, body mass and height for the EC test. For this analysis, significant regression parameters were PbB05 ($p = 0.0001$) and MEP ($p = 0.002$). When this analysis was repeated with

TABLE 1. Bivariate Correlations of Sway Area vs. Geometric Mean PbB (0 - 5 Years) [PbB05].

Test Conditions	N = 109		
	0 - 10 Sec	0 - 20 Sec	0 - 30 Sec
Eyes Open (EO)	0.15 (p = 0.11)	0.12 (0.2)	0.17 (0.08)
Eyes Closed (EC)	0.26 (0.007)	0.25 (0.008)	0.32 (0.0006)
Eyes Open Foam (FO)	0.16 (0.11)	0.16 (0.09)	0.24 (0.01)
Eyes Closed Foam (FC)	0.23 (0.02)	0.24 (0.01)	0.25 (0.008)

MaxPbB2 and covariates of MaxPbB1, age, body mass, body height and MEP, the results were different than those obtained for the regression analysis with SWA. For this analysis, PbB variables as well as age, body mass and height were not significantly related to SWL.

A question of interest was to assess if the relationship between PbB05 and sway follows any definite trend with duration of time on the platform. A review of bivariate correlations in Tables 1 and 2 does not suggest any definite pattern (*i.e.*, neither increasing nor decreasing correlations with time on platform). Furthermore, the changes in the magnitude of the correlations with time on platform were also small. The SWL effect due to duration of standing on platform can be partially attributed to the fact that the value of SWL is directly dependent upon the amount of time spent on the platform. In other words, if one stands longer on the platform, one will accumulate a larger value of SWL. On the other hand, SWA value does not directly depend on the duration of standing on the platform as it is calculated as the outer perimeter of the stabilogram.

TABLE 2. Bivariate Correlations of Sway Length vs. Geometric Mean PbB (0 - 5 Years) [PbB05].

Test Conditions	N = 109		
	0 - 10 Sec	0 - 20 Sec	0 - 30 Sec
Eyes Open (EO)	0.30 (p = 0.002)	0.27 (0.005)	0.30 (0.001)
Eyes Closed (EC)	0.32 (0.0006)	0.29 (0.002)	0.33 (0.0004)
Eyes Open Foam (FO)	0.29 (0.002)	0.26 (0.007)	0.30 (0.002)
Eyes Closed Foam (FC)	0.32 (0.0006)	0.29 (0.002)	0.32 (0.0008)

In summary, these analyses show that the postural sway characteristics do not change from 0 - 10 sec to 10 - 20 sec to 20 - 30 sec periods. Also, results suggest that the relationship between SWA, SWL and PbB variables are not affected in a systematic fashion by the duration (0 - 10 sec vs. 0 - 20 sec vs. 0 - 30 sec) of postural sway test. The relationship between SWL and PbB variable is less influenced by the test conditions (EO, EC, FO and FC) compared to that observed for the SWA and PbB. This difference in sensitivity between two sway variables could be indicative of how one may use SWL for assessing general postural imbalance and the SWA could be used to better understand the contributions of various afferents for the postural control. We have previously shown how SWA data can be used to further investigate the effect of Pb on various afferents (Bhattacharya *et al.*, 1990; Shukla *et al.*, 1991). These findings suggest that a test of less than 30 sec (possibly for 20 sec) may be sufficient to obtain useful sway information. Future studies involving a larger sample size will be used to determine whether or not a test period less than 30 sec is adequate.

Results also suggest that Pb-induced impairment of postural balance is probably mediated by modification of functional capability of proprioception and/or vestibular systems. Therefore, new methods need to be developed to further test the functional roles of proprioception and/or vestibular systems in maintaining balance. Also, methods or criteria need to be developed to better characterize the limits of a "safe postural sway."

LIMITS OF FUNCTIONALLY-SAFE POSTURAL SWAY

Postural sway is a normal phenomenon in human beings. However, when postural sway movement causes the body's CP to approach one's stability boundary, the potential of falling increases. Theoretically, Fig. 2 illustrates that the stability boundary is defined by the outer perimeter of the feet (outlined by ABCDEFA). Actual falling will occur if the body's CP crosses the theoretical stability boundary. Depending upon the presence of risk factors (lighting, surface conditions, peripheral vision, and workload), the subject's sway pattern while performing certain tasks (such as tasks of daily living) might become large and approach the stability boundary, causing the risk of a fall to increase. Therefore, what needs to be determined is how close to the stability boundary one can reach without affecting one's performance of a task as well as not becoming susceptible to a fall. In other words, one needs to define and quantitate how much postural sway is considered func-

