POSTURAL CONTROL IN CHILDREN WITH VISUAL IMPAIRMENTS

THE DEVELOPMENT OF POSTURAL CONTROL
IN
CHILDREN WITH AND WITHOUT VISUAL IMPAIRMENTS

By

KATHLEEN L. LECLAIR, B.H.Sc.(O.T.)

A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfilment of the Requirements

for the Degree

Master of Science

McMaster University

MASTER OF SCIENCE (1993) McMASTER UNIVERSITY

TITLE: The Development of Postural Control in Children With and Without Visual Impairments

AUTHOR: Kathleen L. LeClair, B.H.Sc.(O.T.) (McMaster University)

SUPERVISOR: Cindy L. Riach, Ph.D.

NUMBER OF PAGES: x, 88

ABSTRACT

The development of postural stability in children with and without visual impairments (VI) was compared. Thirty eight subjects (4 - 12 years old) without VI and 12 subjects with VI (5 - 12 years) took part. Stability was measured in 4 quiet standing tasks (normal or foam surface, eyes open (EO) or eyes closed (EC)) and by measuring stability limits (SL) in the anterio-posterior (a-p) and lateral (lat) planes. Results for control subjects were compared using Pearson correlation coefficients, analysis of variance, and analysis of covariance (height as the covariate). For quiet standing tasks, outcome parameters were the standard deviation (SD) of the centre of pressure (CP) in the a-p and lat planes, and mean velocity (vel) of CP movements. For the leaning tasks, SL was measured (normalized to the base of support) in the a-p and lat planes, and SL was compared to CP. Individual results for subjects with VI were compared qualitatively to control subjects.

For control subjects, stability increased with age. Subjects with VI were less stable than controls on all outcome parameters. Differences between groups were more apparent as age increased, particularly for EO conditions. This could indicate a slower pattern of development for subjects with VI compared to controls. The groups were different both in the EO and EC conditions, indicating that postural control with EC is not the same as postural control with a VI, and that vision is important to the development of postural control in children.

ACKNOWLEDGEMENTS

To the members of the thesis committee; Digby Elliott and Jim Dowling from McMaster University and Keith Hayes from Parkwood Hospital in London, Ontario. Thank you very much for your thoughtful assistance with this work.

To Cindy Riach my thesis advisor, thank you for your perseverance and continual support. Your kindness helped me greatly during the completion of this project.

To David LeClair, thank you for encouraging me to stand on my own. I am deeply grateful for the love and freedom that you continue to offer.

TABLE OF CONTENTS

List of Tables

Table Page

List of Figures

Chapter 1

INTRODUCTION

Postural stability is the basis for functional movement. Reed (1989) describes two approaches to the study of postural development in children: i) reflex hierarchy, and ii) action systems approaches. The reflex hierarchy approach assumes that the central nervous system acts as a simple input - output mechanism. Research based on this approach would attempt to describe specific sensory and neural pathways responsible for the maintenance of posture, and to describe reflex reactions to stimuli that can explain movement. This view is likely an oversimplification, and it can not account for the adaptability seen in movement, or for the observation that the ability to adapt responses to stimuli in different contexts increases rather than decreases with development (Reed, 1989; Woollacott, Shumway-Cook, & Williams, 1989).

The action systems approach to the study of posture emphasizes that we learn to move and to control our posture to meet a specific goal, rather than learning specific movements that we can later put together to meet a goal; "children learn how to act and then they learn how to move" (Reed, 1989, p. 11). In exploring their environment, children fall. Reed supports the idea that postural development is a dynamic process, and that even falling provides children with opportunities to learn about their stability limits.

Postural control is conceived of as a dynamic event, hence it's control must continually be calibrated and recalibrated depending on changes in the body (due to growth, age, disability). As children develop, the position of the centre of gravity (CG) relative to the crotch remains constant. The infants trunk is, however, longer in proportion to their entire body as compared to a toddler, or an adult (Jensen, 1986). Therefore, the CG of an infant or toddler is located higher in their trunk as compared to it's location in adults. The biomechanics behind the calibration and recalibration of feedback used in postural control form part of the basis of research in the action systems approach to the study of the development of postural stability.

Postural stability in adults is generally better when visual feedback is available than when it is absent (Lee & Lishman, 1975; Ohashi, Asai, Nakagawa, & Mizukoshi, 1990; Paulus, Straube, & Brandt, 1984). The visual system is also thought to be important in the calibration of feedback from the other two sensory systems responsible for postural control (somatosensory and vestibular systems). When a child without a visual impairment goes through a period of transition, when learning a new skill such as sitting or standing, or when integrating feedback from other sensory systems to be used flexibly together, she will tend to rely more on visual feedback than on other feedback available. This strategy may provide more opportunities to calibrate the other two feedback systems with the visual system (Woollacott et al., 1989).

In addition, there appears to be a transition from open loop or ballistic control of postural stability to a more sensory guided control. This change is noted in the decrease in velocity of CP movements as age increases (Starkes, Riach, & Clarke, 1992). Such a change is only possible if the child has already developed a working understanding of what each sensory feedback system means in relation to her stability. The child must have an understanding of what it means when she can visually see an object coming towards her, at the same time as she can feel through the somatosensory and vestibular systems her body and head tilt forward. Without this understanding, the child will not be able to make the correct changes in her posture to avoid falling toward the object. She may correct too much, and begin falling backwards, or not correct enough, and continue falling forwards.

