DEVELOPMENT OF QUIET STANCE

STRATEGIC CHANGES IN MONOTONIC VERSUS NON-MONOTONIC CHARACTERISTICS OF QUIET STANCE DEVELOPMENT: A LONGITUDINAL STUDY OF YOUNG CHILDREN

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ABSTRACT

The purpose of this longitudinal study was to determine whether a non-monotonic pattern characterizes the development of postural control in children from age 5 to 8 years, as suggested by previous cross-sectional studies. Postural control was considered in terms of control strategy and its variability operationalized by mean and standard deviation of Centre of Pressure velocity (COPvel); and of effectiveness and its variability operationalized by mean and standard deviation of COP anteroposterior excursion (YS). Periods of significant variability were used to indicate behavioural transitions. Seventeen, healthy children (9 males, 8 females) aged 5 to 6 years (61.5 - 75 months) were tested at 3 to 4 month intervals until age 8 years (83 - 97 months) in eyes-open quiet stance (QS) on a force platform for 30 seconds in each of 10 trials. Data were reorganized into 6 developmental categories based on adjacent test dates prior to (-2, -1) and after (+1, +2, +3) a subject's trial with the lowest COPvel. Developmental category is proposed to represent level of sensorimotor integrative skill. A 1-way MANCOVA revealed a significant effect (p <.0001) for developmental category with covariance due to height, weight and actual age removed. Post-hoc 1-way ANCOVAs showed a significant effect (p<.0001) on measures of strategy. However differences in COPvel (type of strategy used) and differences in its variability (denoting a transition between types of strategies) were not always coincident. Performance outcome (YS) changed linearly across categories. From a consideration of the results it was concluded that a non-monotonic change in control strategy describes the development of quiet stance equilibrium. A transition, marked by variability of COPvel occurs from a primarily open-loop to incorporation of open- and close-loop components of control. Honing of strategy used precedes and follows transitions. Constriction of velocity and excursion may typify the early stages of bi-modal strategy use suggesting instability in real-world situations at this stage. Linear change in effective excursion regardless of strategy employed in unchallenged QS may decrease the utility of this measure in assessing stability status in children. Developmental categories describe affiliation with the strategy employed and may represent differentiable levels of sensorimotor integrative skill. As such, they may be more useful in assessing progression of equilibrium control than consecutive age in years.

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INTRODUCTION

In cross-sectional studies of postural development it has been suggested that children progress from a ballistic to a more feedback-oriented mode of control (Hayes & Riach, 1989; Riach & Starkes, 1994) similar to the elaboration of control seen in directed arm movements (Hay, 1979). Investigators have also suggested that the integration of control modes is characterized by a non-monotonic pattern of strategy use: A step change from open loop (ballistic) to close loop (feedback) control may occur between the ages of 6 to 8 years, before effective integration of the two for adult-like responses at around 9 years of age (Bard, Hay & Fleury, 1990; Hay & Redon, 1999; Riach et al., 1994; Shumway-Cook & Woollacott, 1985; Woollacott, Debu & Mowatt, 1987). In the control of quiet stance (QS), Center of Pressure velocity (COPvel) and magnitude of anteroposterior displacement (YS) may indicate the mode of strategy and its effectiveness respectively (Riach & Starkes, 1993; Riach et al., 1994).

A non-monotonic change would support a systems approach to the study of behavioural skill (Kugler, Kelso & Turvey, 1980; Thelen, 1989). The confluence of internal and external factors for a given individual allows the emergence of new, context-appropriate patterns of response as development of component systems proceed. Analysis of the transitions between patterns may identify rate-limiting factors which may determine if and when such progression occurs.

Cross-sectional studies tend to obscure such factors by averaging relevant variables across subjects. A longitudinal study of children encompassing the putative transition period until the adoption of an adult-like pattern of postural control may provide information about individual skill development. This in turn may assist the assessment of a child's postural skills, and choice of appropriate interventions when required to facilitate the progression on an individual basis.

The purpose of this study was to confirm whether a non-monotonic pattern characterizes the development of postural control in children. An analysis of QS longitudinal data in 17 healthy children between the ages of 5 and 8 years was performed to describe and explain postural control changes which may underly patterns found during this period. Consideration of the results served to explore the implications of COPvel and YS patterns on the development of control. Further directions for research were also raised by the results.

BACKROUND

MODES OF CONTROL IN POSTURAL STABILITY TASKS

Postural control in QS may be modeled as an inverted pendulum (Winter, 1995).To maintain upright equilibrium one must adjust the position of COP based on the vertical projection of the Centre of Mass (COM) onto the ground. In QS, this projection is constantly changing (Collins & DeLuca, 1993) due to internal physiological processes (Gurfinkel, Kots & Pal'tsev, 1971; Feldman, 1991), movement -induced alterations (Belinkii, Gurfinkel & Pal'tsev, 1967; Bouisset & Zattara, 1981),external perturbations (eg. Nashner & Cordo, 1981) or may differ from the anticipated location as in unpredictable perturbations (Maki & Ostrovski, 1993). Increasing skill of postural control may rely on the use of sensorimotor feedback to refine spatiotemporal parameters of both initial ballistic and execution phases of movement to contain this variable target with experience (Hayes & Riach, 1989; Massion, 1998; Massion & Woollacott, 1996).

Open loop control implies the use of preprogrammed, coordinated behavior either in anticipation of or in response to challenges to upright equilibrium (Dietz, 1992; Massion, 1992). Although rudimentary response patterns may be innate (Piek & Carman, 1994), such patterns are ineffective in the ever-changing conditions of antigravity movement. Adaptation to varied spatiotemporal characteristics of disturbances must be commensurate with the ability of the individual to evaluate those conditions, and produce an effective response (Assaiante & Amblard, 1995). This implicates learning to modify or expand the repertoire of ballistic movement patterns based on a comparison between predicted and actual events (Forrsberg & Nashner, 1982; Shumway-Cook et al., 1985). The appreciation of actual conditions requires availability and skilled use of sensory afference. Hence the notion that skilled feedforward control emerges later than feedback control (Haas, Diener, Rapp & Dichgans, 1989). In this context, "skill" refers to adaptability or the optimal parametrization (Kugler et al., 1980; Newell, 1985) of postural behavior.

Feedback is also required to execute corrections of the ongoing movement initiated by the ballistic mode of control (Bouisset & Zattara, 1987). Again the ability to monitor, integrate and use sensorimotor information to match prediction with actual conditions is prerequisite. Developmental differences are consistent both with the notion of sensory systems developing at different rates (Forrsberg et al., 1982; Laszlo & Barstow, 1980; Ornitz, 1983; Riach & Hayes, 1987; Riach & Starkes, 1989) and of individual variation in the onset and completion of sensorimotor integrative skill (Woollacott, Shumway-Cook &

Williams, 1989). Another rate-limiting variable may be neuromuscular capacity to produce the required response changes (Thelen, Fisher & Ridley-Johnson, 1984). In the case of dynamic equilibrium, kinematic limitations on producing kinetic requirements of the equilibrium task may also be implicated (Ledebt, Bril & Breniere, 1998).

MEASURES OF EQUILIBRIUM STRATEGY & EFFECTIVENESS

Postural stability may be defined by the control of COM projection onto the ground to maintain (as in QS) or change (as in stepping) the base of support (BOS) without losing vertical postural alignment against gravity. Although it is COM position relative to BOS margins that is being controlled (Murray, Seirig & Scholz, 1967; Patla, Winter, Frank et al., 1990), COP measures may be valid and reliable ($r>.8$) means to quantify postural stability in standing for test periods of greater than 10 seconds (Hasan, Robin, Szurkus et al., 1996a,b; LeClair & Riach, 1996). COP position approximates but is not equivalent to that of COM in quiet stance (Murray et al., 1967; Schenkman, 1990; Winter, 1992) and stepping (Jian, Winter, Ischac et al., 1993). The relationship of COP to COM has been described as a shepherd dog herding the COM within acceptable boundaries (Riach, 1985). COP excursion exceeds that of COM in order to direct and maintain the latter's oscillation (postural sway) within the perceived limits of BOS.

In healthy adults, anteroposterior (a-p) motions of COP and COM are highly (negatively, zero-phase) cross-correlated during QS (Hasan et al., 1996b; Gatev, Thomas, Hepple & Hallett, 1999) and dynamic equilibrium tasks (Jian et al., 1993). Assuming an inverted pendulum model for the analysis of QS equilibrium (Winter, 1995), COP measures may be used as the outcomes of the control strategy being employed. COP displacements reflect adjustments in control torque (Hasan et al., 1996b; Winter, 1995), and are directly related to the horizontal acceleration of the COM (Jian et al., 1993; MacKinnon & Winter, 1993; Winter, 1990). The extent to which COP and COM excursions covary may indicate how well YS is modulated to contain COM within the established BOS. Overshoots and undershoots may evidence errors in targeting a priori.

Alternately, the extent of covariance may indicate how tightly the individual is controlling postural sway. It may bely a real or perceived constriction of stability limits (McCollum & Leen, 1989) due to constraints in evaluating and performing the equilibrium task based on ongoing information about the difference between predicted and actual relative positions of the two variables. That is, the magnitude and frequency of the COP-COM relation may be the error signal used to modulate the gain of the feedback control system (Winter, 1995). Children increase their use of available BOS to adult-like proportions around 7 years of age (Riach et al., 1993). They are able to lean farther without moving their feet in QS; i.e. to promote a larger COP excursion within BOS and maintain the vertical line of COM. This suggests better use of sensory feedback in the task.

COPvel may indicate the strategy being used(Pyykko, Toppila, Meyer et al., 1990; Riach et al., 1994). Ballistic patterns are characterized by rapid movements with few or late corrections (Collins et al., 1993; Schmidt, 1991). (Corrections refer to the oscillation of COP around different mean positions before "settling" around a final, relatively constant mean position). Close loop movements are slower; consistent with time delays inherent in the perception and application of sensory feedback coupled with the inertial properties of responding segment masses, and prolonged deceleration by multiple corrections (Collins et al., 1993; Marteniuk, MacKenzie, Jeannerod et al., 1987). COPvel decreases between 4 and 15 years with the most rapid decline between the ages of 6 to 9 years (Taguchi & Tada, 1988). During this period, a transition between open and close loop strategies may be occurring. In a study of healthy children 4 to 13 years and adults (Riach et al., 1994) a marked drop in COPvel between 7 to 8 years could not be accounted for by rapid anthropomorphic changes. Further, there was significantly smaller between-subject variance among 8 year old subjects than among subjects in the other age groups in conditions of sensory (eyes closed) or narrowed BOS (heel to toe stance) challenges to equilibrium. However in the narrowed stance-eyes closed condition, 8-year olds demonstrated high velocities and high within-group variances. Forced reliance on shorter loop proprioceptive information about YS relative to COM excursion may have adversely affected some but not other children during this period. These results are consistent with the proposal that young children rely heavily on visual information for ballistic movement planning before integration of proprioceptive afference for use during movement execution (Forrsberg et al., 1982; Foster, Sveistrup & Woollacott, 1996; Riach et al., 1987, 1989; Shumway-Cook et al., 1985) and of individual variation in the onset and completion of sensorimotor integrative skill (Woollacott et al., 1989).

In summary, COPvel may be a discriminant measure of the control strategy employed in the QS equilibrium task for test periods greater than 10 seconds. YS may serve as the performance measure. Developmental studies to date suggest that prior to age 7 children use an open-loop strategy. At ages 7 to 8 a transition period occurs to a more closed-loop strategy, marked by increased variability. By the end of the transition there is increased effectiveness of outcome. After age 9, postural control approaches mature patterns and stability.

NON-MONOTONIC PATTERN OF POSTURAL CONTROL DEVELOPMENT

The progression of discrete skills, as in motor milestones, may appear continuous in time. However discontinuities in performance may arise from non-linear and asynchronous change in the underlying processes (Thelen & Ulrich, 1991). Development of postural control strategies may also exemplify this proposal. Two levels of analysis will be entertained: The first involves the development of postural control strategy and the underlying processes which may contribute to its emergence. The second contemplates the characteristics of the postural behaviour - the movement characteristics which derive from the underlying processes afforded by the postural control strategy used at any given age range during development.

Open vs Closed Loop Strategy Development

Rather than a gradual change from open to more close loop strategies of postural control, it is hypothesized that a non-monotonic pattern as a function of age will be evident. If motor behaviour is viewed as an emergent property (Bernstein, 1967), then the manifest behavior is a product of the relative states among intrinsic and extrinsic factors (Kugler et al., 1980; Thelen, 1989). Intrinsic factors include neurological, muscular, skeletal, cognitive, and affective states. Extrinsic factors include environmental, gravity, task, context, and physical constraints on muscles and joints. During development these independent variables (IV) undergo constant change. As discussed previously, the progression of sensory mapping (an IV that changes with age), to synergic responses to perturbation of

QS (the manifest behavior) may exemplify this idea.

The relative state of underlying systems, or IV values, can be considered constraints on the pattern of behaviour which can be produced. When the critical value of an IV or set of IV is reached, the product of the interaction changes as well. That is, the movement pattern produced exhibits a qualitative change. Such discontinuities are revealed when valid and reliable operational definitions of the behavior of interest are applied and used to differentiate between distinct movement patterns. As discussed, research has suggested that COPvel and YS may be such dependent measures (DV) which can differentiate between the use of feedforward and feedback-based patterns of equilibrium control. Discontinuity is characterized by an abrupt shift between patterns when a crucial IV or set of IV reach their critical value. Availability and skilled use of sensory feedback may be such a constraint. It has been suggested, above, that integration of feedforward and feedback control modes may be in part dependent on the ability to use feedback to modify ballistic characteristics with experience and exert context-specific corrections during the execution component of postural behaviors.

Shifts are discerned by presence of a transition period: As IV values (such as age, or some factor related to age) increase and exceed the critical range, stable DV values undergo significant changes in variability before settling at a new, consistent value. The implication of increased variability is that recalibration occurs among the underlying processes from which the pattern emerges. That is, there is a change in the relative values and weighting of constraints. Distinct periods of relative variability have been demonstrated in the COPvel and YS studies cited, where a significant increase in variability in dependent measures is followed by a decrease as adult-like values are reached. Congruence among studies of QS and reactive postural control in varied conditions of sensory information (Riach et al., 1993, 1994; Shumway-Cook et al., 1985) suggest that recalibration may indeed be involved.

Postural Control Movement Coordination

At another level of analysis, the integration of feedforward and feedback mechanisms (the underlying constraints) may contribute to the non-linear succession of qualitative changes in movement patterns (the manifest behaviors) seen in developmental studies of goal-directed movements (Bard, Hay & Fleury, 1990; Hay, 1979), postural support (Mounod, 1986; Riach et al., 1989, 1993, 1994), anticipatory postural adjustments (Hay et al., 1999), reactive postural adjustments (Shumway-Cook et al., 1985; Woollacott et al., 1987) and locomotion (McCollum, Holyroyd & Castelfranco, 1995). Qualitative change may follow from integration of feedback information with which to hone both anticipatory (Massion, 1992) and reactive components (Chong, Horak & Woollacott, 1999) of equilibrium control. Such tuning may provide for improved accuracy of estimating the projected target position a priori; whereas subsequent feedback-based corrections would be less variable or prolonged (Zatsiorsky & Duarte, 1999).