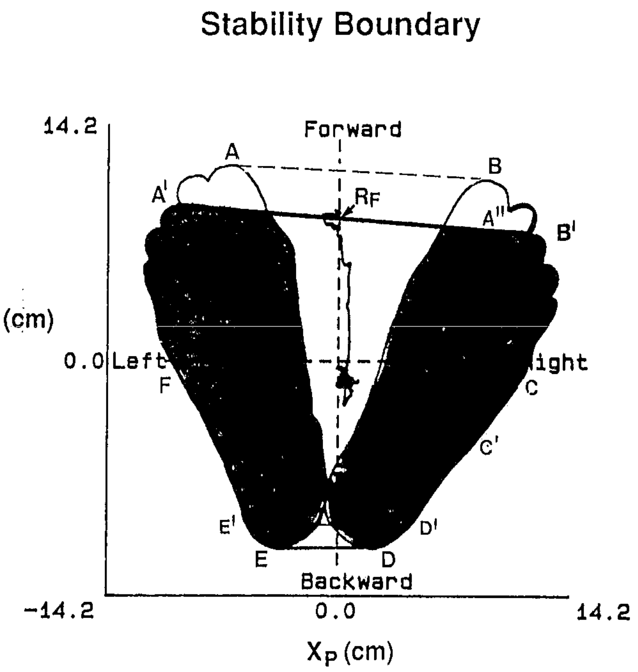

FIG. 2. The Concept of Theoretical (ABCDEFA) and Functional Stability (A'R_FB'CDEFA') Boundaries.

tionally "safe." Many factors affect this issue (such as postural muscle strength, age, feet position, physical environmental factors, health status, task characteristics, etc.). We have developed a method to measure a subject's stability boundary and provide a quantitative measure of proximity of body's CP to his/her stability boundary (Bagchee, *et al.*, 1992).

The functional stability limit was defined as the maximum displacement of CP in the forward, backward, right and left directions of the body immediately before a fall occurs (Fig. 2). This boundary is always smaller than the Theoretical Stability Boundary. The experimental measurements of limits of functional stability in four directions involved the subject to perform four tests of simulated falling in the forward, backward, right and left directions. The experimental details are given in Bagchee *et al.*, 1992. For these experiments an outline of the feet was drawn on the paper placed on the force platform. Each of the test was performed for 30 sec while standing on the force platform with feet in a standardized position (heels at 30 degrees angle). The extreme positions of body's CP were measured by the force platform as the points R_F, R_B,R_R and R_L for forward, backward, right and left directions, respectively (Fig. 2).

The points R_F, R_B,R_R and R_L represent functional limits of body's ability to balance in four respective directions before a fall might occur. These points are superimposed in Fig. 2 to obtain functional stability limits defined by the outline A'R_FA''R_RC'D'R_BE'FR_LA' (lightly shaded area). This stability region will be different for different subjects and will depend on various factors such as postural muscle strength, feet position, coordination, age and health status. We have performed these four tests several times in adults and found that the reproducibility of the R_F value for the forward fall test is significantly better than those for the remaining three tests. Therefore, for obtaining more reproducible data, the "Functional Stability Boundary" (A'R_FB'CDEFA') is defined based on the value of R_F only and the outer perimeter of the feet (Fig. 2). Once this stability boundary is determined, then the subject's stabilograms obtained during postural sway tests (simulating tasks of daily living performed under various environmental conditions such as poor lighting, uneven/compliant standing surface, blocked peripheral vision, etc.) are superimposed on that stability boundary to determine how the body's CP behaved during the sway test and how close to the boundary the CP approached. In order to quantitate the proximity of body's CP to the stability boundary, an Index of Proximity to Stability Boundary is defined as the ratio of the maximum radius vector of CP to the radius vector of the stability boundary (see Fig. 3). This variable is calculated for each of the four quadrants of the stabilogram. A value approaching "1" for this ratio implies that the subject is at a potential risk of a fall. We have tested the usefulness of this method in studying fall potential in a pilot study where an adult subject was tested for postural sway while performing a simulated industrial task of lifting a 5 lb. weight under poor light-