People who are born with visual impairments do not have the opportunity to use visual feedback in the same way to help maintain postural stability, or to use vision to calibrate feedback from other sensory systems. People with visual impairments tend to develop motor skills more slowly than people without visual impairments. One reason proposed for this difference is that people born with visual impairments explore their environments less frequently, and therefore have fewer opportunities to experience how they can move their bodies (Sonksen, Levitt, & Kitsinger, 1984). Most people with visual impairments do, in fact learn to control their posture and to move effectively through their environment. It is not clear if children with visual impairments develop the ability to control their posture in a way similar to children without visual impairments. It is also not clear if one of the systems remaining intact takes the role of the "gold standard" needed for calibration of the other system.

Purposes of the study

The study has been designed to propose answers to the question:

Do children with visual impairments demonstrate the same trends as they develop postural stability compared with children without visual impairments? Or, more specifically:

1. Do both visual ability groups have the same magnitude of

CP movements relative to their age when they are asked to stand quietly or lean, with eyes open or closed, on a stable surface or on foam?

2. Do both groups have the same stability limits (SL) relative to their age?
3. Do both groups respond to postural challenges in the same way?

Answers to these questions will increase knowledge about the development of postural stability in one special population. Additionally, they could be useful for the clinician working with children who have visual impairments for programme planning purposes. The techniques implemented in this study could be used to evaluate the effectiveness of programmes designed to improve postural stability.

Hypotheses

Quiet Standing Tasks

1) Magnitude of CP movements will decrease with an increase in age. This is a consistent finding with children who have normal vision (Forssberg & Nashner, 1982; Riach & Hayes, 1987). It indicates an increase in stability with age.

2) Velocity (vel) of CP movements will decrease as the age of the

subject increases. This has been shown to be true of children without visual impairments and may indicate a change from ballistic to sensory guided postural control (Starkes et al., 1992). Children with visual impairments will develop sensory feedback control with the use of the vestibular and somatosensory systems.

3) Children with visual impairments will be affected to a greater degree than children without visual impairments in conditions in which somatosensory feedback is diminished. This hypothesis is based on the assumption that children limited to two sensory systems (vestibular and somatosensory) will be more destabilized with postural challenges, or when they experience reduced feedback in one of their two remaining systems (Magnusson, Enbom, Johansson, & Pyykko, 1990).

4) CP movements in the anterio-posterior (a-p) plane will be greater than CP movements in the lateral (lat) plane for children with visual impairments as compared to children with normal visual acuity. Paulus et al. (1984) investigated the role of visual acuity in stability with adult subjects. They reported that a reduction in visual acuity across the entire visual field affected CP movements in the a-p plane to a greater extent

than in the lat plane.

Leaning Tasks

1) Younger children will have smaller SL than older children (Starkes et al., 1992), and children with visual impairments will demonstrate decreased SL compared to age matched children without visual impairments. This will reflect decreased overall stability in that group.

Comparison of the excursions of the Centre of Pressure (CP) to SL during quiet stance

1) It is expected that as age increases in both groups of subjects, they will use a smaller percentage of their SL during quiet standing tasks. This would reflect an increase in stability with age. It is further expected that subjects with visual impairments would overall, use more of their available base of support than control subjects.

<u>Limitations of the study</u>

1) People who have visual impairments are not a homogeneous population. Children who meet the age and physical inclusion criterion for this study compose a very small proportion of the population with visual impairments. One possible confounding

factor in the interpretation of results is that children will not all have the same degree of visual impairments. Visual acuity has been demonstrated to have an effect on postural stability (Paulus et al. 1984).

2) Many of the children without visual impairments were recruited from children active in recreational programmes at McMaster University. These children represent healthy, active children. Physical activity may influence postural development and children with visual impairments are often less active (Sonksen et al., 1984). The differences found between the two vision groups may be partially due to the influence of impaired vision on postural experience.

Chapter 2

LITERATURE REVIEW

The ability to control and maintain posture provides the basis for normal human movement. Postural control mechanisms have been a focus of investigation for the larger part of the past century. Humans derive feedback regarding posture and the state of stability through three main sensory channels: the visual, vestibular, and somatosensory systems. We have the ability to use sensory information to make postural adjustments both before and after we have experienced changes in posture.

Biomechanics of Postural Control

The ability to maintain posture, as with other movements is governed by both neurological and biomechanical constraints. Hayes (1982) describes three 'principles of stability'. First, stability is proportional to the area of the base of support. Second, stability is related directly to the height of the centre of gravity above the base of support, and finally, the line of gravity must be within the area of the base of support for the subject to maintain upright stance. The degree of stability is related to the distance between the line of gravity and the edge of the base of support.

The line of gravity is the vertical projection of the centre of gravity (CG) downward to the base of support. The centre of pressure of ground reaction forces (CP) is the centre of all supportive forces acting upward from the base of support. When an individual tilts forward, the line of gravity moves forward. To keep from falling, the individual will attempt to move the line of gravity back towards the centre of the base of support. This can be accomplished through ankle plantar flexion. By putting more pressure on the toes, the individual has moved the CP forward, and has, in effect "chased" the line of gravity back towards a more stable position. The positions of the CP and the line of gravity are related to one another, but they are not the same. The CP can be thought to move to maintain the line of gravity in a stable position (Murray, Seireg, & Scholz, 1967).

During quiet standing, the CP and CG are very closely aligned (Murray et al., 1967). Measures of the variability of CP of ground reaction forces are commonly used to quantify postural stability. The monitoring of CP is a measure of the postural control systems in maintaining the CG within a stable area (Murray et al., 1967).