Rapid, ballistic control typical of 3 to 6-year olds is characterized by large inter- and intra-individual variability. This period reflects primary reliance on feedforward programming. Tuning may be limited. From 6 to 8 years slower, more close loop movement is evident with noticeable constriction of variability between but not within subjects, consistent with greater reliance on feedback. In this period, greater tuning may be possible. Thereafter, mixed movement characteristics suggest use of both strategies as integration of the two modes is attempted. By age 9 years an adult-like pattern emerges, characterized by an initial ballistic component followed by a corrective feedback component and more consistent responses.

Studies have shown significant changes in mean and variability of quantitative measures when children between ages 4 and 12 years are subjected to conditions of decreased or incongruous sensory afference. For example, variability of a-p and lateral COP excursions (Riach et al., 1989), COPvel (Riach et al., 1994) and QS stability limits in leaning (Riach et al., 1993) have been compared in these subjects between eyes open and closed conditions. Children less than 7 years showed little effect of eye closure suggesting primary use of an open loop strategy, without benefit from visual information. Between 7 and 8 years there was an increase in variability. During this period, children would avail themselves of available visual afference. After 9 years, an adult pattern was evident. Tuning and reliance on alternate sources of information such as proprioception could support equilibrium control.

In summary, a non-monotonic pattern of postural control during development is consistent with the notion of non-linear, asynchronous states of the underlying processes. Step rather than gradual change in the strategies employed by the control system will also manifest as non-linear change in defining parameters of postural behaviour over the period of development. As the parameters of movement change, one may expect that the outcome, postural stability, will also change. How to detect such changes in individual subjects in a developmental population remains to be considered.

LONGITUDINAL VS CROSS-SECTIONAL STUDIES

Maturation of motor skill and its component subsystems may proceed concurrently, but individual variation in the progression is evident in quantitative movement studies in recent years (Kamm, Thelen & Jensen, 1991). Further, that a rudimentary, innate motor repertoire exists cannot explain how those behaviours change in character, rather than degree, in response to altered conditions (Thelen, 1986). Different rates of change among intrinsic and extrinsic factors from which distinct patterns of motor behaviour emerge may serve to explain why such individual variation may occur (Thelen et al., 1991).

Cross-sectional and longitudinal developmental investigations may serve distinct purposes. Differences among age groups in cross-sectional studies are useful in setting age-related norms in the description of functional categories of behavior and their qualitative characteristics (Geuze, 1993). Thus they serve to identify the patterns of interest and general timing of their appearance. Across-age- comparisons also yield tentative explanations for pattern differences. However, the ability to monitor how the qualitative changes occur is limited. To understand transitions between categories of behavior, one must consider putative rate-limiting variables which may differ within individuals across time, as well as between individuals at a given point in time. By averaging such variables across subjects in cross-sectional analyses, development changes as a function of age are obscured (Schneider ,1993).

Further, which subsystem acts as the relevant constraint may vary at different ages. For example, Thelen and co-workers (1982,1984) showed that "disappearance" of the stepping reflex in infants may be due to a sudden increase in lower extremity mass without a concomitant increase in strength rather than neurological change. Addition of weights to infants' legs could extinguish the reflex. Its elicitation was possible when non-stepping infants were immersed chest-level in water, such that buoyancy compensated for insufficient strength against gravity. Similarly, the inability of young children to achieve steady-state gait velocity within a single step, as in adults, may be due to shorter foot length, rather than to absence of the anticipatory postural adjustment to gait initiation as first proposed (Bril & Breniere, 1992). As foot length increased with age, the magnitude of a-p shift increased, as then did the velocity achieved by the end of forward fall into the first step (Ledebt et al., 1998). Longitudinal research may therefore provide for identification, description, explanation and ultimately prediction of influential constraints.

Longitudinal studies may also serve to determine how stable or unstable individual differences remain over time (McCall, 1977 cited by Schneider, 1993, p. 319). Stability of a strategy (COPvel) or its outcome (YS) is reflected in measures of variability of its operational definition. Although the average value of the DV may appear monotonic as a function of age, its variability at each age may significantly differ. Monitoring periods of significant differences in variability may discern periods of transition in the behavior each measure is said to represent. Elaboration of the age norms suggested by cross-sectional studies may be provided by incorporating the age ranges within which individual differences in variability patterns occur.

An advantage of repeated measures is "matching" of putative variables across time. In essence, subjects serve as their own controls. By assessing difference scores on an individual basis, a significant change in the DV would imply that the process being measured may have reached its critical value. For example, if relative COPvel values reflect different control strategies being employed, then a significant change in those values represents a switch in control strategy for a given individual. Therefore longitudinal analyses may increase sensitivity to discontinuity of a DV over time (Wolhill 1980, cited by Schneider 1993, p. 319). Whether the elaboration of postural control is characterized by a gradual improvement of targeting with the use of feedback information, or whether an abrupt shift between strategies describes the developmental progression can be ascertained by the continuity or discontinuity of the monitored measure of the behavior.

In addition, if multiple DVs are measured, each representing different but related aspects of the function in question, difference scores may provide unbiased estimates of true change and resist the pitfalls of regression toward the mean (Schneider, 1993). That is, if a change in mean COPvel is accompanied by a change in its variability, then it is reasonable to conclude that (1) a change in strategy occurred, and (2) the strategy change was effected to influence the targeting outcome and was not an artifact of musculoskeletal variability in performance.

Finally, it has also been suggested that concern about retest bias, where subsequent behaviour is affected by previous testing, can be minimized if longitudinal data are confirmed by cross-sectional data on the same cohort (Hopkins, Beek & Kalverboer, 1993). One may be less concerned that such bias pertains if the same pattern as a function of age can be demonstrated within and between subjects once a correction is made for timing of transitions as a function of intersubject differences in underlying rates of change of contributing subsystems. In our case, if evidence of transitions in individual patterns are discerned, time-shifting individual data to align the transition periods should reveal the same overall pattern over time. Alternately, data from previous cross-sectional studies should be similar.

In summary, longitudinal research may be particularly well suited to the study of transitions. It may serve to: (1) identify intraindividual change; (2) identify interindividual differences in individual change; (3) identify interrelationships among behavior categories during development; (4) analyze causes of intraindividual change; (5) analyze causes of interindividual differences in intraindividual change; and (6) predict individual differences among particular aspects of a skill (Schneider, 1993).

PURPOSE

The purpose of this study was to determine whether a non-monotonic pattern characterizes the development of postural control in children from age 5 to 8 years. Postural control was considered in terms of control strategy, operationalized by relative values of COPvel, and effectiveness operationalized by YS.

HYPOTHESES

Given that longitudinal research monitors individual change, it may be better suited to detect transitions. We asked whether a longitudinal analysis:

1 Would find a step change in strategy - where COPvel manifests strategy;

2 If non-linearity also describes performance - where YS manifests performance; and

3 If transitions surround step changes - where Standard Deviation of COPvel and YS manifests their variability.

METHODS

Seventeen children (9 males, 8 females) were recruited through advertisements in the local newspapers. Eligibility was determined by meeting the required entry age of 5 to 6 years (61.5 - 75 months), willingness of the subject and parents to commit to testing at 3 to 4 month intervals until age 8 years (83 - 97 months), and no evidence of neuromusculoskeletal problems as reported by parents in response to a verbal questionnaire. All subjects participated in the entire length of the study. Testing was performed at McMaster University, Hamilton, Ontario.

Measurement of height, weight and foot tracings were taken during each testing visit. In each test session the child was asked to stand in each of 10 trials with shoes off and feet together as quietly as possible on a force platform for 30 seconds (Le Clair & Riach, 1996). Due to the young age of subjects at the onset of the study, an animated video was provided to motivate the maintenance of quiet stance for the 30 second period. An attempt was made to cue the video to affectively neutral portions of the film so as not to induce an added source of variability due to arousal (Maki & McIlroy, 1996) and to test at approximately the same time (between 4 PM and 8 PM) due to change of variability and reliability of postural stability in 6- to 9- year olds over the course of the day (Hattori, Starkes & Takahashi, 1992).

Although 4 conditions (eyes open or closed, standing on normal or foam surfaces) were tested in random order to assess postural sway, only the results of the eyes open, normal surface condition will be considered here. Subjects stepped off the force platform between trials and were given rests and/or a snack if they wished, to minimize fatigue (Nardone, Tarantola, Giordano et al., 1997).

Ground reaction forces were recorded using an AMTI OR6-5-1 force platform (Advanced Mechanical Technology, Inc., Newton MA) sampled at 50HZ after amplification (AMTI SGA 6-3 Signal Conditioner/Amplifier). Centre of Pressure, mean and standard deviation of COPvel and YS were calculated by an IBM- compatible 286 computer using AMTI BEDAS-2 data acquisition and analysis software (Computer Automated Stabilograph program).

Preparation of Data for Analysis

The average over 10 trials per test of each DV was calculated for each subject. There appeared to be a common pattern of COPvel and YS values over time among individual subjects (Figures 1a-b): An initial decrease, followed by an increase and a subsequent drop or leveling off of parameter values. Mean COPvel of the 17 subjects were compared across successive ages of occurrence (Figures 2a-d). Again there seemed to be a common pattern across subjects although time shifted among individuals.

In order to (1) ascertain whether the same pattern did indeed prevail over relevant periods of putative change, and (2) enable an analysis of whether the values between such periods were significantly different to impute such relevance, an attempt was made to normalize actual age differences. Subject data were aligned relative to the test at which the minimum COPvel value occurred. The minimum was designated the "0" category value. Values for adjacent test dates prior to (-3,-2,-1) and after (+1,+2,+3) individual minima were tabulated. Corresponding YS data were then reorganized using the same procedure. These categories were then considered the different conditions of the design, based on the hypothesis that in one or more conditions, the state of the control system being tested will differ due to a critical change in values of the underlying factors subsumed by the measures of interest.

Mean values for each parameter, mean age and sample size per category submitted to analysis are provided in Table 1. It should be noted that the range of ages (5.1 - 6.2 years, mean age 5.6 years) at the onset of the experiment, and individual variation in the test age of the minimum precluded an even sample size in the 3 categories prior to "0". The sample size of the -3 - category (n = 6) was too small to impute statistical significance to the results and was therefore omitted from the data to be analyzed. Further, one subject missed the test date corresponding to the +1 condition due to illness.

HYPOTHESES RESTATED

We were interested in the changes of strategy (COPvel) and of performance effectiveness (YS) as well as in detecting transitions between strategies (VELv) and behavioral patterns typifying performance (YSv) using the strategy. It was hypothesized that:

1. Developmental category affects strategy use and manifests itself as a step change at a critical period;
2. Developmental category affects performance effectiveness and manifests itself as a step change at a critical period;
3. Transition periods, defined by significant differences in variability , surround the developmental category at which a switch in strategy occurs.

Due to the wide age ranges in each category, a fourth hypothesis was generated:

4. A main effect of developmental category will persist when variances due to physical

change (height and weight) and actual age within a developmental category are removed, suggesting that underlying systems other than musculoskeletal or cognitive/affective factors have reached critical values to promote changes in control strategy and effective stability patterns of behaviour.

From the graphed results of the normalized data(Figures 3a-d) it was demonstrated that a common pattern may indeed exist. However, the characteristics of change for COPvel and YS measures appeared to differ (Figure 4a). Specifically, whereas a step change overtime was manifest in COPvel parameters, the YS parameters appeared to change linearly over developmental categories. A similar difference was found in a comparison of the variability patterns (Figure 4b).

ANALYSIS

A 1-way MANCOVA was performed on the 4 DV values (COPvel, VELv, YS, YSv) exhibited by the subjects in each of 6 conditions (Developmental categories -2,-1, 0, +1, +2, +3), with covariance of height, weight and actual age at test category removed. Height and weight have been shown to contribute significantly to the variance of COP measures (Berger, Trippel, Discher et al., 1992; Riach et al., 1993) consistent with an inverted pendulum model of QS control. With respect to actual age, factors other than those reflected by the variables of interest (eg. cognitive, affective volatility) may have been implicated due to the wide range of ages comprised within each category. In an attempt to increase sensitivity to detect change in the defined parameters, error variance due to actual age was factored out. It was reasoned that if a significant difference between developmental categories was still found, the results may lend further credence to the validity of the theoretical constructs proposed to underly the categorization. That is, developmental categories may reflect change in the underlying neurological substrates associated with sensorimotor integration rather than in physical or other factors associated with age. A post-hoc 1-way ANCOVA was then performed on each DV to determine the source of a significant main effect of developmental category. Tukey's Unequal N HSD tests were performed to discriminate significant effects between conditions.

RESULTS

There was a significant effect of developmental category (Wilkes' Lambda and Rao R (20,266); p= 0.000029) with variance due to height, weight and actual age removed. Post-hoc 1-way ANCOVAs performed for each DV (Table 2) showed a significant effect for developmental category on COPvel and VELv (p= 0.000025, 0.000005 respectively), but not on either YS measure.

Post-hoc Unequal-N HSD tests of the developmental category effect are summarized in Table 3. The relative patterns of COPvel and VELv behaviours are illustrated in Figure 5. A significant difference for COPvel was found between categories -2 and 0, and between -2 and +1 without a corresponding difference in VELv. A change in mean values without a change in variability may indicate absence of a transition period. Together with the linear decrease in COPvel between -2 and 0, the pattern may instead suggest an improvement in use or resistance to change of strategy. Significant differences in both COPvel and VELv were evident between categories of 0 and +2, and between 0 and +3 which may denote a transition pattern during this period. The linear increases of COPvel and of VELv between the 0 and +2 conditions may reflect that more numerous and faster corrections are being made commensurate with increased use of sensory feedback. Finally, there was a significant difference in VELv between +1 and +2 categories without a significant difference in COPvel. Such a pattern may suggest that honing of a mixed-use strategy has followed the transition.

The lack of significance over time for YS measures is consistent with the visual inference from the graphed data and that approximately 1 mm constitutes the largest difference between adjacent categories. The range of QS a-p excursion in healthy, young adults may exceed 20 mm (Gatev et al., 1999; Blasczcyk, Hansen, Lowe et al., 1993; Gu, Schultz, Shepard et al, 1996; Bonnet, Gurfinkel, Popov et al., 1976; Gurfinkel, Popov & Smetanin, 1992). The observation may serve to raise concerns about the interpretation of outcome measures in the assessment of postural stability, to be discussed below.