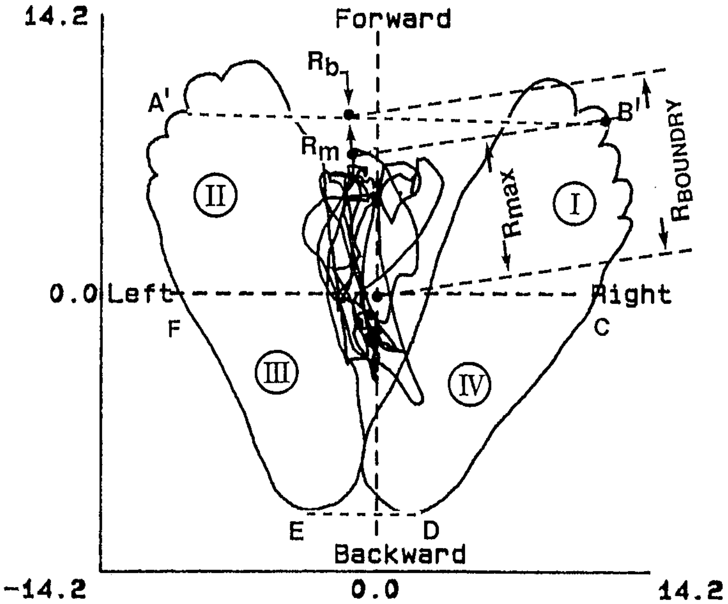

FIG. 3. The postural sway pattern obtained during lifting 5 lb. weight test for illustrating the relationship between functional stability boundary (A'B'CDEFA') and potential of fall. The potential of falling increases as the value of Rmax approaches the $R_{Boundary}$ value. An actual fall will occur when Rmax = $R_{Boundary}$; Rmax = 7.4 cm and $R_{Boundary}$ = 9.3 cm.

ing and standing on a compliant surface (Fig. 3).

The application of the above method in determining the functional stability boundary of the children from the Cincinnati Lead Program Project has just begun in our laboratory. It remains to be determined how reproducible the measure of the functional limit value (R_F) in the forward direction is in children. For our study with children, we intend simply to use the theoretical stability boundary (ABCDEFA in Fig. 2).

Dynamic Test of Postural Control (Trunk Bending Test)

This is a new test to be administered annually on all children in the Cincinnati Lead Program Project cohort. The purpose of this test is to measure the effect of rapid movement of the trunk on the body's ability to restore postural sway to the pre-movement (stimulus) level. Furthermore, such a test will allow us to test the effect of perturbing those afferents (particularly proprioceptive and/or vestibular) which have so far been shown to be affected by Pb exposure (Bhattacharya *et al.*, 1990). This test can be performed in about 30 sec.

Background and Rationale for the Test

The rationale for developing this test and its characteristics are as follows: (1) There is a need to use tests which can effectively and functionally challenge the postural control system in such a way that the Pb effect on postural sway (if any) can be accentuated and detected; and (2) There is a need to design tests which are acceptable to young children without producing fear and a resulting unwillingness to return for retests on a regular basis. Based on our pilot data (see below) from children, we feel this test merits further evaluation.