Some investigations into the biomechanical aspects of postural stability are based on the assumption that the upright body can be modelled as an inverted pendulum of two or more segments (Hayes, 1982; Koozekanani, Stockwell, McGhee, & Firoozmand, 1980; Stockwell, 1985). Using this approach, it has been possible to learn about the interplay between biomechanical and motor control components of postural stability.

Sensory Control of Postural Stability

It is not possible for humans to stand completely still. When standing upright, our body is in continual motion, small movements compensate for the effects of breathing and the heart beat, as well as the change in stability caused by the movement of a body part.

Feedback on position in space is provided by visual, vestibular and somatosensory information (somatosensory feedback refers to both proprioceptive and pressor feedback; Magnusson & Johansson, 1988). Each feedback system provides information based on it's own reference system. Visual, with reference to surrounding objects, vestibular, with reference to inertial-gravitational space, and somatosensory with reference to the supporting surface (Nashner, 1985). Four factors reduce the redundancy of the feedback in the control of posture (Amblard, Assainte, Cremieux, & Marchand, 1990): 1) the localization of the receptors 2) their frame of reference, including the provision of information regarding internal and external conditions 3) their frequency domains; and 4) their sensitivity to position or motion.

Adult subjects are able to maintain an upright stance with feedback from only one of the three available systems if they are not disturbed. When challenges to stability are introduced, more than one feedback system appears to be required for the maintenance of stability (Diener, Dichgans, Guschlbauer, & Bacher, 1986). When one feedback system is not providing sufficient, or reliable information on stability, adults without physical or sensory difficulties are able to rely more on the other feedback systems. Children are less able to adapt to sensory deprivation or conflict (Magnusson et al., 1990).

Sensory Development

Sensory systems are well developed by the time children are learning to stand (Amblard et al., 1990; Ornitz, 1983; Woollacott, Debu, & Shumway-Cook, 1987). The children are learning, however, how to use the sensory systems together in postural control. Incongruencies between the three feedback systems can induce instability (Brandt, 1988). In the laboratory, incongruencies are caused by providing false or diminished feedback to the subject through one or more of the feedback channels. Under natural conditions, the incongruencies can be caused by specific disorders of the sensory systems (ie visual, vestibular, or somatosensory loss or distortion), or disorders of the central mechanisms interpreting the feedback (eg. Cerebellar Ataxia, Lucy & Hayes, 1985).

Lee and Aronson (1974) had human infants between the ages of 13 to 16 months stand inside a room with a stable floor, and suspended walls. When the walls of the room were moved, the infants received conflicting information from their three feedback systems. Vestibular and somatosensory information told the infants that they were on a stationary surface, while visual information told the infant that they were moving. In that situation, visual feedback dominated the infants reactions, and the infants tended to fall. Lee and Aronson (1974) postulated that the somatosensory feedback system is sensitive to changes in the infants weight, and is not fine tuned to provide positional feedback until the infant has had considerable experience standing. Since the visual system is not dependent on the infant's size to calibrate the feedback, the infant has experienced more success using vision, and relies on it more heavily when learning the new skill of standing. The same growth factors may influence the effectiveness of feedback from the vestibular system on the maintenance of stability. Pre-adolescent children respond differently to vestibular stimulation than do adolescents and adults (Ornitz, 1983), therefore maturation plays a role in the use of vestibular feedback. It is possible that under normal circumstances feedback from the visual system is used to calibrate the feedback received from the vestibular system as well as feedback from the somatosensory system.

The vestibular system, while intact at birth, demonstrates differences in response to stimulation over the developmental period. Children respond more strongly to vestibular stimulation than adults, as measured by a reduced latency, threshold, and increased amplitude and velocity of nystagmus (Ornitz, 1983). The vestibular system is most reactive to stimulation during infancy (6-12 months). Reactivity also peeks when the child is learning to stand and walk. Ornitz (1983) suggests that the vestibular system may be facilitating the transition between pre-ambulation to ambulation by monitoring or decreasing the conflicts between active and passive motion experienced by the child.

In children aged 2 - 3 years, a reduction in muscle response latencies of muscles involved in postural control and an increase in the total number of monosynaptic reflexes are seen when visual feedback is removed (Woollacott, Debu, & Mowatt, 1987). This implies that in this age group, the postural control system is more responsive to changes in stability when vision is absent than when vision is present. It also implies that when visual feedback is available, it is preferred over other sensory feedback available (Woollacott, Debu, & Mowatt, 1987), confirming the findings reported by Lee and Aronson (1974).

The extent of the visual field is thought to be immature during the first year of life. The infant focuses more on objects in the peripheral visual field as compared to the central visual field. It has been reported to become similar to that of an adult by at least 2 years (Cummings, van Hof-van Duin, Mayer, Hansen, & Fulton, 1988). The first evidence of binocular visual abilities occur at approximately two months of age. The infant is able to accommodate to objects placed at different lengths away from the face by four months of age. Visual acuity is thought to be similar to that of adults without visual impairments by approximately 12 months (Harrison, 1975).

Visual Feedback

A common clinical and research finding is that adults are more stable when standing with eyes open (EO) than with eyes closed (EC) (Lee & Lishman, 1975; Ohashi et al., 1990; Paulus et al. 1984). The powerful role of vision in infants was illustrated by Lee and Aronson (1974). In other studies, where no attempts are made to create conflicts in sensory feedback, subjects are found to be more stable when they visually fixate a target than when no fixation target is available (Riach &

Starkes, 1989). In addition, the availability of a visual fixation target affects anterio-posterior (a-p) and lateral (lat) stability in different ways. If a fixation target appears to be getting larger or smaller, the subject is aware of movement in the a-p plane. If a fixation target appears moving laterally, the subject is aware of movement in the lat plane (Paulus et al., 1984).