DISCUSSION

Strategy (COPvel) Patterns

A step change in strategy defined by COPvel and transitions delineated by VELv measures were confirmed. The mean velocity at the 0-defined category is significantly different from -2 category but preceded by a linear decrease over the intervening -1 condition. This intermediate gradual change and a significant difference in mean but not variability of velocity may allude to a honing of anticipatory ballistic strategy (Riach & Hayes, 1990) rather than a strategy transition. Concurrent evidence for this notion may hail from developmental studies of anticipatory postural adjustments (APA). Hay and Redon (1999) investigated the respective contributions of feedforward and feedback control in stance among children 3 to 10.5 years and adults using a simple reaction time task. They compared APA to self- and externally-induced unloading on the basis of change in COP a-p position normalized to height among pre-unloading, unloading and post-unloading periods. Mean and individual variability of onset, peak amplitude and time to peak amplitude of the COP shifts were compared. All age groups demonstrated APA to self- more than to externally-generated disturbances. Further, age-related changes reflected a tuning of amplitude, rather than timing of APA relative to focal movement. Therefore, ballistic control is typical of young children but improved targeting may occur with age. Also, individual variability during self-induced perturbation exceeded the externally-induced condition in the youngest children. The ability to modify trajectory of the ballistic pattern from trial to trial appeared compromised. Although 3 to 5-year olds showed directionally appropriate APA, the amplitudes of COP shifts were more variable than those of older children. If considered in light of previous evidence of immature sensorimotor integration at this point in development (Berger, Quintern & Dietz, 1987; Haas, Diener, Bacher et al., 1986), perhaps tuning of ballistic amplitude is limited by the ability to assess the error between expected and actual target position and integrate the results to modify ballistic targeting.

Further, age-related changes were non-monotonic. The 6- to 8-year olds manifested earlier anticipatory adjustments, with greater variability of shift magnitude than either younger or older age groups. This suggests an allowance for the time-consuming reliance on feedback and fine tuning of postural adjustments during and after APA execution. As suggested here and in studies of reactive postural control development (eg., Shumway-Cook et al., 1985), recalibration of multisensory information may promote incipient use of sensory feedback. Early in the transition period, immature skill in sensorimotor integration may underly the seeming "regression" in both feedforward and feedback postural control mechanisms.

Greater use of closed-loop control is underscored by a linear increase in COPvel between 0 and +2 categories with commensurate increases in variability. This concurrence may indicate that a transition in strategy may be underway. Increased velocity is consistent with more numerous and faster corrections, which suggests use of ongoing feedback, as discussed above.

Lack of statistical significance in mean velocity despite significant difference in variability between +1 and +2 may reflect a mixed-use strategy. Although not significant, the visual trend indicates a leveling off of velocity values. Were the trend to continue, one might argue that children are honing the target criterion for both ballistic and on-going corrections based on better use of sensory feedback to evaluate the error between COP and COM positions. Learning through experience (Sveistrup & Woollacott, 1997) may consolidate use of information from maturing sensory systems.

A-P Excursion (YS) Patterns

Excursion did not show the expected non-linear pattern. Children at 5 years are practiced in standing. Evidence for calibration of internal referents with experience in the equilibrium task has been shown in children soon after they achieve each milestone of antigravity posture, such as independent standing and walking (Sveistrup & Woollacott, 1993, 1996). Therefore, by the first time of test, YS magnitude and variability should have achieved relatively stable values using the early ballistic strategy. As more sensory feedback is used, it was expected that variability would increase. With subsequent learning and tuning of both open and close loop response based on the additional information, we anticipated that YS would settle at a new, less variable and lower magnitude. In short, we expected improved evaluation of the COP-COM error signal and improved COM targeting as a result.

Instead, there was a linear decrease in YS overtime and lack of significant differences between excursion measures among developmental categories. This may suggest that performance, or effectiveness of response, is appropriate for a given state of the underlying control mechanism. That is, a real or perceived restriction of component processes may limit a-p excursion the child is willing or able to perform - inasmuch as doing so does not incur a loss of equilibrium.

Previous cross-sectional studies of challenged QS in children have shown an increase in variability of a-p and lateral COP excursion measures (Riach et al., 1989), in stability limits (Riach et al., 1993) and COPvel (Riach et al., 1994) between the ages of 7 and 8 years. Consider the tightly controlled period of variability during the 0-category in the present study: LeClair and Riach (1995) have shown that healthy young adults increase COM oscillation in QS with test duration, whereas ground reaction forces and velocity decrease over test duration. Because COP measures reflect the number and magnitude of corrections of posture, they suggested that corrections decrease as a subject "settles in" over a 30s test duration. That is, the control system allows a more forgiving range of COM drift within the established BOS, also reflected as an increase in stability limits.

One might postulate that children in the 0-category do not relax perceived stability limits. At the minimum velocity point, there was a notable constriction in its variability.

Thereafter, while a-p excursion continues to linearly decrease, velocity values increase. Increased COPvel should be accompanied by increased YS. Small YS values despite higher COPvel values may reflect a transitory restriction. A restriction of stability limits would be commensurate with difficulty resolving multimodal information, or by selective reliance on another kind of information to assess the error signal between COP and COM projection over time. Therefore, during the transition between use of predictive and integrated sensory feedback modes for QS stability control, children manifest a less forgiving pattern when controlling sway.

Hay and Redon (1999) found a similar "transient overcontrol of posture" among 6 to 8-year olds. The anticipatory postural adjustments of this age group were significantly larger than required and had earlier onsets thereby reducing the amplitude of perturbation a priori. Earlier onsets may also allow more time for use of sensory afference to correct for excessive adjustments. In an arm raise task, Riach and Hayes (1990) found that 4 to 6-year olds may first shift in the direction of perturbation before counteracting it. Perhaps the children were minimizing the error signal a priori.

This invokes the notion of adaptability, defined as the ability to change the value of response parameters within the same behavioural pattern. A high level of skill is marked by the capacity to make a quantitative change within the range of a given behaviour's parametric values, without necessitating a qualitative change, or change of control behaviour. In essence one would be quantifying the ability to use an ankle strategy and maintain the same BOS, without resorting to a change-BOS strategy.

One must ask if a constriction of operating range - limiting the use of available BOS for which a given strategy is effective - is also sufficiently adaptable in the face of challenge. Can a perturbation (whether internally or externally generated) of COM beyond that imposed limit be accommodated by increasing the otherwise narrow COP operating range of the fixed-support strategy? Will it instead result in a step (change-of-support strategy) at best, and fall at worst? If the level of sensorimotor integrative skill is the underlying constraint in progressing from the defined 0-category through to a multi-modal strategy in the +2 - category, it is necessary to investigate the adaptability of the QS patterns found among subjects within and between the categorized stages of equilibrium control. In conditions of challenge, one tests the ability to expand the range of COP excursion and its velocity to contain the excursion of the projected COM within the existing BOS in order to preserve verticality.

CLINICAL IMPLICATIONS

The apparent constriction of both YS and COPvel range in values around the 0-category makes the potential for skilled adaptation unlikely. In young, healthy adults YS may range as high as 21 mm COP (Gatev et al., 1999; Blasczcyk, Hansen, Lowe et al., 1993; Gu, Schultz, Shepard et al., 1996; Bonnet, Gurfinkel, Popov, et al., 1976; Gurfinkel, Popov & Smetanin, 1992), and COPvel as high as 21 mm/s (Riach et al., 1994). In our data, within subject variability (SD) in the 0-category was 1.79 mm excursion and 8.1 mm/s velocity. Between subject variability (SE) in this condition was .43 mm excursion and 1.96 mm/s velocity.

It is difficult to compare the results of our data to available cross-sectional studies in children due to the significant age range within each developmental category and absence of raw data in some reports. From a visual inspection of the figures provided in one study (Taguchi et al., 1988), it appears that range of velocity decreases linearly from age 4 to 15 years to approximate adult ranges whereas a-p range does not appreciably differ across age groups. In contrast, Riach and Starkes (1994) studied QS velocity changes in children aged 4 to 13 years. They found severe constriction of variability (SE) in 8-year olds, the age at which subjects appeared to "regress" in conditions of sensory (eyes closed) and BOS (narrowed, heel-to-toe stance) conditions. A closer look at individual performances revealed that 2 of 6 subjects had higher velocities typical of ballistic control; whereas 4 subjects had lower velocities typical of closed-loop control. Therefore, individual differences in completion of the transition to a dual-mode strategy may not be detected by cross-sectional designs and the constriction found here and the cited study may typify transitions in progress.

Variability is essential, as it reflects the continuous modulation of movement parameters to accommodate contextual variations in the forces acting on the body at any given moment (Reed, 1989). The implications of the constriction are (1) an inability to adapt the prevailing strategy to accommodate conditions of challenge; and (2) lack of skilled equilibrium control relying on the use of sensory feedback to hone both ballistic and close loop aspects of QS targeting behaviour.

The lack of significant differences over time for YS measures raises cautionary hypotheses with regards to the interpretation of outcome measures in the assessment of postural stability. In the developmental (eg. Hayes, Spencer, Riach, et al., 1985; Sheldon, 1963) and pathology literature (eg. Brandt & Paulus, 1989; Dickstein, Nissan, Pillar et al., 1984; Herdman, 1990; Hufschmidt, Dichgans, Mauritz et al., 1980; Stelmach, Phillips, DiFabio et al., 1989) increased or inordinate amounts of COP excursion have been interpreted as compromised QS stability. It may instead reflect the appropriateness of COP modulation to the given strategy or capacity of the control system at a given juncture (Latash & Anson, 1996). At the same time, severe restriction may be symptomatic of the inability to successfully adapt control behaviour to challenge, and raise concerns about a subject's potential to fall.

Variability of movement parameters within a given strategy in response to changing demands has been demonstrated for both gait (Winter, 1984, 1985) and stance (eg. Duarte & Zatsiorsky, 1999; Gatev et al., 1999; Hasan et al., 1990; Nashner & McCollum, 1985) among healthy, young adults. Increased variability of movement parameters have been associated with balance expertise in athletes (eg. Mouchnino, Aurenty, Massion et al., 1990; Pedotti, Crenna, Deat et al., 1989). Reduced variability has been associated with compromised functional stability in static and dynamic tasks among subjects with neurological and musculoskeletal pathology (eg. Bouisset, 1996; Goldberg & Mayer, 1996; Klatzky, 1996; Newell & Morrison, 1996; Walter & Kamm, 1996). It has also been implicated in limitations on functional stability in children with neurological deficits (eg., Horak, Shumway-Cook, Crowe et al., 1988; Jeng, Holt, Fetters et al., 1996; Shumway-Cook & Horak, 1986; Winter, Olney, Conrad et al., 1990; Woollacott, Burtner, Jensen et al., 1998).

The ability to modulate spatiotemporal parameters of movements within a given coordinative strategy may therefore be more informative about use of afference in promoting progression of postural skill. Altering afferent aspects of the task has been extensively used to explicate developmental and pathological differences in sensorimotor integration for equilibrium control(see reviews by Massion, 1992, 1998). When a primarily open loop strategy is used, the loss of visual feedback in eyes-closed (EC) test conditions (Riach et al., 1989) or inaccuracy of proprioceptive information (F)when standing on foam (Shumway-Cook & Horak, 1986) seems to have little effect on YS measures in young children. In contrast, an F-EC condition promotes increased a-p excursion and variability, and may result in a fall (Shumway-Cook et al., 1986) If prior to the 0-category the postural strategy is primarily ballistic, eye closure to decrease visual information, or standing on foam to reduce or befuddle proprioceptive information should have no effect on QS parameters. An F-EC condition should be reflected by greater YS variability.

Throughout the later process of multi-sensory calibration, vision is thought to play a pivotal role (Foster, Sveistrup & Woollacott, 1996; Lee & Aronson, 1974) and the use of proprioceptive information increases (Forrsberg & Nashner, 1982). During this period, children have been shown to be keenly susceptible to destabilization of inter-sensory conflict (Forssberg et al., 1982; Shumway-Cook et al., 1985). As the transition to a multi-modal strategy ensues between 0- and +3 developmental categories, one should see a decrease in COPvel as ballistic and feedback modes are integrated but an increase in YS reflecting a greater range within which the adopted control system can operate.

Another approach to the problem of constriction may be to test the ability to use ongoing sensory information about relative COP-COM positions in a forward lean task. Changing the location of COM projection, as in forward lean, requires a different use of available base of support relative to the limits of stability. The manipulation may challenge the control system's ability to monitor and adapt targeting of COM by COP on a continuous basis.

It is unclear whether it is possible to predict performance in the 0-category, where it is proposed there is excessive reliance on sensory information. Whereas one might expect increased variability of excursions, the apparent constriction of a-p excursion a priori may preclude use of a fixed-BOS capability, and increase use of a change-of-support reaction. Further, the restriction may occasion multiple, rather than single step compensatory responses (Maki & McIlroy, 1997). If children at this level of skill rely on several steps to compensate for the self- generated perturbation of COM, one might consider the adaptation of expectations placed on a child in, for example, a baseball game. One might need to relax the spatial limitation on the child at bat. A larger area within which to move during the swing would be appropriate.

Incorporation of conditions of challenge emphasizes the dynamic nature of QS control. Whether the equilibrium task is to maintain or change BOS, the velocity of COP excursion must be commensurate with the spatial and temporal targeting requirements of projected or actual COM projection onto the support surface. If skilled equilibrium control is predicated on sensorimotor integrity (Stelmach & Worringham, 1985), and skilled sensorimotor behavior relies on active movement (Glencross, 1995; Newell & McDonald, 1992; Scheerer, 1990), then both assessment and re/habilitation must incorporate conditions of predictable and unpredictable target perturbation to sufficiently reflect a subject's level of stability. In fact, casual observation of children at play will reveal that they are always testing "boundaries". Similarly, stretching the envelope is necessary for increased motor expertise in sports, or expertise in cognitive skills.

A corollary may be found in studies of compromised equilibrium in subjects with neurological pathology who appear to decrease the boundaries within which a fixed-BOS strategy is employed (Maki et al., 1997). Perhaps a constriction of stability limits is an attempt to minimize a novel error signal which would require adaptation of the spatiotemporal characteristics of postural behaviour. For example, there is an inability to modulate velocity and amplitude in cerebellar pathology (Diener & Dichgans, 1988; Timmann & Horak 1997,1998) and of direction and timing in elderly associated with peripheral or central neuropathies (Inglin & Woollacott, 1988; McIlroy & Maki 1996). This further implies that the imposed stability limits are based on assessment of: (1) response parameters relative to an established criterion based on previous experience (immediate or more long term); and (2) adaptability relies on continual assessment and modification of criterion according to prevailing conditions. The ability to avail oneself of and use sensory feedback to assess appropriateness of response parameters may be requisite.

LIMITATIONS AND FURTHER STUDY

To further test the hypothesis that sensorimotor integration may be the component of control subsumed by the developmental category, it is necessary to apply the analysis to data collected in conditions of challenge as suggested above. It is expected that mean and variability measures of the same subjects in and around the switch of control strategy should significantly differ from QS. To maintain verticality and the established BOS, a-p excursion will increase in magnitude and variability.

It was proposed that a continued trend to decrease COPvel without a significant difference in VELv past the +3 category may support the contention that a honing of a mixed-use strategy occurs. The present analysis should be extended to include follow-up data collected on 9 subjects to test this suggestion.