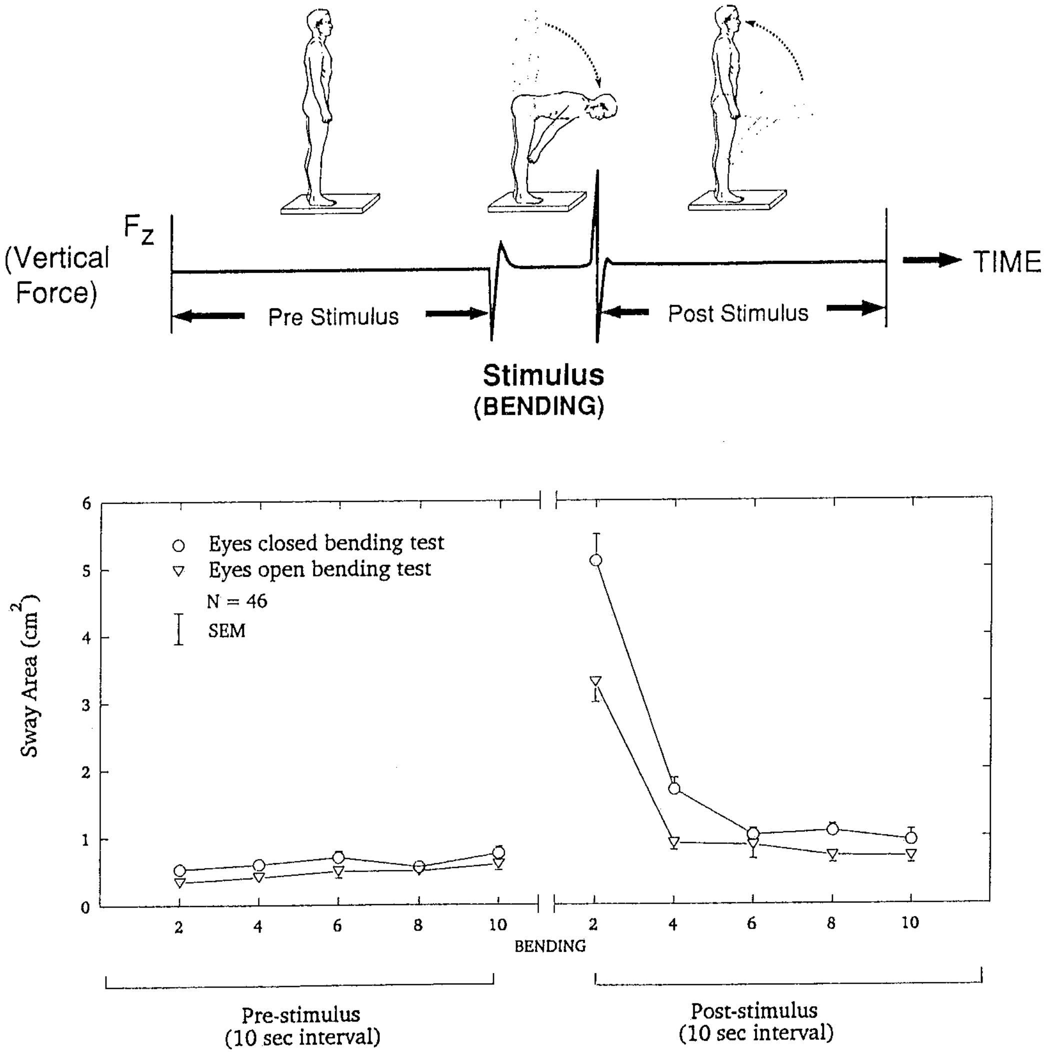

FIG. 4. (Top) Dynamic Trunk Bending Test for Postural Balance. (Bottom) Average Sway Area Data from Pre- and Post-Stimulus Periods of the Trunk Bending Tests Performed on 46 Children.

There is evidence in the literature regarding the postural adjustment effect of rapid arm movement (Horak, 1984; Cordo, 1982; Belenkii, 1967). These investigators have shown that rapid displacement of a body segment usually results in a displacement of center of gravity – causing perturbation of postural equilibrium, which must be corrected by the activation of appropriate muscles. These investigators reported that there is an activation of postural musculature in advance of movement of the body segment in question. For example, Belenkii (1967) documented contraction from lumbosacral muscles of the back and hip about 70 - 80 msec in advance of contraction of the anterior deltoid muscle directly responsible for the rapid arm movement. Such advance activation of the postural stabilizing muscle network allows minimization of postural sway produced by the body segment movement. Therefore, we hypothesize that the postural sway after trunk movement (post-stimulus) will be significantly higher than that observed for the pre-movement (pre-stimulus) phase in the Pb-exposed children. If Pb has caused damage to any of the neural networks relevant to postural equilibrium, the advance postural stabilizing forces (produced due to rapid movement of trunk) will be ineffective in reducing the sway produced by the primary movement of the trunk.

Test Protocol

The subject stands on the force platform in a fashion similar to that used for the regular postural sway test. For the first 12 sec, the subject maintains an upright posture; this is called the "Pre-Stimulus" phase (Fig. 4). This initial upright head and trunk position is aligned with a vertical line in the background. Next, a voice command is given to direct the subject to rapidly bend his/her trunk about 90° (with respect to the vertical) in the sagittal plane (Stimulus Phase). The alignment of the trunk in the sagittal plane is checked by comparing its orientation visually with the vertical line in the background. This posture is maintained for five sec. Finally, with another voice command, the subject is asked to rapidly bring back his/her trunk to upright position and stay in this position for an additional 13 sec (Post-Stimulus Phase). Data are collected during the entire 30 sec of this test. Using our custom-designed software, the postural sway (x *vs* y plot of CP) from the Post-Stimulus Phase is compared with that from the Pre-Stimulus Phase.