Paulus et al. (1984) varied the number and relative positioning of fixation targets in a darkened room. In adult subjects, one (centrally located) fixation target decreased CP movements in the a-p plane compared with the EC condition. Additional decreases in CP movements in the a-p plane were observed when four, or five fixation targets were available to the subjects (the five fixation targets were positioned to form a cross). CP movements in the lat plane were reduced to a greater extent by the central fixation target, than by the other four targets. The central fixation target was located in the foveal region of the visual field (the most central 1 to 2 degrees of vision). The finding indicates that the movement detected within the foveal field contributes to the maintenance of posture in the lat plane. Changes in target size are detected to a greater extent by the more peripheral visual fields, therefore targets located more peripherally would be more useful in maintenance of posture in the a-p plane. Children are also able to use a fixation target to improve stability (Riach & Starkes, 1989).

Adult subjects are able to use augmented visual feedback to improve postural stability (Ohashi et al., 1990). Visual feedback was augmented by having the subject watch (on a computer monitor) the displacement of their CP in relation to a fixed central point. In this task, the foveal visual field receives equal feedback about CP movements in the a-p and lat planes. Feedback received through the foveal visual field is thought to be primarily responsible for the maintenance of posture in those situations (Ohashi et al., 1990).

Visual acuity has an influence on postural stability. In adults without visual impairments, a reduction in visual acuity (using semitransparent plastic foils in glasses to decrease acuity across the entire visual field) affected CP movements in the a-p plane to a greater extent than in the lat plane (Paulus et al., 1984). Visual acuity is a measure of a persons ability to distinguish and identify stimuli at a given distance (Allen, 1957), primarily a foveal task. It is possible that by decreasing visual acuity across the entire visual field, the subject attempts to focus on the foveal field to the detriment of visual information received from the more peripheral fields.

Adults with visual impairments, when tested by Edwards in 1946, were found to sway approximately two times as much as adults without visual impairments when both groups were asked to stand in a normal stance with their eyes closed. Additionally, adult subjects were less stable with eyes open than with eyes closed. This indicates that some adults with visual impairments are somewhat destabilized by their residual vision. Paulus, Straube, Quintern, and Brandt (1989) investigated the postural stability of subjects who required bifocal or multifocal corrective lenses for optimal visual functioning. They found that subjects did not have significantly higher CP excursions without their glasses than with glasses. They proposed that the lenses improved visual acuity while causing some optical distortions that interfered with postural stability.

When adults have difficulties with both the visual and vestibular systems, they find it more difficult to stand in challenging stances, such as standing on one foot with eyes closed. Adults with vestibular but not visual impairments are able to accomplish that task (Worchel & Dallenbach, 1948). Lee and Lishman (1975) hypothesize that the lack of the ability to calibrate the vestibular and somatosensory systems using the visual system leads to the difficulties that people with visual impairments experience with postural stability, even in the EC condition.

Visual targets that appear to be moving are either followed using smooth, or saccadic eye movements. In smooth pursuit of a visual target, continuous information is provided regarding the subjects position relative to the object. In saccadic eye movements, intermittent visual information may be provided regarding the subjects position relative to the object. Paulus et al. (1984) measured the effect of varied frequencies of intermittent visual information on the adult subjects ability to maintain postural control. Intermittent visual information provided at a frequency of 8Hz caused an increase in movements of CP not evident in conditions in which information was provided at a frequency of 16, or 32Hz, or in a continuous illumination condition.

Children demonstrate more visual saccades during postural tasks than adults, and the number of visual saccades observed increases with the difficulty of the postural task. Riach and Starkes (1989) propose two possible explanations for the finding. Children may be using the saccades in an attempt to improve postural stability, or they may be unable to fixate on a specific fixation target.

The effectiveness of visual feedback in the maintenance of posture is affected by the subjects foot position. Kollegger, Wober, Baumgartener, and Deecke (1989) manipulated the lateral spacing of the adult subjects feet. Visual information was found to be more important in reducing movements of the CP in conditions in which the subject was least stable (when feet were positioned close together).

Vestibular Feedback

The human vestibular system provides feedback regarding linear and angular accelerations of the head relative to inertia and to gravity. Under normal circumstances, information received from the vestibular system indicates body motion, and therefore the need to correct, or maintain posture. The visual system, on the other hand, can indicate movement occurring by the body, or by the visual area surrounding the body, and therefore may, or may not indicate the need for the body to make postural adjustments. The vestibular system, offers an internal referent of stability. Paulus et al. (1988) indicate that when adult subjects are aware of a sensory mismatch between visual and vestibular stimulation, they tend to rely on the vestibular information (as the more accurate internal referent) rather than on the visual information in the maintenance of posture. For this reason, it is difficult to investigate the role of the vestibular system in the maintenance of posture in adults.

When the vestibular system is physically altered, postural stability is diminished initially, but is improved with time (Black, Shupert, Peterka, & Nashner 1989). Under natural conditions, adults who have adapted to a loss of vestibular feedback have learned to rely more heavily on visual feedback (Bles, 1990). Difficulties with postural stability are still encountered in situations in which visual feedback is unavailable or inaccurate (Black et al., 1989; Bles, 1990).

The interaction between the visual and the vestibular systems in the control of posture have not been widely studied. Ornitz (1983) suggests that this information would be very useful in an understanding of the development of postural stability and other motor skills.