Differences according to gender and foot width might be considered. It has been shown that the best predictor for a-p range in adults is gender (>foot width,>weight) and the 3 factors combined account for 83% of variance (Riach et al., 1993). With regards to gender, it is expected that girls would attempt to incorporate sensory information at an earlier age than boys based on earlier rates of maturation (Menkes, 1985). Oddly, gender differences may not be apparent in the present study. An exploratory t-test was performed on actual age of 9 males and 8 females in the 0-category and no significant difference (p level = .05) was found. However, in studies of challenge conditions it may be prudent to pay heed to possible gender differences.

With regards to foot width, the present study tested stability in a feet-together stance. A-p excursion in terms of area or percent of available stability limits used (Riach et al., 1993) may be a useful concurrent measure for comparison of changes in velocity and excursion. This is congruent with the notion that perceived stability limits may be related to use of somatosensory information to assess the error signal between COP and COM relative to the available BOS. "Risk taking" of the system will be presumably based on the capacity of the system to respond within a range of a-p excursion deemed acceptable to maintain BOS. Alternately, it may explain the need to use a change- BOS response instead.

The possible effect of arousal level effect on variability of COP measures (Maki et al., 1996) could be considered by evaluating skin conductance, heart or respiratory rate during testing.

Learning and practice in conditions of challenge may also contribute to performance or rate of progression (Cremiuex & Mesure, 1990; Debu, Werner & Woollacott, 1989; Mesure, Bonnet & Cremieux, 1992). Data from each subject was collected regarding the type, duration and frequency of athletic and related physical activities in organized and leisure settings over the course of the experiment. The data requires coding and a method of analysis to investigate whether practice amount, type, or variability may affect the rate or characteristics of progression.

Finally, a limitation imposed by the method of data preparation is the ability to analyze intra-subject differences. Except for actual age of individual members in a developmental cohort, within-subject variability is accounted for by the covariates. The results are therefore also limited by the extent to which appropriate and meaningful covariates are identified to successfully isolate factors associated with age other than those which may represent the putative, underlying variable responsible for the monitored outcome: In our case, the ability to differentiate between sensorimotor integration and other age-related factors. This observation underscores the importance of cross-sectional studies in identifying important variables and their relationship to possible operational definitions of control behaviours. Longitudinal studies of development can then put those relationships to the test.

CONCLUSIONS

A non-monotonic change in control strategy describes the development of quiet stance equilibrium. Linear change in effective Centre of Pressure excursion, regardless of strategy employed in quiet stance, may decrease the utility of this measure to assess the stability status of children. Its meaningfulness may increase when monitored in conditions of challenged quiet stance. A transition occurs from a primarily open-loop strategy to incorporation of open and close loop components of COM targeting. The transition is marked by variability of velocity of excursion before completion of the transition. The early ballistic mode may be followed by excessive reliance on feedback-based correction before mergence of a dual-mode response. Developmental category describes affiliation with the strategy employed. Such categories may represent differentiable levels of sensorimotor integrative skill. They may also be more useful in assessing progression of equilibrium control than consecutive age in years. Finally, constriction of velocity and excursion in the early stages of bi-modal strategy use may contribute to instability in real-world situations.

REFERENCES

Assaiante, C., Amblard, B. (1995). An ontogenetic model for sensorimotor organization of balance control in humans. Human Movement Science, 11, 533-548.

Bard, C., Hay, L., Fleury, M. (1990). Timing and accuracy of visually directed movements in children: control of direction and amplitude components. Journal of Experimental Child Psychology, 50, 102-118.

Belinkii, V.Y., Gurfinkel, V.S., Pal'tsev, Y.I. (1967). Elements of control of voluntary movement. Biophysics 12, 154-160.

Berger, W., Quintern, J., Dietz, V. (1987). Afferent and efferent control of stance and gait: developmental changes in children. Electroencephalography and clinical Neurophysiology, 66, 244-252.

Berger, W., Trippel, M., Discher, M., Dietz, V. (1992). Dependency of body height and body stabilization. In, M. Woollacott 7 F. Horak (Eds.). Posture and Gait: Control Mechanisms. Vol II. (pp 343-345). Eugene, Oregon: University of Oregon.

Bernstein, N. (1967). The Coordination and Regulation of Movement. New York: Pergamon Press.

Blaszczyk, J.W., Hansen, P.D., Lowe, D.L. (1993). Perception of stability borders. Perception, 22, 1333-1341.

Bonnet, M., Gurfinkel, V.S., Popov, K.E., Lipshits, M.I. (1976). Central programming of lower limb muscular activity in the standing man. Aggressologie, 17, 35-42.

Bouisset, S. (1996). Posturo-kinetic capacity in the disabled. Behavioral and Brain

Bouisset, S., Zattara, M. (1981). A sequence of postural movements precedes voluntary movement. Neuroscience Letters, 22, 263-270.

Bouisset, S., Zattara, M. (1987). Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. Journal of Biomechanics, 20, 735-742.

Brandt, T., Paulus, W. (1989). Postural retraining in exceptional populations. In, M.H. Woollacott & A. Shumway-Cook (Eds.). Development of Posture and Gait Across the Lifespan (pp 299-319). Columbia, South Carolina: University of South Carolina Press.

Bril, B., Breniere, Y. (1992). Postural requirements and progression velocity in young walkers. Journal of Motor Behavior, 24, 105-116.

Chong, R.K.Y., Horak, F.B., Woollacott, M.H. (1999). Time-dependent influence of sensorimotor set on automatic responses in perturbed stance. Experimental Brain Research, 124, 513-519.

Collins, J.J., De Luca, C.J. (1993). Open-loop and closed-loop control of posture: a random-walk analysis od center-of-pressure trajectories. Experimental Brain Research, 95, 308-318.

Cremieux, J., Mesure, S. (1990). The effects of judo training on postural control assessed by accelerometry. In, T. Brandt (Ed.). Proceedings of the Tenth International Symposium on Disorders of Posture and Gait, Munich, September 2-6 (pp 302-306). New York: Georg Thieme Verlag.

Debu, B., Werner, L., Woollacott, M. (1989). Influence of athletic training on postural stability. In, M.H. Woollacott & A. Shumway-Cook (Eds.). Development of Posture and Gait Across the Life Span (pp 280-198). Columbia, South Carolina: University of South Carolina Press.

Diener, H-C., Dichgans, J. (1988). Pathophysiology of posture. In, B. Amblard, A. Berthoz & F. Clarac (Eds.). Posture and Gait: Development, Adaptation and Modulation (pp 229-235). Amsterdam: Elsevier Science Publishers.

Dickstein, R., Nissan, M., Pillar, T., Scheer, D. (1984). Foot-ground pressure pattern of standing hemiplegic patients: major characteristics and patterns of movement. Physical Therapy, 64, 19-23.

Dietz, V. (1992). Human neuronal control of automatic functional movements; interactions between central programs and afferent input. Physiological Reviews, 72, 33-69.

Duarte, M., Zatsiorsky V.M. (1999). Patterns of center of pressure migration during prolonged unconstrained standing. Motor Control, 3, 12-27.

Foster, E., Sveistrup, H., Woollacott, M.H. (1996). Transitions in visual proprioception: a cross-sectional developmental study of the effect of visual flow on postural control. Journal of Motor Behavior, 28, 101-112.

Forrsberg, H., Nashner, L.M. (1982). Ontogenetic development of postural control in man: adaptation to altered support and visual conditions during stance. Journal of Neuroscience, 2, 545-552.

Gatev, P., Thomas, S., Kepple, T., Hallett, M. (1999). Feedforward ankle strategy of balance during quiet stance in adults. Journal of Physiology, 514, 915-928.

Geuze, R.Hh (1993). Longitudinal and cross-sectional approaches in experimental studies of motor development. In, A.F. Kalverboer, B. Hopkins, & R. Geuze (Eds.). Motor Development in Early and Later Childhood: Longitudinal Approaches (pp 307-316). Dorchester, New York: Cambridge University Press.

Glencross, D.J. (1995). Motor control and sensory integration. In, D.J. Glencross & J.P. Piek (Eds.). Motor Control and Sensory Integration Issues and Directions (pp 3-7). New York: Elsevier Science Publishers.

Goldberg, G., Mayer, N.H. (1996). The goal of treatment for motor impairment is not to "normalize" but to "functionalize" through facilitative modulation and enabling context. Behavioral and Brain Sciences, 19, 75-76.

Gu, M-J., Schultz, A.B., Shepard, N.T., Alexander, N.B. (1996). Postural control in young and elderly adults when stance is perturbed: dynamics. Journal of Biomechanics, 29, 319-329.

Gurfinkel, V.S., Kots, Y.M., Pal'tsev, Y.I., Feldman, A.G. (1971). The compensation of respiratory disturbances of the erect posture of man as an example of organization of interarticular interaction. In, I.M. Glefland, V.S. Gurfinkel, S.V. Fomin, & M.LI Tsetlin (Eds.). Models of Structural Functional Organization of Certain Biological Systems (pp 361-372). Cambridge, MA: MIT Press.

Gurfinkel, V.S., Popov, K.E., Smetanin, B.N. (1992). The support as a reference for postural control. In, M. Woollacott & F. Horak (Eds.). Posture and Gait: Control Mechanisms, Vol I. (pp 186-189). Eugene, Oregon: University of Oregon.

Haas, G., Diener, H.C., Bacher, M., Dichgans, J. (1986). Development of postural control in children: short-, medium-, and long latency EMG responses of leg muscles after perturbation of stance. Experimental Brain Research, 64, 127-132.

Haas, G., Diener, H.Cc, Rapp, H., Dichgans, J. (1989). Development of feedback and feedforward control of upright stance. Developmental Medicine and Child Neurology, 31, 481-488.

Hasan, S.S., Robin, D.W., Szurkus, D.C., Ashmead, D.H., Peterson, S.W., Shiavl,R.G. (1996a). Simultaneous measurement of body center of pressure and center of gravity during upright stance. Part I: methods. Gait & Posture, 4, 1-10.

Hasan, S.S., Robin, D.W., Szurkus, D.C., Ashmead, D.H., Peterson, S.W., Shiavi, R.G. (1996b). Simultaneous measurement of body center of pressure and center of gravity during upright stance. Part II: amplitude and frequency data. Gait & Posture, 4, 11-20.

Hattori, H., Starkes, J., Takahashi, T. (1992). Diurnal variability and reliability of postural sway assessment. In, M. Woollacott & F. Horak (Eds.). Posture and Gait: Control Mechanisms, Vol II. (pp 259-262). Eugene, Oregon: University of Oregon.

Hay, L. (1979). Spatial-temporal analysis of movements in children: motor programs versus feedback in development of reaching. Journal of Motor Behavior, 11, 189-200.

Hay, L., Redon, C. (1999). Feedforward versus feedback control in children and adults subjected to postural disturbance. Experimental Brain Research, 125, 153-162.

Hayes, K.C., Riach, C.L. (1989). Preparatory postural adjustments and postural sway. In, M.H. Woollacott, & A. Shumway-Cook (Eds.). Development of Posture and Gait Across the Lifespan (pp 95-127). Columbia, South Carolina: University of South Carolina Press.

Hayes, K.C., Spencer, J.D., Riach, C.L., Lucy, S.D., Kirshen, A.J. (1985). Age-related changes in postural sway. In, D. Winter, K. Hayes & A. Patla (Eds.). Biomechanics IX-A (pp 383-387). Champagne, Illinois:Human Kinetics.

Herdman, S. (1990). Assessment and treatment of balance disorders in the vestibular-deficient patient. In, P. Duncan (Ed.). Balance: Proceedings of the APTA Forum (pp 161-8). Alexandria, Virginia: APTA.

Hopkins, B., Beek, P.J., Kalverboer, A.F. (1993). Theoretical issues in the longitudinal study of motor development. In, A.F. Kalverboer, B. Hopkins, & R. Geuze (Eds.). Motor Development in Early and Later Childhood: Longitudinal Approaches (pp 343-371). Dorchester, New York, Cambridge University Press.

Horak, F., Shumway-Cook, A., Crowe, T., Black, F.O. (1988). Vestibular function and motor proficiency in children with hearing impairments and learning disabled children with motor impairments. Developmental Medicine and Child Neurology, 30, 64-79.

Hufschmidt, A., Dichgans, J., Mauritz, K-H., Hufschmidt, M. (1980). Some methods and parameters of body sway quantification and their neurological applications. Archiv fur Psychiatrie und Nervenkrankheiten (Archives of Psychiatry and Neurological Sciences), 228, 135-150.

Inglin B, Woollacott MH (1988). Age-related changes in anticipatory postural adjustments associated with arm movements. Journal of Gerontology 43, M105- M113.

Jeng, S-F., Holt, K.G., Fetters, L., Certo, C. (1996). Self-optimization of walking in nondisabled children and children with spastic hemiplegic cerebral palsy. Journal of Motor Behaviour, 28, 15-27.

Jian, Y., Winter, D.A., Ishac, M.G., Gilchrist, L. (1993). Trajectory of the body COG and COP during initiation and termination of gait. Gait & Posture, 1, 9-22.

Klatzky, R.L. (1996). What makes a population atypical - priorities or constraints? Behavioral and Brain Sciences, 19, 78-9.

Kugler, P.N., Kelso, J.A.S., Turvey, M.T. (1980). On the concept of coordinative structures as dissipative structures. I. theoretical line. In, G.E. Stelmach, & J. Requin (Eds.). Tutorials in Motor Behavior (pp 3-47). New York: North-Holland Publishing Company.

Laszlo, J., Bairstow, P. (1980). The measurement of kinaesthetic sensitivity of children and adults. Developmental Medicine and Child Neurology, 22, 454-464.

Latash, M.L., Anson J.G. (1996). What are "normal" movements in atypical populations? Behavioral and Brain Sciences, 19, 55-106.

LeClair, K., Riach, C.L. (1996). Postural stability measures: what to measure and for how long. Clinical Biomechanics, 11, 176-178.

Ledebt, A., Bril, B., Breniere, Y. (1998). The build-up of anticipatory behavior. Experimental Brain Research, 120, 9-17.

Lee, D.N., Aronson, E. (1974). Visual proprioceptive control of standing in human infants. Perception and Psychophysics, 15, 529-532.

Kamm, K., Thelen, E., Jensen, J.L. (1991). A dynamical systems approach to motor development. In, Movement Science (pp 11-10). American Physical Therapy Association Monograph.

MacKinnon, C.D., Winter, D.A. (1993). Control of whole body balance in the frontal plane during human walking. Journal of Biomechanics, 26, 633-644.

Maki, B.E., McIlroy, W.E. (1996). Influence of arousal and attention on the control of postural sway. Journal of Vestibular Research, 6, 53-59.

Maki, B.E., McIlroy, W.E. (1997). The role of limb movements in maintaining upright stance: the "change-in-support" strategy. Physical Therapy, 77, 488-507.

Maki, B.E., Ostrovski, G. (1993). Scaling of postural responses to transient and continuous perturbations. Gait and Posture 1, 93-104.

Marteniuk, R.G., MacKenzie, C.L., Jeannerod, M., Athenes, S., Dugas, C. (1987). Constraints on human arm movement trajectories. Canadian Journal of Psychology, 41, 365-378.

Massion, J. (1992). Movement, posture and equilibrium: interaction and coordination. Progress in Neurobiology, 38, 35-56.