The identification of the beginning of the post-stimulus phase can be seen as a distinctive spike in the Fz (vertical force) *vs* time trace made by the rapid movement of the trunk. The speed of trunk movement (Fig. 4) will be used as a covariate in the statistical analysis. The speed or velocity of trunk rotation change can be estimated by measuring the duration of spike on the Fz trace. Also, the data during the post-stimulus phase is analyzed in small intervals (two sec) to see how quickly one's sway returns to the postural sway values of the pre-stimulus phase. This test is performed once with eyes open, and then with eyes closed.

Fig. 5 presents stabilograms from three subjects performing the trunk bending test with eyes open and eyes closed conditions. The ages of Subjects #1, 2 and 3 were 85 mon, 84mon and 95 mon, respectively. Their PbB05 values were 5.5 μg/dL, 20.3 μg/dL and 13.6 μg/dL, respectively. A qualitative comparison of stabilograms from Subjects #1 and 2 shows that Subject #2 with a higher PbB05 had a more erratic and larger sway pattern than that observed for Subject #1 with a lower PbB05 (Fig. 5). Both of the subjects were about the same age (± 1 mon). The SWA values for Subject #2 were considerably larger than those of Subject #1 for both the test conditions. A comparison of stabilograms from Subject #3 of 95 mon age and with higher PbB05 (13.6 μg/dL) with that from Subject #1 of age 85 mon and lower PbB05 (5.5 μg/dL) indicates that the SWA in the former subject was considerably larger even though Subject #3 was 10 mon older than Subject #1. In other words, in this case comparison, it implies that, in the presence of higher PbB05, even an older child with a larger foot area (base of support) and comparable feet positions shows a relatively poorer performance on this test. The effect of feet positioning on sway performance for comparisons between subject #1 and #2 needs further explanation. A larger foot area as well as wider stance (depends on feet positioning used during the test) may decrease body sway. While the subject #1 had somewhat wider stance compared to that of subject #2, the former had considerably smaller foot area (152.8 cm^2) than that of subject #2 (193.2 cm^2).

This test so far has been performed on 46 children from the Cincinnati Lead Program Project. The mean age (± SD) was 7.8 ± 1.6 years and the PbB05 value was 11.6 ± 1.6 μg/dL (range:3.9 - 27.4 μg/dL). Fig. 4 shows the average SWA data from all of the subjects for the pre- and post-stimulus periods for both eye conditions. For both eye conditions, the post-stimulus sway (up to 4 sec post-stimulus period) is considerably larger than that observed for the pre-stimulus phase. The increase in sway for the post-stimulus phase is larger for the eyes closed condition compared with the eyes open case. Pearson bivariate correlation analysis between PbB variables and post-stimulus period sway variables was also performed. Preliminary results show significant correlation between SWL and MaxPbB1 ($r = 0.29$, $p = 0.05$) and marginal correlations between SWL and MaxPbB2 ($r = 0.27$, $p = 0.07$) and PbB05 ($r = 0.27$, $p = 0.07$) for the eyes closed no foam condition only. Detailed analysis are