Somatosensory Feedback

It has been hypothesized that postural responses that correct upright stance are organized in an ankle pattern (corrections occurring at the ankle) or a hip pattern (Nashner, Shupert, Horak, & Black, 1989). Somatosensory feedback mechanisms are located in the feet and ankles, in the same area that the corrections occur when the ankle pattern of postural stabilization is used. Somatosensory feedback mechanisms consist of joint, muscle, and force receptors.

Adult subjects find standing with their eyes closed to be more difficult when they are also standing in a condition with decreased somatosensory feedback. Magnusson et al. (1990) decreased the somatosensory information available from the soles of subjects feet by having adult subjects sit for 20 minutes with their feet in a basin of ice-water (about 3 deg C), and by having children stand on a piece of foam rubber during the measurement of stability. Lee and Lishman

(1975) decreased somatosensory feedback by having adult subjects stand on a stack of ten pieces of foam, each 2.5 cm thick. In both studies somatosensory information was critical for maintenance of posture, and the loss or dampening of somatosensory information was not completely compensated for by the availability of vision.

Children with congenital bilateral vestibular loss found the condition of impoverished somatosensory feedback to be more destabilizing than eye closure. The opposite was true for children with intact vestibular systems (Magnusson et al., 1990). Lee and Lishman (1975) hypothesize that the visual and vestibular systems are used to "tune up" the somatosensory system. Magnusson et al. (1990) hypothesize that somatosensory feedback is useful in controlling CP movements occurring at high frequencies, while vision is useful in controlling low frequency CP movements (Johansson, Magnusson, & Akesson, 1988).

Evaluation / Measurement of Postural Stability

A variety of outcome parameters have been used to help evaluate questions of postural stability. The index of measure used is dependent on the research question. Goldie, Bach and Evans (1989) compared the reliability and validity of variability in ground reaction forces to variability in CP in the measurement of postural stability in adult subjects. They reported that both types of measures were able to detect differences in stance difficulty, that CP and force measures did not correlate highly with each other, and that force measures were more reliable than CP measures in some test-retest situations.

LeClair and Riach (1992) also investigated measurement parameters of postural stability. Both force and CP measures were found to detect differences in stance difficulty. Both force and CP measures were found to be reliable in test-retest situations. One difference between the Goldie et al. (1989) study and the LeClair and Riach (1992) study was test duration. Goldie et al. analysed results at a test duration of 15 seconds. LeClair and Riach (1992) analysed results for test durations of 10, 20, 30, 45, and 60 seconds. A test duration of 10 seconds was not found to provide a reliable estimate of postural stability. The test duration chosen may have been one reason for the different results reported in the two investigations.

Postural stability is dependent, in part, on the height of the CG above the base of support (Hayes, 1982). The CG of infants and children remains located a consistent distance above the crotch when compared to adults (Swearingen, Badgley, Branden, & Wallace, 1969). As children develop, the relative proportions of body parts change. Even though the distance of the CG above the crotch line remains relatively consistent, it's position within an infants body is different from that of a toddler or preschooler. In an infant, the CG is located at chest height, while for a three year old, the six inches above the crotch is located lower in the abdomen. This has biomechanical implications for the strategies that young children use to maintain postural stability as compared with older children and adults.

Riach and Hayes (1987), in a study with children, found that between subject variability of the amplitude of CP movements could only be partially explained by physical characteristics of the children. This indicates that the development of central postural control mechanisms also play an important role in postural control and stability in children.

The Romberg test, used as a clinical indicator of central nervous system function (Barrows, 1980) has been applied to the experimental investigation of postural stability. The test compares a subjects postural stability with eyes closed to their stability with eyes open. It can be expressed as a Romberg Quotient (RQ) (Njiokiktjien & van Parys, 1976):

$$RQ = \frac{\text{CP movements with eyes closed}}{\text{CP movements with eyes open}} \times 100\%$$

An RQ of less than 100% indicates that the subject is more stable with eyes closed than with eyes open, as is the case with some children (Riach & Hayes, 1987). An RQ of greater than 100% indicates that the subject is less stable with eyes closed than with eyes open, as is the case with adults (Lucy & Hayes, 1985).

Another measure of stability is the SL (McCollum & Leen, 1989; and Starkes et al., 1992). McCollum and Leen (1989) use the term to describe a cone within which a subject is able to move while maintaining a feet together, upright stance. The concept was used to explore the effect of response latency and mechanical properties of the stance position on the characteristics of the stability limits. Starkes et al. (1992) define stability limits as the area (under the feet) that the subject can use in maintaining postural stability. It is obtained by asking the subject to lean as far as they can without falling to the front, back, and to either side, and asking that they hold each position for a short time. This amount, the maximum distance the subject is able to move their CP while remaining upright (SL(cm)) is normalized to the subjects anatomical base of support in the a-p and lat planes (where the subject is standing with both feet together). SL can be described by the equation:

$$SL = \frac{SL\ (cm)}{\text{foot size (cm)}} \times 100\ \%$$

It is calculated separately for the a-p and lat planes. A SL close to 100

% would indicate that the subject could use most of their anatomical base of support during a standing task without losing their balance. A lower SL would indicate that the subject could use a smaller amount of their anatomical base to maintain stability. Starkes et al. (1992) applied the concept in the study of developmental changes in posture, and the effect of vision on postural stability limits. They reported that children under the age of seven years can potentially use less of their available anatomical base of support compared to adults. Children under seven years of age, are still attempting to learn what their stability limits are. They have not yet developed the adults ability to effectively use feedback to control postural stability.