Massion, J. (1998). Postural control systems in a developmental perspective. Neuroscience and Behavioral Reviews, 22, 465-472.

Massion, J., Woollacott, M.H. (1996). Posture and equilibrium. In, A.M. Bronstein, T. Brandt, & M.H. Woollacott (Eds.). Clinical Disorders of Balance, Posture and Gait (pp 1-18). New York: Oxford University Press.

McCall, R.B .(1977). Challenges to a science of developmental psychology. Child Development, 58, 33-37.

McCollum, G., Holyrod, C., Castelfranco, A.V. (1995). Forms of early walking. Journal of Theoretical Biology, 176, 373-390.

McCollum, G., Leen, T.K. (1989). Form and exploration of mechanical stability limits in erect stance. Journal of Motor Behavior, 21, 225-244.

Mcllroy WE, Maki BE (1996). Age-related changes in compensatory stepping in response to unpredictable perturbations. Journal of Gerontology: Medical Sciences 51A, M289-M296.

Menkes, J.H. (1985). Textbook of Child Neurology. 3rd ed. Philadelphia: Lea & Febiger.

Mesure, s., Bonnet, M., Cremieux, J. (1992). Postural reaction time and performance during static equilibrium. In, M. Woollacott & F. Horak (Eds.). Posture and Gait: Control Mechanisms. Vol. I. (pp 214-217). Eugene, Oregon: University of Oregon.

Meyers, J.L. (1972). Fundamentals of Experimental Design. Boston: Allyn & Bacon, Inc.

Mouchnino, L., Aurenty, R., Massion, J., Pedotti, A. (1990). Coordinated control of posture and equilibrium during leg movement. In, T. Brandt, W. Paulus, W. Bles, M. Dietrich, S. Krafczyk & A. Straube (Eds.). Disorders of Posture and Gait. Tenth International Symposium (pp 68-71). Stuttgart: Georg Thieme.

Mounod, P. (1986). Action and cognition: cognitive and motor skills in a developmental perspective. In, M.G. Wade, & H.T.A. Whiting (Eds.). Motor Development in Children: Aspects of Coordination and Control (pp 373-390). Boston: Martinus Nijhoff Publishers.

Murray, M.P., Seirig, A., Scholz, R.C. (1967). Center of gravity, center of pressure, and supportive forces during human activities. Journal of Applied Physiology, 23, 831-838.

Nardone, A., Tarantola, J., Giordano, A., Schieppatti, M. (1997). Fatigue effects on body balance. Electroencephalography and clinical Neurophysiology, 105, 309-320.

Nashner, L.M., Cordo, P.J. (1981). Relation of automatic postural responses and reaction-time movements of human leg muscles. Experimental Brain Research, 43, 395-405.

Newell, K.M. (1986). Constraints on development of coordination. In, M.G. Wade, & H.T.A. Whiting (Eds.). Motor Development in Children: Aspects of Coordination and Control (pp 341-360). Boston: Martinus Nijhoff Publishers.

Newell, K.M., McDonald, P.V. (1992). Searching for solutions to the coordination of function: learning as exploratory behavior. In, G.E. Stelmach & J. Requin (Eds.). Tutorials in Motor Behavior II (pp 517-532). North-Holland: Elsevier Science Publishers BV.

Newell, K.M., Morrison, S. (1996). Frames of reference and normal movement. Behavioral and Brain Sciences, 19, 83-4.

Ornitz, E. (1983). Normal and pathological maturation of vestibular function in the human child. In, R. Romand (Ed.). Development of Auditory and Vestibular Systems (pp 479-536). New York: Academic Press.

Patla, A.E., Winter, D.A., Frank, J.S., Walt, S.E., Prasad, S. (1990). Identification of age-related changes in the balance-control system. In, P.W. Duncan (Ed.). Proceedings of the APTA Symposium on Balance, Nashville, Tennessee, June 13-15, 1989 (pp 43-56). APTA.

Pedotti, A., Crenna, P., Deat, A., Frigo, C., Massion, J. (1989). Postural synergies in axial movements: short and long-term adaptation. Experimental Brain Research, 74, 3-10.

Piek, J.P., Carman, R.C.(1994). Developmental profiles of spontaneous movements in infants. Early Human Development, 39, 109-126.

Pyykko, I., Toppila, H., Meyer, E., Aalto, H., Starck, J., Ishizaki, H. (1990). Postural instability after bilateral vestibular lesion - an error in sway velocity estimation? In, T. Brandt, W. Paulus, W. Bles, M. Dietrich, S. Krafczyk & A. Straube (Eds.). Disorders of Posture and Gait. Tenth International Symposium (pp 136-139). Stuttgart: Georg Thieme Verlag.

Reed, E.S. (1989). Changing theories of postural control. In, M.H. Woollacott & A. Shumway-Cook (Eds.). Development of Posture and Gait Across the Life Span (pp 3-24). Columbia, SouthCarolina: University of South Carolina Press.

Riach, C.L. (1985). The development of feedforward and feedback control of posture in children. PhD Dissertation. University of Waterloo.

Riach, C.L., Hayes, K.C. (1987). Maturation of postural sway in young children. Developmental Medicine and Child Neurology, 29, 650-658.

Riach, C.L., Hayes, K.C. (1990). Anticipatory postural control in children. Journal of Motor Behavior, 22, 250-266.

Riach, C.L., Starkes ,J.L .(1989). Visual fixation and postural sway in children. Journal of Motor Behavior, 21, 256-276.

Riach, C.L., Starkes, J.L. (1994). Velocity of centre of pressure excursions as an indicator of postural control systems in children. Gait & Posture 2, 167-172.

Riach, C.L., Starkes, J.L. (1993). Stability limits of quiet standing postural control in children and adults. Gait & Posture, 1, 105-111.

Scheerer, E. (1990). Relations between perception and action: unity in diversity. In, O. Neumann & W. Prinz (Eds.). Relationships Between Perception and Action (pp 367-

387). Heidelberg: Springer-Verlag.

Schenkman, M. (1990). Interrelationship of neurological and mechanical factors in balance control. In, P.W. Duncan (Ed.). Balance, Proceedings of the APTA Forum, Nashville, Tennessee, June 13-15, 1989(pp 29-42). APTA.

Schmidt, R.A. (1991). Motor Learning and Performance: From Principles to Practice. Champagne, Illinois: Human Kinetic Books.

Schneider, W. (1993). The longitudinal study of motor development: methodological issues. In, A.F. Kalverboer, B. Hopkins, & R. Geuze (Eds.). Motor Development in Early and Later Childhood: Longitudinal Approaches (pp 317-342). Dorchester, New York: Cambridge University Press.

Schutz, R.W., Gessaroli, M.E. (1987). The analysis of repeated measures designs involving multiple dependent variables. Research Quarterly for Exercise and Sport, 58, 132-149.

Sheldon, J.H. (1963). The effect of age on control of sway. Gerontologica Clinica, 5, 129-138.

Shumway-Cook, A., Horak, F. (1986). Assessing the influence of sensory interaction on balance. Physical Therapy, 66, 1548-1550.

Shumway-Cook, A., Woollacott, M.H. (1985). The growth of stability: postural control from a developmental perspective. Journal of Motor Behavior, 17, 131-147.

Stelmach, G.E., Phillips, J., DiFabio, R.P., Teasdale, N. (1989). Age, functional postural reflexes and voluntary sway. Journal of Gerontology, 44, B100-106.

Stelmach, G.E., Worringham, C.J. (1985). Sensorimotor deficits related to postural instability: implications for falling in the elderly. Clinics in Geriatric Medicine, 1, 679-676.

Sveistrup, H., Woollacott, M.H. (1993). Systems contributing to the emergence and maturation of stability in postnatal development. In, G.J.P. Savelsburgh (Ed.). The Development of Coordination in Infancy (pp 319-336). North-Holland, Elsevier Science Publishers B.V.

Sveistrup, H., Woollacott, M.H. (1996). A longitudinal study of the development of postural control in infants. Journal of Motor Behavior, 28, 58-70.

Sveistrup, H., Woollacott, M.H. (1997). Practice modifies the developing automatic postural response. Experimental Brain Research, 114, 33-43.

Taguchi, K., Tada, C. (1988). Change of body sway with growth of children. In, B. Amblard, A. Berthoz, & F. Clarac (Eds.). Posture and Gait: Development, Adaptation and Modulation (pp 59-65). Amsterdam: Elsevier Scientific Publishers.

Thapa, P.B., Gideon, P., Brockman, K.G., Fought, R.L., Ray, W.A. (1996). Clinical and biomechanical measures of balance as fall predictors in ambulatory nursing home residents. Journal of Gerontology: Medical Sciences, 51A, M239-M246.

Thelen, E. (1986). Treadmill-elicited stepping in seven-month-old infants. Child Development, 57, 1498-1506.

Thelen, E. (1989a): Development of coordinated movement: implications for early human development. In, M.H. Woollacott & A. Shumway-Cook (Eds.). Development of Posture and Gait Across the Lifespan (pp 107-124). Columbia, South Carolina: University of South Carolina Press.

Thelen, E. (1989b). Evolving and dissolving synergies in the development of leg coordination. In, S.A. Wallace (Ed.). Perspectives on Coordination of Movement (pp 259-281) North-Holland: Elsevier Science Publishers.

Thelen, E., Fisher, D.M. (1982). Newborn stepping: an explanation for a disappearing reflex. Developmental Psychology, 18, 760-775.

Thelen, E., Fisher, D.M., Ridley-Johnson, R.(1984). The relationship between physical growth and a newborn reflex. Infant Behavior and Development, 7, 479-493.

Thelen, E., Ulrich, B.D. (1991). Hidden skills: a dynamic systems analysis of treadmill stepping during the first year. Monographs of the Society for Research in Child Development, 56 (1, Serial No 233).

Timmann D, Horak FB (1997) Prediction and set-dependent postural gain control in cerebellar patients. Brain, 120, 327 - 337.

Walter, C.B., Kamm, K. (1996). Optimal search strategies for optimal motor solutions: self-determination or informed guidance? Behavioral and Brain Sciences, 19, 91-92.

Winter, D.A. (1984). Kinematic and kinetic patterns in human gait: variability and compensating effects. Human Movement Science, 3, 51-76.

Winter, D.A. (1985). Concerning the scientific basis for the diagnosis of pathological gait and for rehabilitation protocols. Physiotherapy Canada, 37, 245-252.

Winter, D.A. (1990). Biomechanics and Motor Control of Human Movement. 2nd ed. New York: John Wiley & Sons, Inc.

Winter, D.A. (1992). How biomechanical variables reveal the net integrated strategy of the CNS in balance control in human gait. In, M. Woollacott & ., Horak (Eds.). Posture and Gait: Control Mechanisms. Vol I.(pp 328-331). Eugene, Oregon: University of Oregon.

Winter, D.A. (1995). Anatomy, Biomechanics and Control of Balance During Standing and Walking. Waterloo: Waterloo Biomechanics, University of Waterloo.

Winter, D.A., Olney, S. J., Conrad, J., White, S.C., Ounpou, S., Gage, J.R. (1990). Adaptability of motor patterns in pathological gait. In, J.M. Winters & S. L-Y. Woo (eds.). Multiple Muscle Systems: Biomechanics and Movement Organization (pp 680-693). New York: Springer-Verlag.

Wohlwill, J.F. (1980). Cognitive development in childhood. In, O.G. Brim Jr, & J. Kagan (Eds.). Constancy and Change in Human Development (pp 359-444). Cambridge, MA: Harvard University Press.

Woollacott, M.H., Burtner, P., Jensen, J., Jasiewicz, J., Roncesvalles, N., Sveistrup, H. (1998). Development of postural responses during standing in healthy children and children with spastic diplegia. Neuroscience and Behavioural Reviews, 22, 583-589.

Woollacott, M.H., Debu, B., Mowatt, M. (1987). Neuromuscular control of posture in the infant and child: is vision dominant? Journal of Motor Behavior, 19, 167-186.

Woollacott, M.H., Shumway-Cook, A., Williams, H.G. (1989). The development of posture and balance control. In, M.H. Woollacott & A. Shumway-Cook (Eds.). Development of Posture and Gait Across the Lifespan (pp 77-96). Columbia, South Carolina: University of South Carolina Press.

Woollacott, M.H., Sveistrup, H. (1992) Changes in sequencing and timing of muscle response coordination associated with developmental transition in balance abilities. Human Movement Science, 11, 23-36.

TABLE 1. Reorganization of Data: Developmental Categories

AGE CAT.	n	COPvel cm/s mean (SD)	VELv cm/s mean(SE)	YS cm mean (SD)	YSv cm mean (SE)	AGE years mean(SD)	AGE RANGE years
-2	9	9.280 (.989)	.31233 (.20990)	.688 (.163)	.05122 (.02028)	5.6(.35)	5.1-6.2
-1	16	7.883 (.754)	.23831 (.14227)	.631 (.166)	.05881 (.05104)	5.9(.32)	5.4-6.3
0	17	6.650 (.423)	.13406 (.07699)	.599 (.179)	.04865 (.02259)	6.2(.34)	5.6-6.8
+1	16	8.055 (.674)	.21356 (.13318)	.554 (.175)	.04463 (.02506)	6.5(.40)	5.8-7.2
+2	17	8.530(1.194)	.37747 (.21594)	.554 (.158)	.04347 (.01823)	6.8(.39)	6.1-7.5
+3	17	8.061 (.978)	.30053 (.17712)	.556 (.193)	.05235 (.03346)	7.1(.38)	6.9-8.1

TABLE 2. Main Effect of Developmental Category: ANCOVA results for each Dependent Measure

Dependent Measure	**F (5, 83)**	**p - level**
COPvel	6.993774	.000025 *
VELv	6.792829	.000005 *
YS	.562812	.758011
YSv	.521576	.468051

* denotes significant effects

TABLE 3. Main Effect of Developmental Category
Post-Hoc Tukey's HSD for Unequal Ns
Summary of Significant Effects, p < .05

BETWEEN CATEGORIES	p - level: COPvel (VELv)
-2, and 0	.00076
-2, and +1	.03757
0, and +2	.00099 (.00388)
0, and +3	.02594 (.01912)
+1, and +2	(.04322)