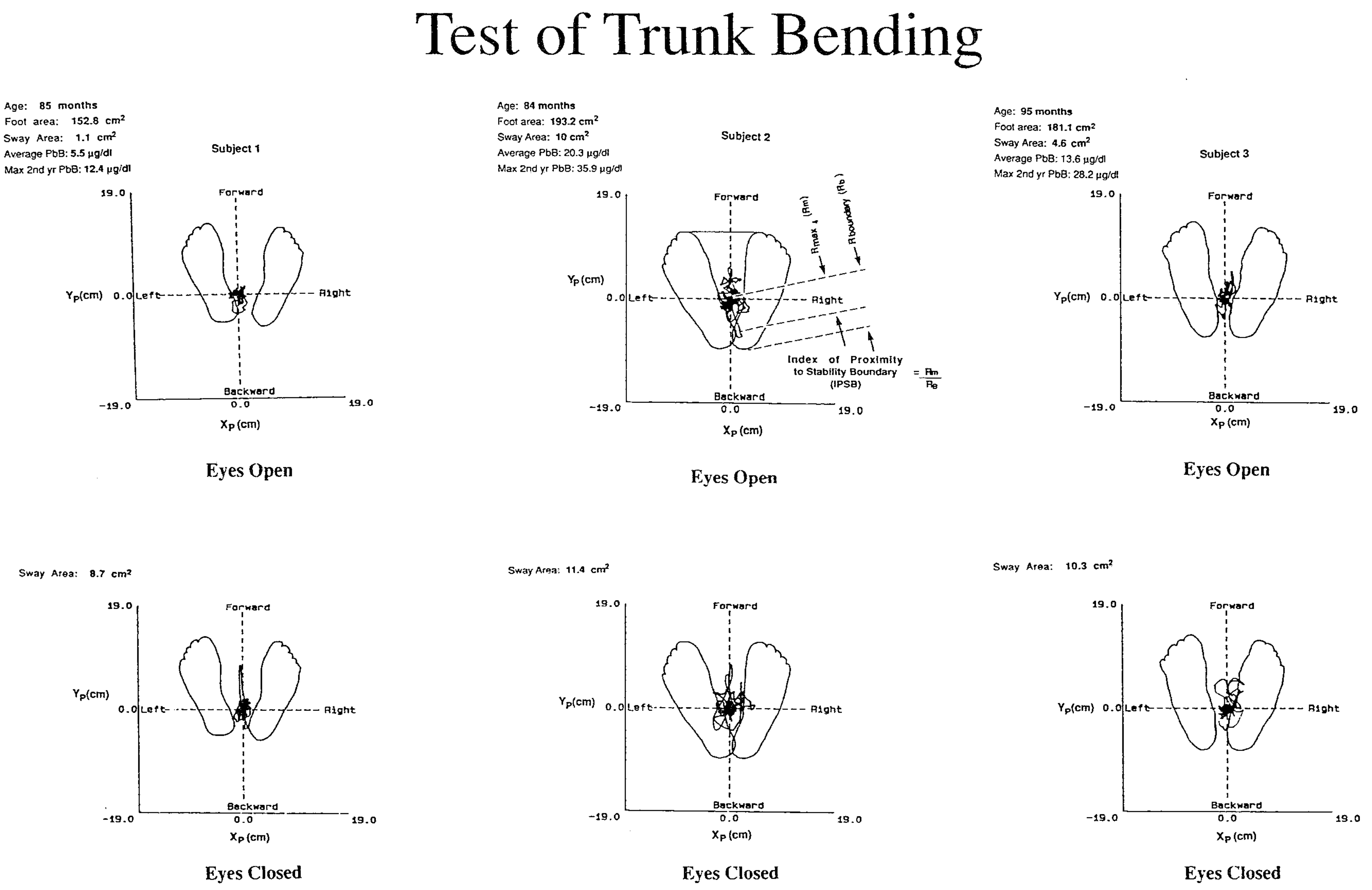

FIG. 5. Illustrative examples of stabilograms from trunk bending tests performed by three children with varying levels of PbB.

being planned to further investigate the relationship between PbB variables and post-stimulus period SWL after controlling for all the covariates and confounding factors.

In summary, preliminary results indicate that the rapid trunk movement test might be an additional challenging test which would allow us to focus more precisely on the Pb-effect on postural sway.

FUTURE DIRECTIONS

The PbB profiles of children in the Cincinnati Lead Program Project (Dietrich *et al.*, 1991) indicates that highest exposure levels were experienced generally during the first two years of life. Therefore, it is quite likely that a significant impact on the nervous system related to posture control might have taken place during that phase of early childhood. In a case study (Bhattacharya *et al.*, 1991) involving a 15 year boy who was Pb-intoxicated at two years of age, we found that his current postural sway performance was significantly poorer than those from a non-exposed 14 year old and a group of 26 year old adults (Bhattacharya *et al.*, 1987). This provides suggestive evidence that early childhood excessive Pb exposure might have long-term detrimental effects on postural balance. However, more research is needed to determine the time course and mechanism of Pb-induced changes of the postural balance. In order to assess the effect of Pb on postural stability at the early childhood stage, one needs to first review the age-associated developmental stages of postural control.

The process of upright postural stability is strongly related to age. The maturation of the nervous system as it relates to postural control continues throughout childhood. Neuromuscular development related to postural control is manifested as a predetermined sequence of milestones achieved at certain ages. These milestones are control of head/neck stability (sway), control of trunk stability and its interaction with head/neck sway to allow a child to sit upright without external support and, finally, control of lower extremity stability and its interaction with the upper body to allow upright stability of the whole body (Fig. 6). Ninety-five percent of normal unexposed children will achieve head-neck control, trunk control in the sitting position, and upright standing postural control around 5 mon, 8 mon and 16 mon of age, respectively (Evans, 1987).