Another potentially useful parameter for evaluating postural stability is the ratio of the variability of CP to the maximum distance the subject is able to move their CP while remaining upright (SL(cm)). It can be described by the equation:

$$CP/SL = \frac{2\text{ (standard deviation of CP) (cm)}}{\text{SL (cm)}} \times 100\%$$

This is calculated separately for the a-p and lat planes. A value of close to 100% would indicate that the subject was using almost all of the area available during a standing task and that the subject was precariously close to the limits of stability.

Development of Postural Stability

The development of postural stability can be divided into some distinct stages or phases. Transitions between stages are marked by increased reliance on visual feedback for postural stability (Woollacott et al., 1989). It is hypothesized that during these periods of transition, the body goes through a period of re-calibration of the vestibular and somatosensory feedback systems, using the visual system. The variability of stability results of children decreases as children increase in age (Forssberg & Nashner, 1982; Riach & Hayes, 1987). Transition periods occur at times when the children are learning a new postural skill, such as independent sitting, or independent standing (Woollacott, Debu, & Shumway-Cook, 1987).

Another transition period is between the ages of four and six years. During this period, children appear to regress in the organization of their postural responses (as measured by the onset of EMG in muscles used to maintain posture). Woollacott, Debu, and Mowatt (1987) hypothesized that children at this age were learning how to integrate information from visual, vestibular, and somatosensory systems. This integration is essential for mature postural responses, which are characterized by the ability to shift between sensory feedback systems depending on what is appropriate for the situation (Lee & Lishman, 1975).

Postural responses of children are similar to those of adults by the age of 10 - 12 years (Taguchi & Tada, 1988), or by 7 - 10 years (Shumway-Cook & Woollacott, 1985). It is unclear if children who have visual impairments experience the same transitions as children with complete visual feedback. It is also unclear how they are able to calibrate their vestibular and proprioceptive feedback in relation to growth.

Haas and Diener (1988) investigated the development of feedback and feedforward control of postural stability in children between the ages of 6 months and 15 years. They compared results of children who were developing normally to children with delayed development, and another group who presented with clumsiness. Feedback control was evaluated by introducing a toe-up perturbation of the base of support. All children demonstrated responses of the anterior tibial and triceps surae muscle groups. The latencies of onset, and success of recovery from the perturbation differed from group to group. Feedforward control was evaluated by asking subjects to stand on their toes as soon as they heard a tone. Children under the age of four years and children with developmental delays were unable to perform the task. The reaction time of children at four years was considerably longer than that of older children, however, they were still able to accomplish the task of maintaining balance on their toes. The reaction time of clumsy children was also longer than that of children who were developing normally.

Riach and Hayes (1987) investigated changes in postural stability between the ages of 2 and 14 years. Subjects were tested with eyes closed, and visually fixating a target with eyes open. They noted greater variability in the extent of CP movements within young subjects than within older subjects. Young males demonstrated greater instability than young females of the same age. Males, however, have a greater rate of improvement in stability with age so that gender differences decrease as age increases. Young females also develop postural stability similar to adult levels at a younger age than males. The effect of eye closure on postural stability (measured through RQ) was found to be at adult levels in children at 9 to 11 years of age. Children below this age demonstrated low RQ values compared to adults, indeed, some children were relatively less stable with eyes open than with eyes closed. Subjects under the age of 4.2 years were unable to stand with eyes closed for the test. The RQ findings could be due to the greater overall level of instability noted in younger children, or due to differences in the way that children process visual information in relation to other sensory feedback.

The spectral composition of CP movements in children was also analysed by Riach and Hayes (1987). The principal power was (similar to that of adults) found within the 0.05 to 0.7 Hz bandwidth, however young children demonstrated greater CP movements throughout the spectrum and greater power in the high frequencies (Riach & Hayes, 1987). The frequency analysis was not affected by eye closure, and was similar for both a-p and lat CP movements. Riach and Hayes (1987) suggested that the higher frequency of CP movements observed in the very young children (2 years old) may be due to decreased ability to process proprioceptive input, or due to impoverished proprioceptive input.

It is possible that as children develop postural stability, they are changing their control strategy from one that is essentially ballistic, or open loop, to one that relies more on sensory feedback, or a closed loop approach. Evidence for this hypothesis comes from examination of the velocity of CP movements in various groups of children. Starkes et al. (1992) examined the velocity of CP movements of children between 4 and 13 years. Velocity was directly related to magnitude of CP movements (i.e., when magnitude of CP movements decreased, velocity also decreased). In a ballistic control strategy, the child would make fast movements, and would not be able to make necessary adjustments in the movements until late in the movement. This could result in a series of overcompensations. With slower movements, the subject has time to make use of sensory feedback. In this way, subjects can make corrections early in the postural adjustment process, and can avoid overcompensating. This would result in increased postural control and stability.

Starkes et al. (1992) reported a decrease in velocity of CP movements in subjects at 8 years. Shumway-Cook, and Woollacott (1985) suggested that children between 4 and 6 years of age were learning how to integrate the use of all available sensory feedback. This would provide them with the skills needed to change their postural control strategy from one involving ballistic control to one involving sensory guided control.

Motor Development / Motor Control in People with Visual Impairments

Postural control (and the development of postural stability) in the presence of a visual impairment is more complex than standing with eyes closed. Some residual vision may be present. This residual vision could have either a stabilizing or a destabilizing effect on the development of postural stability. At certain times during the developmental process, children tend to rely on visual feedback more than somatosensory or vestibular feedback (one such stage occurs between the ages of four and six years; Woollacott, Debu, & Mowatt, 1987). If residual vision provides the child with distorted, or inaccurate visual information, children may find it particularly destabilizing during that period.