Figure 1a **COPvel: Individual Subjects**

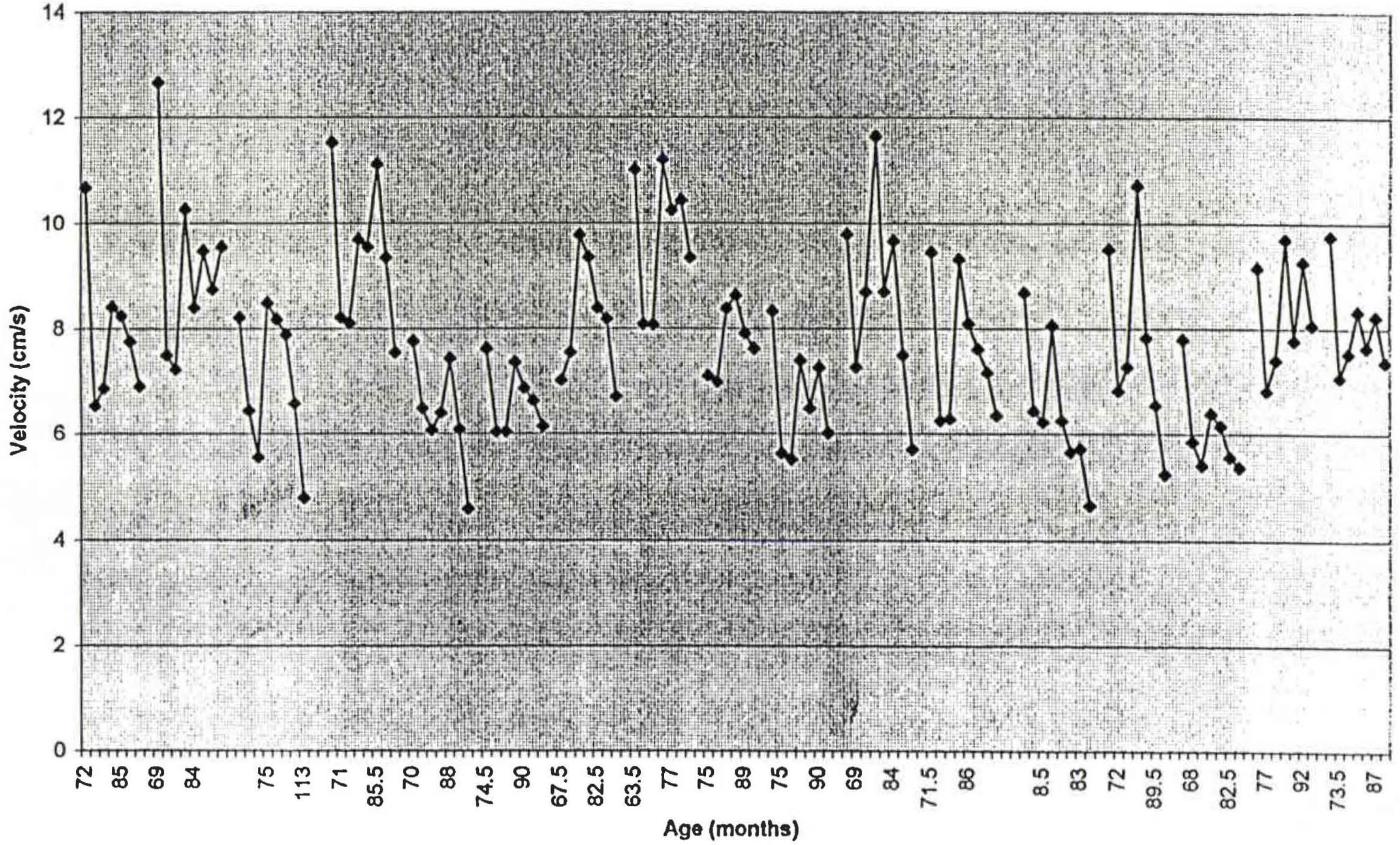

Figure 1b. **Ys: Individual Subjects**

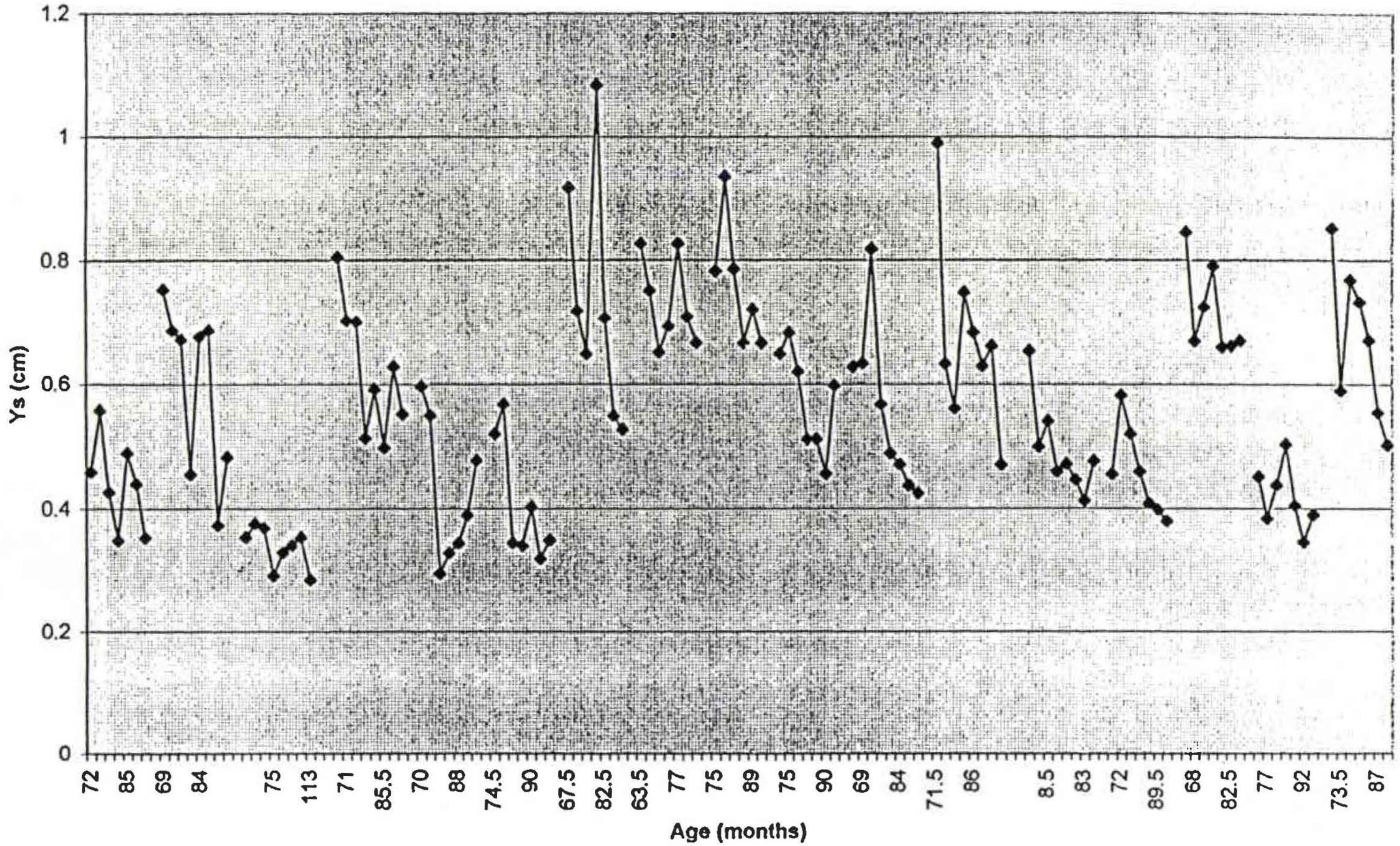

Figure 2a. COPvel

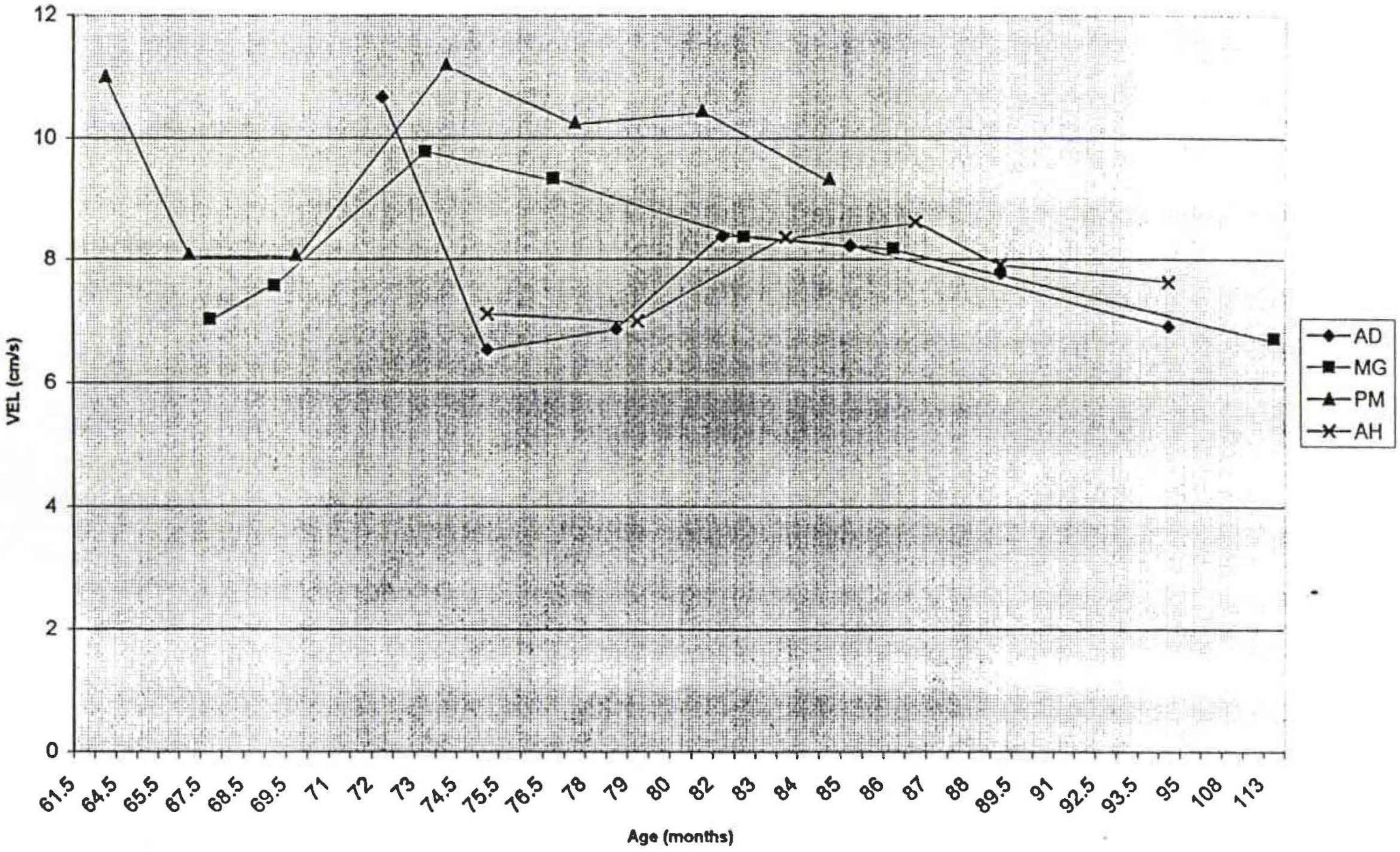

Figure 2b.   COPvel