There are several unanswered questions regarding the influence of early childhood exposure to neurotoxicants on the early neuromuscular development of head-neck

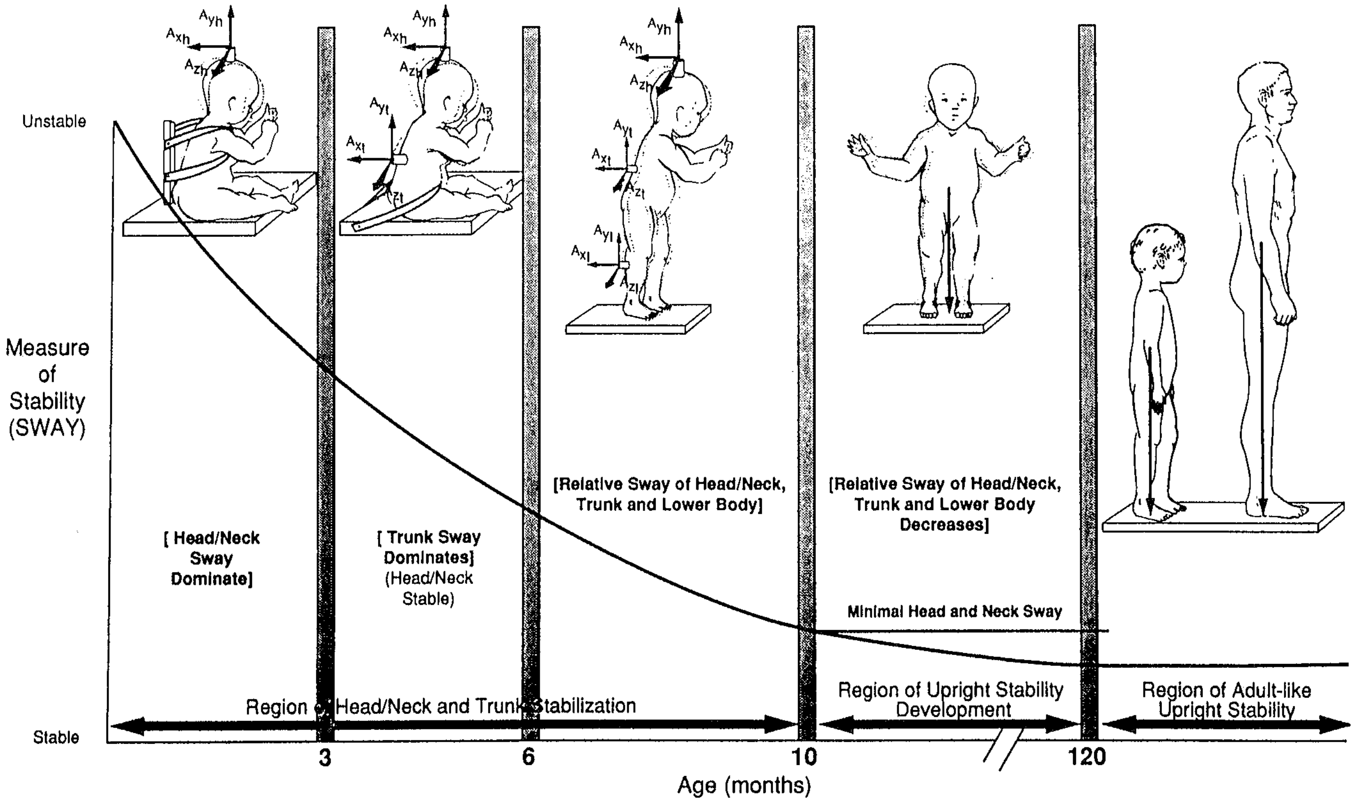

FIG. 6. Conceptual relationship between measures of body segment stabilities (as it relates to upright postural balance) and age. Figure also shows the use of noninvasive tri-axes miniature accelerometers for quantifying body segment movement patterns.

sway and trunk sway. First, will these neuromuscular milestones be significantly delayed or irreversibly impaired in the proper development of final upright postural control? There is a need to quantitate the patterns of segmental body sway in early childhood to determine early signs of toxic chemical effects on neuromuscular development as it relates to mature whole-body upright postural control achieved later around the age of 10 years (Shumway-Cook *et al.*, 1985). With the availability of miniature, low mass, and noninvasive three-dimensional accelerometers, one can quantitate the head/neck, trunk and lower body sway patterns (Fig. 6). Data obtained from these transducers needs to be processed to assess each body segment's movement patterns along three orthogonal directions both in frequency and time domains. Secondly, an equally important task is to study the phase relationships among various body segment movement patterns. Finally, efforts should be made to study how the movement patterns of various body segments relate to early childhood exposures to neurotoxicants and its effect on the development of segmental body part stability and eventually to whole-body upright postural stability.