Vision appears to develop first in the control of posture. It is thought to be used to develop and calibrate the other two feedback systems for use in postural control (Lee & Aronson, 1974; Woollacott et al., 1989). Children with visual impairments may rely on the vestibular system to calibrate feedback from the somatosensory system, or they may rely on the somatosensory system for calibration.

Children who are born without vision develop early motor skills within the same ranges as children born with vision. That is, they learn to control their head and trunk in sitting and standing in a time period similar to their peers without visual impairments (as measured by the Bayley scales of infant development, and the Denver Developmental screening test). They show lags in motor development of skills that children without visual impairments use to explore their environments, such as bringing the hands together, crawling, and walking (Adelson & Fraiberg, 1974).

Children born with vision use that sense as a motivation to explore their environment, they see something interesting, and experiment with moving and controlling their body to get close to the object. This form of motivation is not as naturally present in the environment of children born with visual impairments. Their environment must be adapted to provide opportunities for exploration similar to those available to other children. The infant uses vision to learn about their bodies. For example, children without visual impairments watch their hands move at an early age. This form of play is followed closely by attempts to reach at objects within their visual field. Children with visual impairments (VI) demonstrate less spontaneous hand play (Sonksen et al., 1984).

It has been assumed that people who develop without visual feedback learn to use other feedback systems more efficiently than people who have visual feedback. This is not necessarily the case. Toole, McColskey, and Rider (1984) investigated the retention of movement cues in adults with and without visual impairments. Subjects in the study were 22 college students (11 with no visual impairments, and 11 with visual impairments). None of the subjects with visual impairments had been born with the impairments. All subjects were blindfolded for the test. Subjects practised moving a linear slide until a stop was reached. After a retention interval, they were required to replicate the movement without the stop in place. They noted that both groups were equally able to use kinesthetic feedback to recall movement and distance cues. In addition, the subjects with visual impairments demonstrated greater variability in the recall task, not less variability as expected if they were better able to use kinesthetic feedback.

Summary

In summary, the ability to maintain posture is governed by both neurological and biomechanical constraints. The positions of the CP and the line of gravity are related to one another, but they are not the same. During quiet standing, however, the CP and CG are very closely aligned (Murray et al., 1967).

Feedback on position in space is provided by visual, vestibular and somatosensory information. Sensory systems are well developed by the time children are learning to stand (Amblard et al., 1990; Ornitz, 1983; Woollacott, Debu, & Shumway-Cook, 1987). In the development of postural control, children learn how to use the sensory systems together.

The development of postural stability can be divided into some distinct stages or phases. Transitions between stages are marked by increased reliance on visual feedback for postural stability (Woollacott et al. 1989). It is hypothesized that during these periods of transition, the body goes through a period of re-calibration of the vestibular and somatosensory feedback systems, using the visual system. Transition periods occur at times when the children are learning a new postural skill, such as independent sitting, or independent standing (Woollacott, Debu, & Shumway-Cook, 1987). Another transition period is between the ages of four and six years. During this period, children appear to regress in the organization of their postural responses (as measured by the onset of EMG in muscles used to maintain posture). Woollacott, Debu, and Mowatt (1987) hypothesized that children in this age group were learning how to integrate information from their visual, vestibular, and somatosensory systems. Postural responses of children are similar to those of adults by the age of 10 - 12 years (Taguchi & Tada, 1988), or by 7 - 10 years (Shumway-Cook & Woollacott, 1985).

It is not clear if children who have visual impairments experience the same transitions as children without visual impairments. It is also not clear how they are able to calibrate their vestibular and proprioceptive feedback in relation to growth. Children with visual impairments may rely on the vestibular system to calibrate feedback from the somatosensory system, or they may rely on the somatosensory system for calibration.

Visual acuity has an influence on postural stability. In adult subjects a reduction in visual acuity (using semitransparent plastic foils in glasses to decrease acuity across the entire visual field) affects CP movements in the a-p plane to a greater extent than in the lat plane (Paulus et al., 1984).

Chapter 3

METHODS

Subjects

Thirty eight control subjects between the ages of 4 and 12 years took part in the study (2 females and 2 males at ages 4, 5, 6, 7, 8, 9, and 10 years, 2 females and 3 males at age 11 years and 3 females and 2 males at age 12 years). Twelve subjects with congenital visual impairments, between the ages of 5 and 12 years also took part in this study. Characteristics of this group are summarized in Table 1.

Subjects in the control group were free from any neurological or orthopedic disorders. They were recruited from community programmes associated with McMaster University. Children with congenital visual impairments were recruited from community agencies, and school boards serving visually impaired children in Southern Ontario. The children with visual impairments had no other neurological, sensory, or orthopedic disorders that would affect postural stability.

Apparatus

Testing took place at two sites (McMaster University in

Table 1.
Summary of visual abilities of subjects with visual impairments.

Subj.	Age (yrs) / gender	Diagnosis	Visual Abilities
1	5 / F	Persistent hyperplastic (PH) primary vitreous (PV)	Totally blind
2	7 / M	Retinitis Pigmentosa (RP)	Light perception
3	7 / M	Bilateral PH, PV and Retinopathy of Prematurity (ROP)	Totally blind
4	9 / M	Congenital blindness, microphthalmos	light perception in left eye
5	9 / F	Retrolental Fibroplasia	20/200
6	9 / F	Retrolental Fibroplasia	light perception
7	10 / M	Congenital stationary night blindness with very high myopia and congenital nystagmus	10/100 both eyes
8	11 / M	Retrolental Fibroplasia	20/60 right 20/200 left
9	11 / M	Lebers Amourosis	Totally blind
10	11 / F	Not available	Totally blind from birth
11	12 / F	Retrolental Fibroplasia	Totally blind
12	12 / F	Hereditary cone rod syndrome	Totally blind

Hamilton, ON., and W. Ross MacDonald school in Brantford, ON.). Subjects stood on a force platform (AMTI model OR6-5-1). Ground reaction forces in the vertical plane (Fz), and moments of force in the lat and a-p planes (Mx, My) were sampled at a frequency of 50 Hz (sampling rate .02 sec) after amplification (AMTI SGA 6-3 Signal Conditioner/Amplifier).