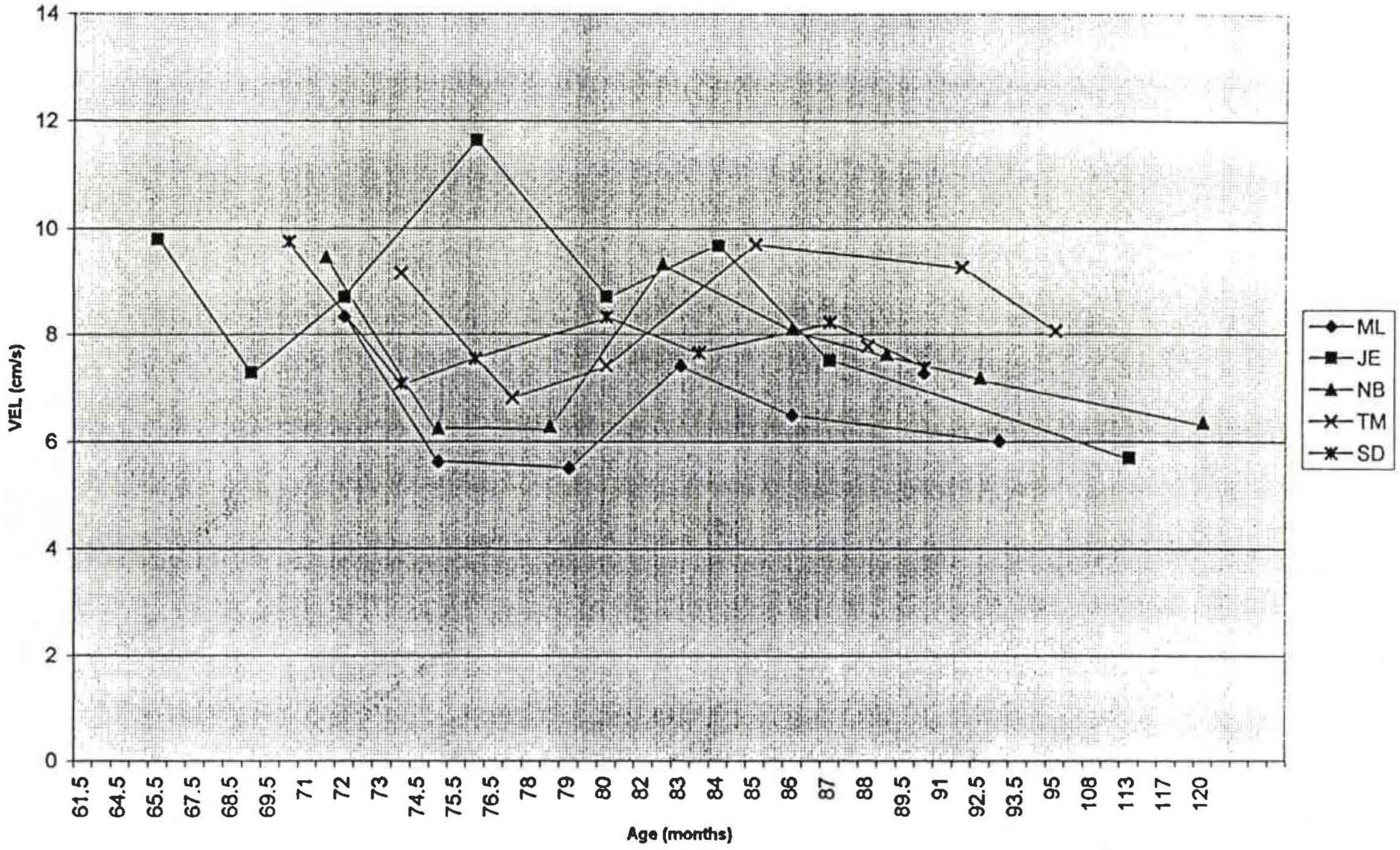

Figure 2c. **COPvel**

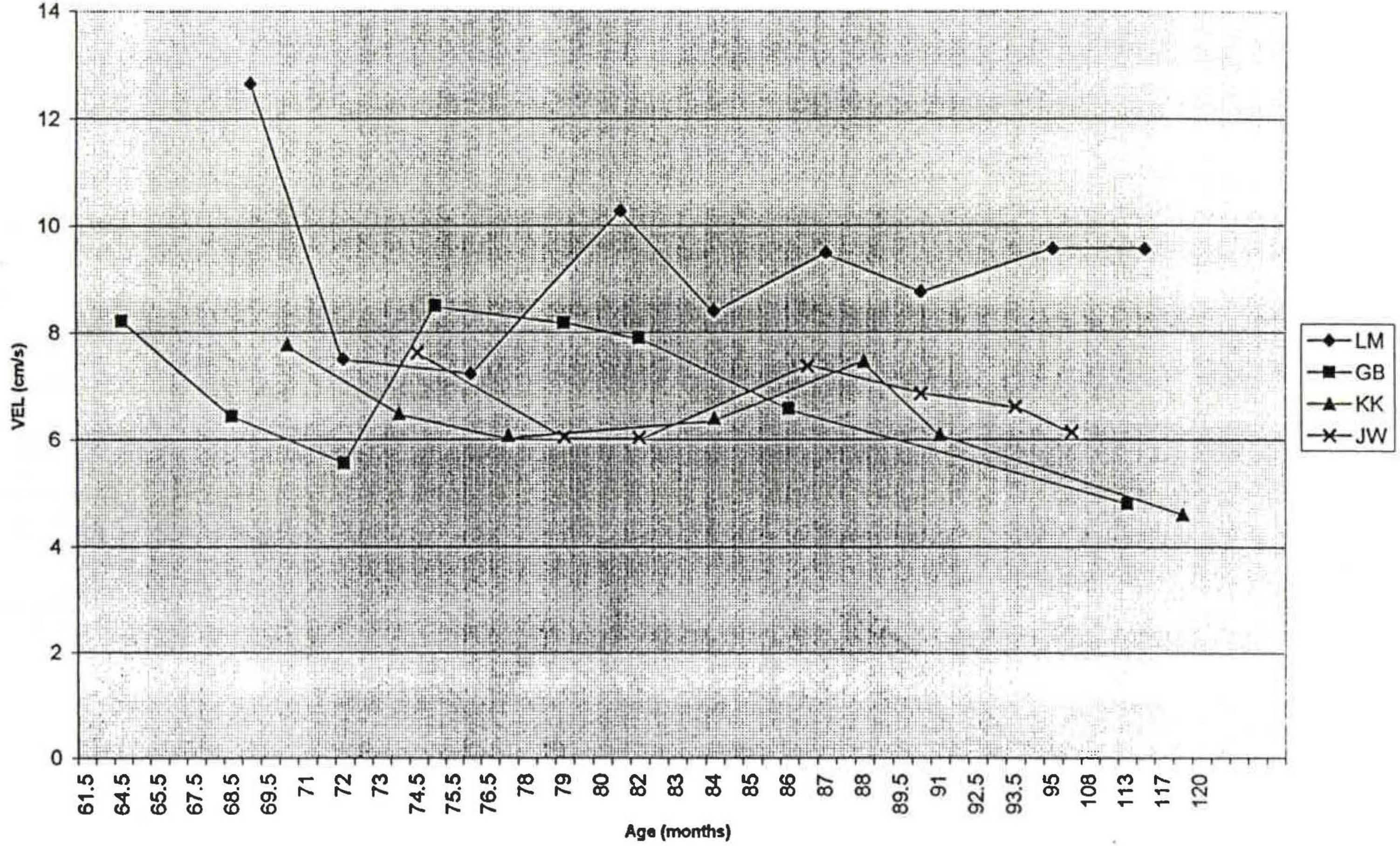

Figure 2d. COPvel

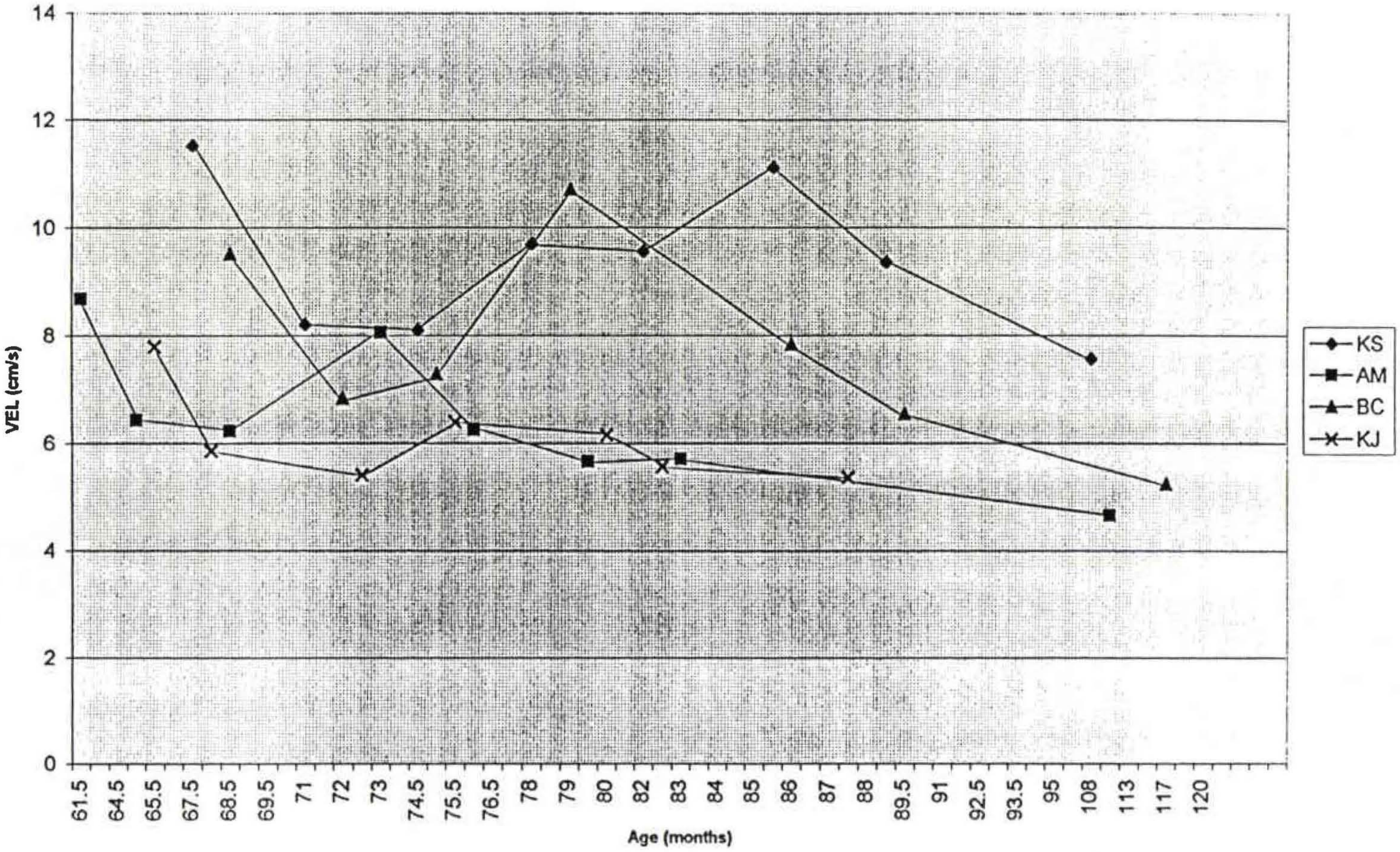

Figure 3a: COP Velocity

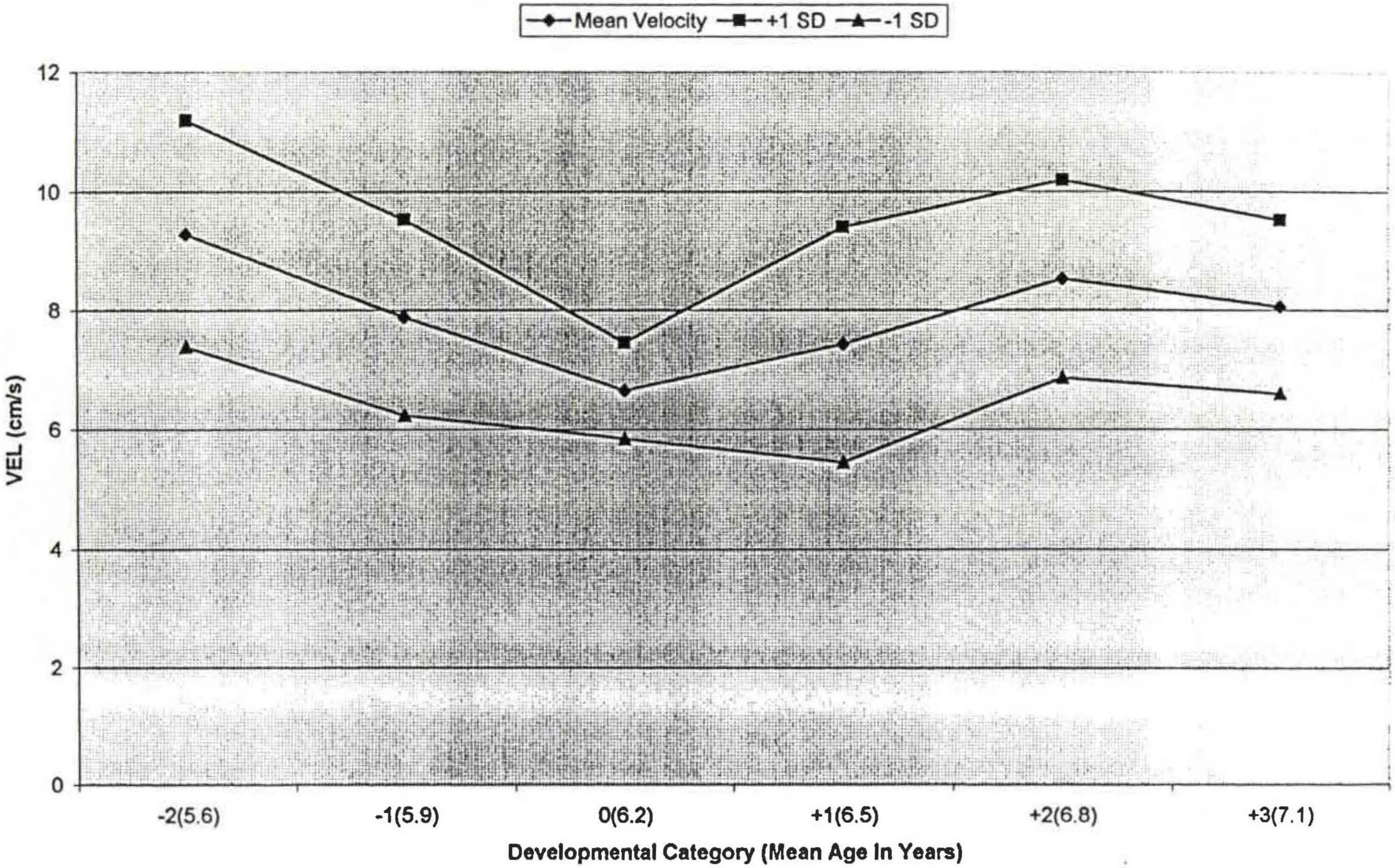

Figure 3b: COP A-P Excursion (YS)