Future studies should also address postural disequilibrium as it relates to functional capability of a child to perform routine tasks of daily life. An impairment in postural sway which disrupts the child's ability to perform basic tasks (such as carrying, reaching, games requiring whole-body motor control, walking, riding a bicycle, climbing steps, bending down and picking up items from floor level) will allow a better characterization of the functional significance of information obtained from postural balance tests. Therefore, future studies are needed to determine the correlations between the postural sway results and the tasks of daily living. These tests should be designed to provide a quantitative estimate of functional impairments caused by poor postural balance. We have described a new method of defining stability boundary which could be used to establish criteria for functional impairments associated with postural disequilibrium. The method described here is reproducible in adults and has been used to assess the effects of degraded environmental conditions (poor lighting, compliant standing surface, and blocked peripheral vision) on postural sway on lifting. Currently, we are using this methodology to assess the effect of lead exposure on the development of postural equilibrium in children.

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REFERENCES

Belenkii VY, Gurfinkel VS, Pal'tsev YI. Elements of control of voluntary movements. *Biophysics* 1967; 12:135-141

Bellinger D, Leviton A, Waternaux C *et al.* Longitudinal analyses of prenatal and postnatal lead exposure and early cognitive development. *N Engl J Med* 1987; 316(17): 1037-1050

Benetou-Marantidou A, Nakou S, Micheloyannis J. Neurobehavioral estimation of children with lifelong increased lead exposure. Arch Envir Health 1988; 43(6):392-395

Bagchee A, Bhattacharya A. Method for estimating fall potentials in clinical, occupational and environmental exposure cases. *Proceedings of the American Society of Biomechanics Conference,* Chicago, IL; August, 1992

Bhattacharya A, Linz D. Postural sway analysis of a teenager with childhood lead intoxication – A case study. *Clinical Pediatrics* 1991; 30(9):543-548

Bhattacharya A, Shukla R, Bornschein RL *et al.* Lead effects on postural balance of children. *Envir Health Perspect* 1990; 89:35-42

Bhattacharya A, Shukla R, Bornschein RL *et al.* Postural disequilibrium quantification in children with chronic lead exposure: A pilot study. *Neurotoxicology* 1988; 9(3):327-340

Bhattacharya A, Morgan R, Shukla R *et al.* Noninvasive estimation of afferent inputs for postural stability under low levels of alcohol. *An Biomed Eng* 1987; 15:533-550

Centers for Disease Control. *Preventing Pb Poisoning in Young Children: A Statement by CDC.* Department of Human Health Series Publ, Oct 1991

Cordo PJ, Nashner LM. Properties of postural adjustments associated with 'rapid arm movements. J *Neurophys* 1982; 47(2):287-302

Dietrich KN, Succop PA, Berger OG *et al.* Lead exposure and the cognitive development of urban preschool children: The Cincinnati Lead Study Cohort at age 4 years *Neurotoxicol Teratol* 1991; 13:203-211

Evans OW. Manual of child neurology. *Publ Churchill Livingstone,* 1987

Horak FB, Esselman P, Anderson ME, Lynch MK. The effects of movement velocity, center of mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. *Neurol Neurosurg Psychiatry* 1984; 47:1020-1028

Needleman HL, Schell A, Bellinger D ***et al.*** The long-term effects of exposure to low doses of lead in childhood: An 11 year follow-up report. *N Engl J Med* 1990; 322(2):83-88

Roberts TM, Hutchinson TC, Paciga J ***et al.*** Lead contamination around secondary smelters: Estimation of dispersal and accumulation by humans. *Science* 1979; 196:1-20

Sahlstrand T, Ortengren R, Nachemson A. Postural equilibrium in adolescent idiopathic scoliosis. *Acta Orthop Scand* 1978; 49:354-365

Shukla R, Bhattacharya A, Dietrich KN, Bornschein R. Effects of lead exposure on postural control pathways – An exploratory factor analysis. Proceedings of *8th Intl Conf on Heavy Metals in the Environment,* (ISBN 0905941 46 2), Farmer JG, ed., Publ., LTD Edinburgh, Scotland, CEP Consultants, Sept. 16-20, 1991

Shumway-Cook A, Woollacott MH. The Growth of stability: Postural control from a developmental perspective. *J Motor Behavior* 1985; 17(2):131-147

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