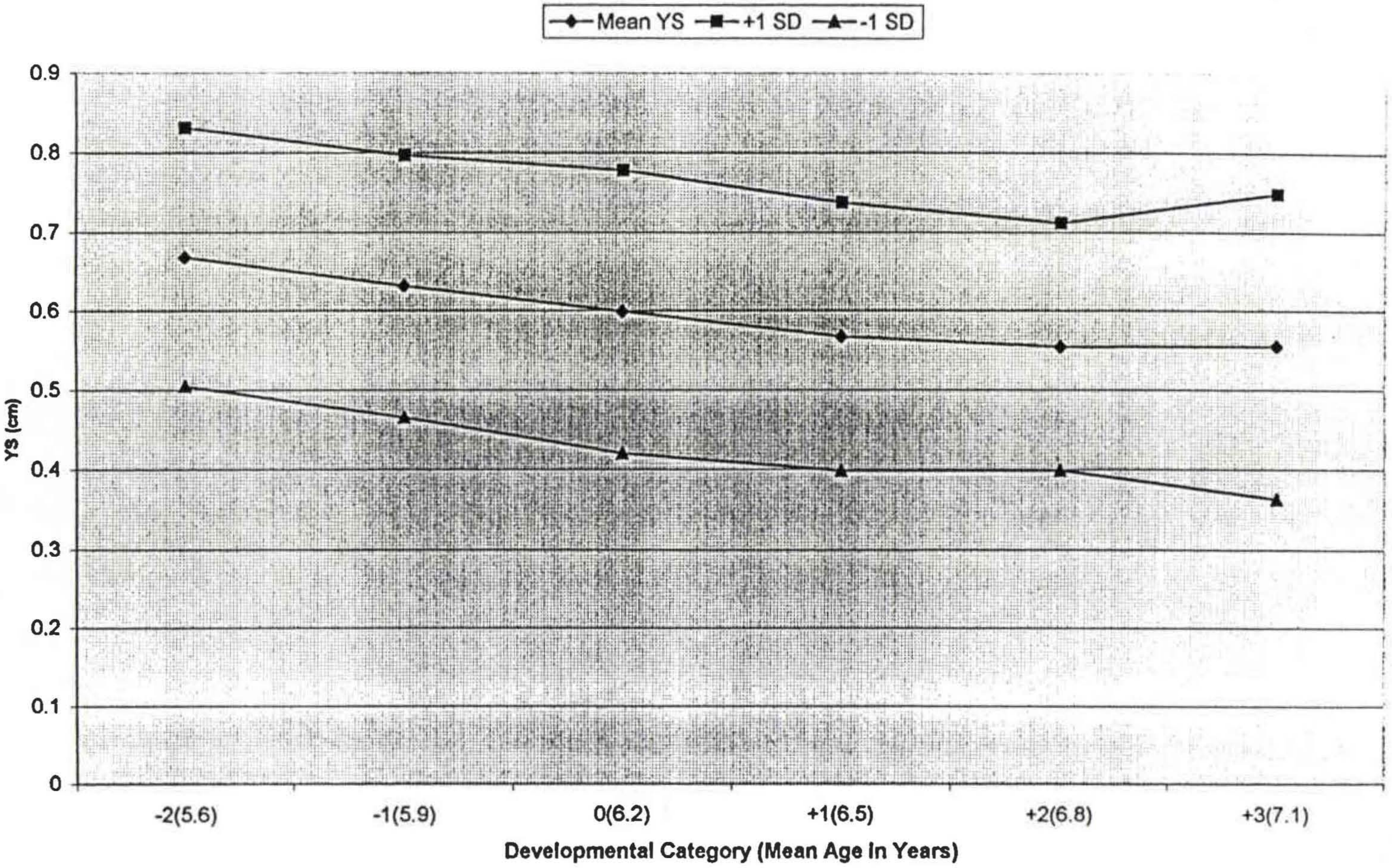

Figure 3c: Variability of COP Velocity

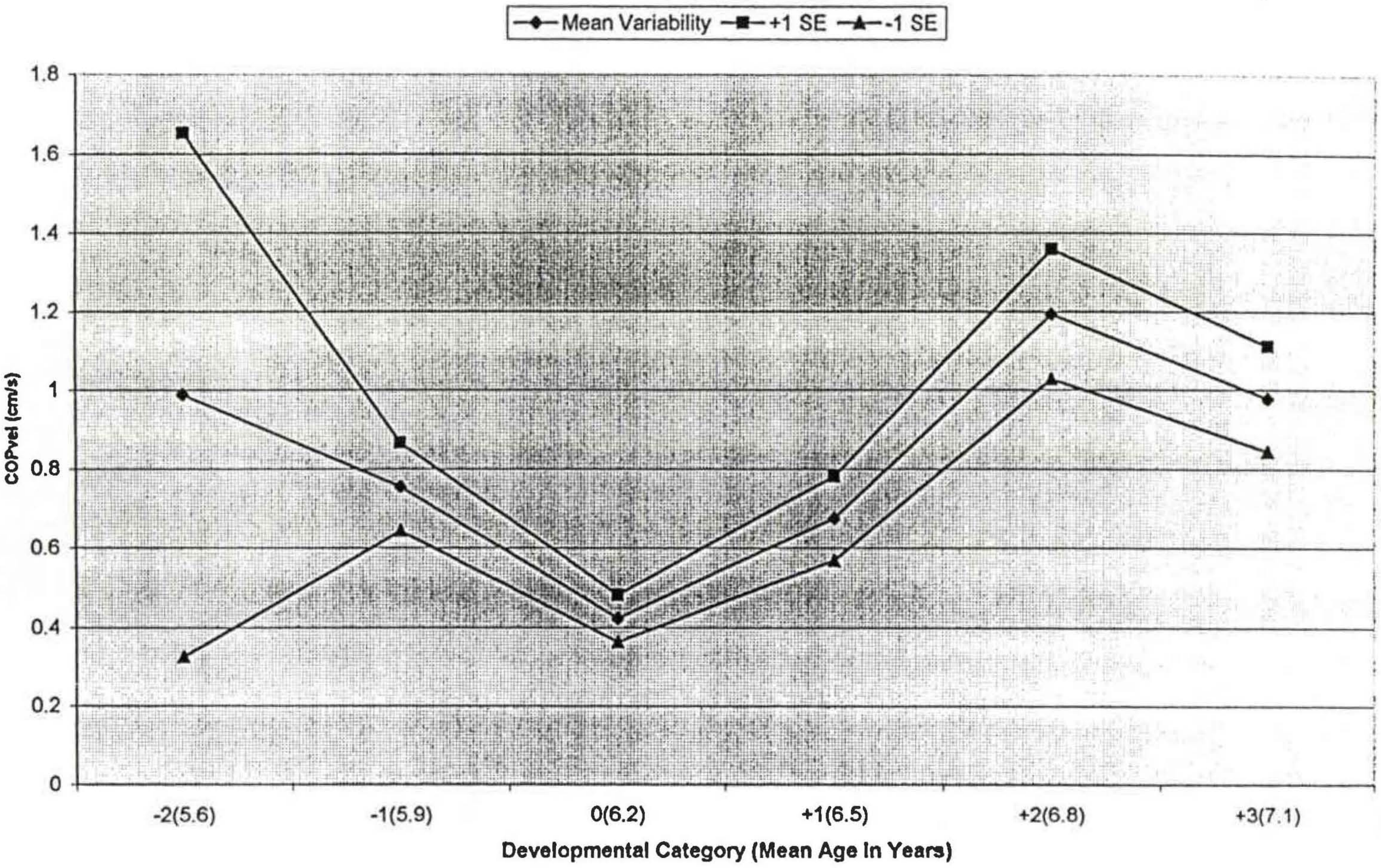

Figure 3d: Variability of A-P Excursion (YS)

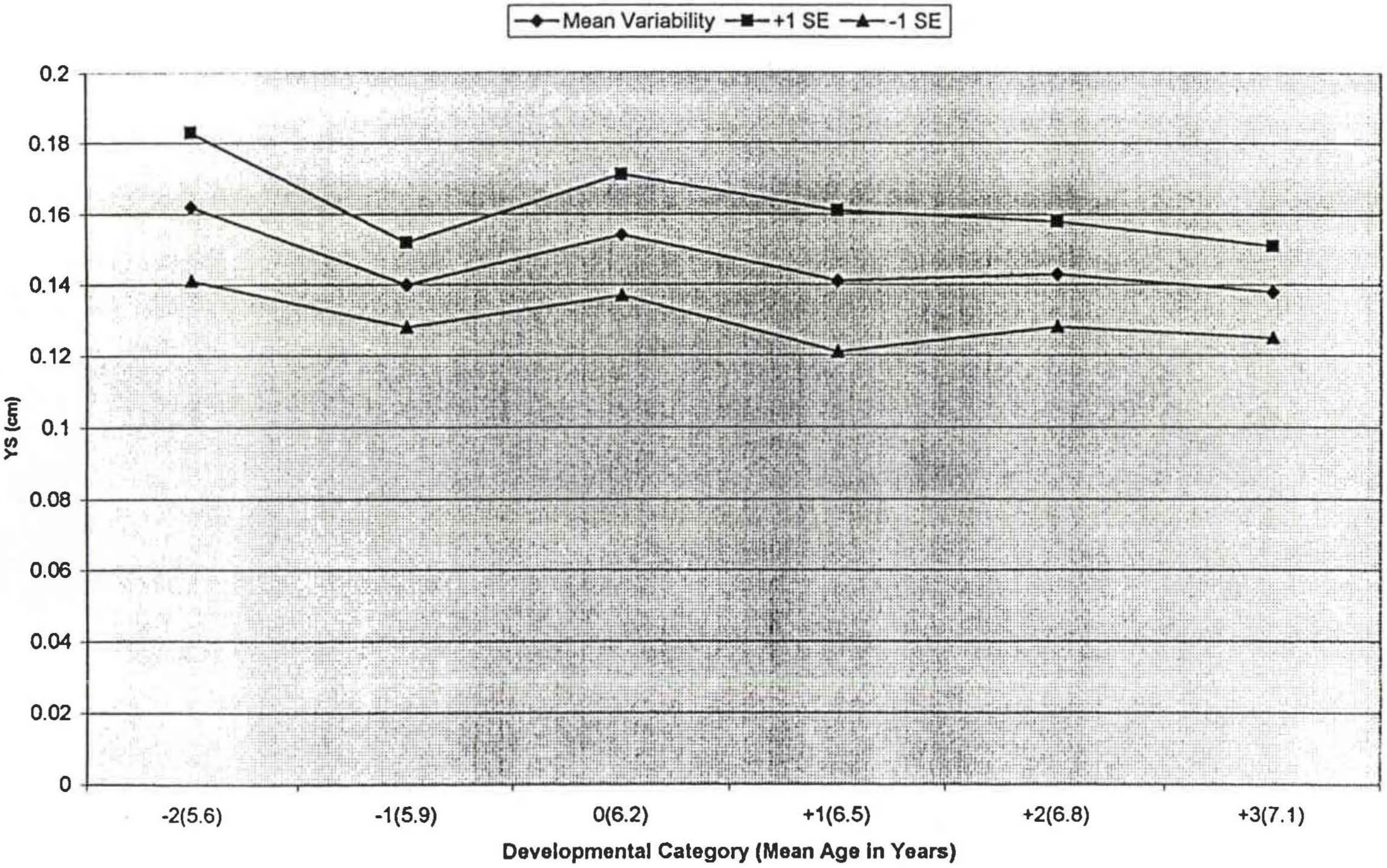

Figure 4a: A-P Excursion (YS) vs Velocity

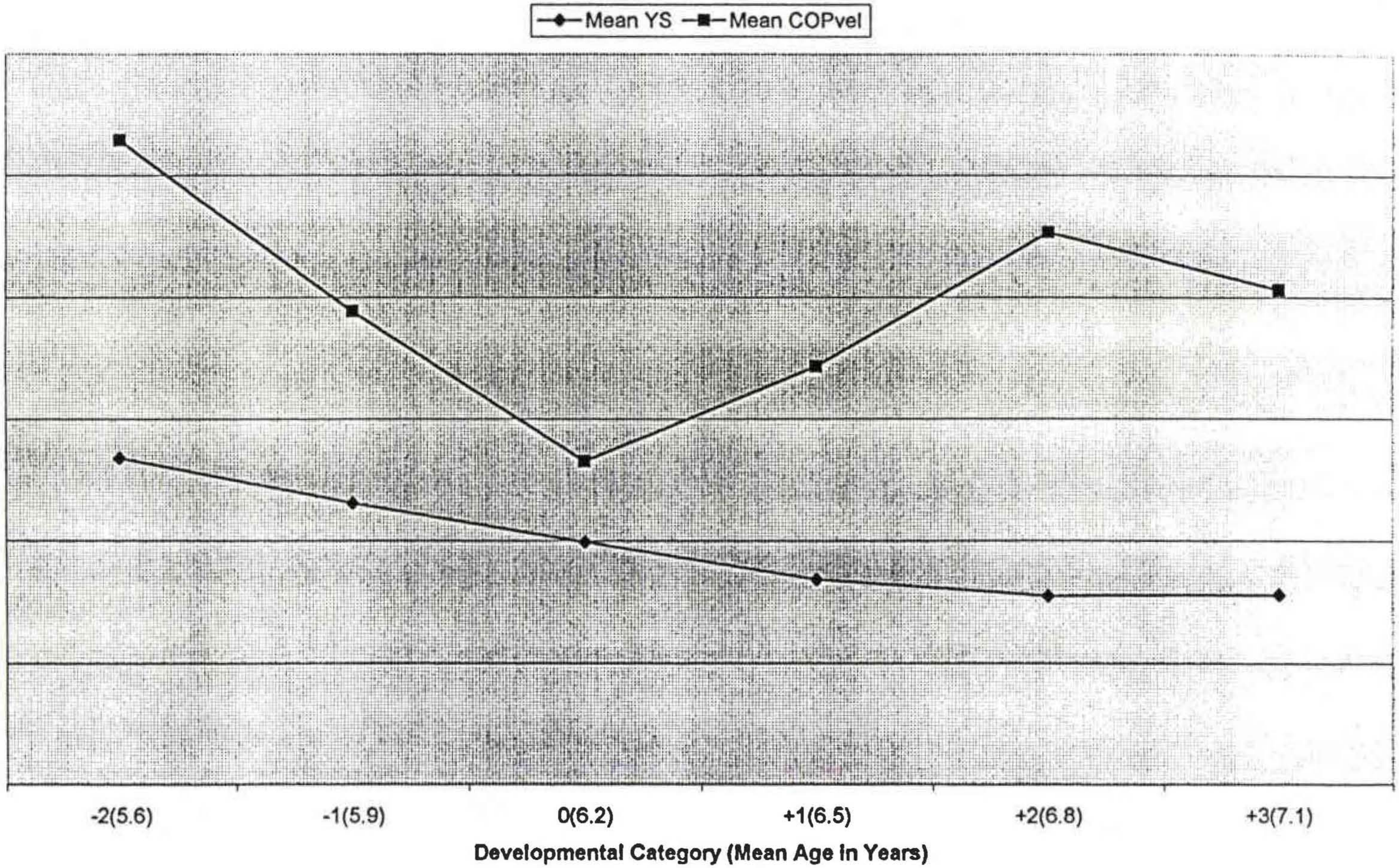

Figure 4b: Variability of A-P Excursion vs Velocity

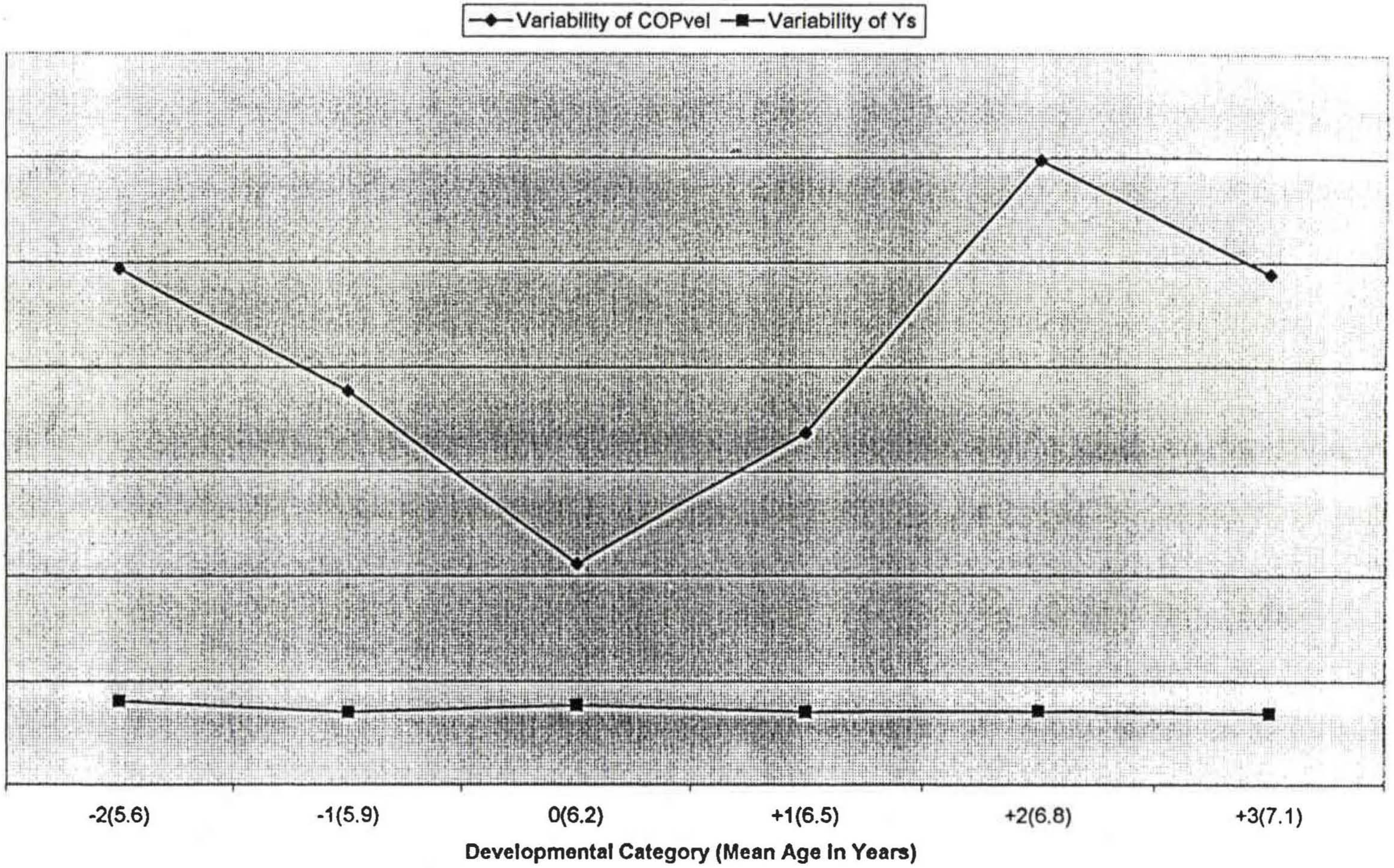

Figure 5: Comparison of Velocity Patterns - Mean vs Variability