Centre of Pressure in the x and y planes were calculated using the AMTI BEDAS-2 data acquisition and analysis software (Computer Automated Stabilograph programme). They were calculated based on the formula:

$$CPx = \frac{My}{Fz} \qquad CPy = \frac{Mx}{Fz}$$

Task

Subjects were asked to stand with shoes off, feet together on the force plate. An outline of their feet was traced on a piece of paper to measure the anatomical base of support. In order to ensure that subjects were comfortable with the test procedure, practice trials were given, one at the beginning of each set of trials. The subject was instructed to stand on the force platform with feet together, and to remain as still as possible until asked to relax (30 seconds). This was completed under 4 conditions:

1. quiet standing, feet together, EO
2. quiet standing, feet together, EC
3. quiet standing on foam, feet together, EO
4. quiet standing on foam, feet together, EC

Foam used in this study was 5 thicknesses of carpet underpadding (recycled polyethelyne composite foam mat), having a total thickness of 5 cm.

These trials were followed by trials in which the subjects were asked to lean as far as possible forward, backward, to the left and to the right without falling. This was conducted under 4 conditions.

1. feet together, EO
2. feet together, EC
3. feet together, standing on foam, EO
4. feet together, standing on foam, EC

Zero values for force platform output were taken prior to each trial. Care was taken to ensure that for each trial, subjects stood with their feet together, and their heels aligned. Data were collected for 30 seconds in each condition. Data collection commenced 5 seconds after each trial began (subjects stood on the force platform for a total of 35 seconds each trial). Subjects were given a rest period between trials. Based on previous work (LeClair & Riach, 1992), a 30 second trial can provide an accurate and reliable measurement of stability.

Data were collected for one trial in each condition. It is unlikely that learning is a factor in tasks such as these (Riach & Hayes, 1987; Zernicke, Gregor, & Cratty, 1982). It has been established (LeClair & Riach, 1992) that one trial gives a reliable estimate of postural stability. Order and carry over effects were balanced in both test blocks using a four condition Williams square method.

In four test conditions, children stood on 5 cm of foam. Foam has been used in previous work (Lee & Lishman, 1975; Magnusson et al., 1990; McClenaghan & Williams, 1991) to provide an additional postural challenge, and to alter the somatosensory feedback available to assist with maintenance of posture.

Measures of stability

For each quiet standing trial, stability was measured using:

1. standard deviation of the CP about the mean position in the lat plane (CPx)
2. standard deviation of the CP about the mean position in

the a-p plane (CPy)

3. The velocity (vel) of CP movements

For each leaning condition, stability was measured using:

1. The SL in the lat plane.
2. The SL in the a-p plane.

To determine the amount of the usable base of support (i.e. SL) that was used to maintain postural stability, the following were calculated for both stance and vision conditions:

1. The ratio of two times the standard deviation of CPx to the SL (cm) in the lat plane.
2. The ratio of two times the standard deviation of CPy to the SL (cm) in the a-p plane.

Analysis of data

Data for control subjects were analysed separately from subjects with visual impairments. A Pearson correlational analysis was used to examine the relation between age and outcome parameter for both groups of subjects. For additional analyses, subjects were grouped by age into four groups (age 4-5, 6-7, 8-9, 10-12). Data were initially analysed using a 3 way, mixed design ANOVA for all outcome parameters; 1 factor between subjects (4 age groups) and 2 factors within subjects (2 vision conditions EO, EC; and 2 stance conditions, normal and foam).

Physical factors such as height, weight and foot size have been found important in determining stability results (Riach & Hayes, 1987). These factors change relative to age in children. Without controlling for these factors, changes seen with age may be a result of physical growth, rather than a result of sensory-motor developmental changes in the ability to maintain postural stability. One method of removing the variability associated with these physical factors is to complete an analysis of covariance (ANCOVA). The Pearson correlation coefficient was calculated to look at the relation between control subjects age, height, weight and foot size (in the a-p and lat planes). These analyses were used to determine the covariate for use in the ANCOVA. Tukey post hoc analysis was used to examine significant results.

Results for individual subjects with visual impairments were compared to the control subjects at each age and in each condition. Inspection of the results revealed the subjects or groups of subjects with visual impairments that fell outside of two standard deviations above and below the mean for the control subjects. If the results for the control subjects are assumed to represent a normal distribution, 95.4% of the observations would be expected to lie within this area (Colton, 1974). The probability of an observation for a control subject falling outside of this distribution (above or below) would be $p = 0.046$. If the results from the subjects with VI fall outside of this distribution, then they could be considered different from the results of the control subjects at $p = 0.046$.

Chapter 4

RESULTS

One control subject (4 year old male) and one subject with a visual impairment (8 year old male) were not able to complete the tasks required for this study. The control subject was not fluent in English, and the subject with VI was not able to follow one step directions such as "stand here". None of their data were used in data analysis. A total of 38 control subjects and 12 subjects with VI data were used in these analyses. Trials in which the subject lifted one foot from the force platform were repeated. The failed trials were not used in the data analysis. Failed trials occurred most frequently during the leaning tasks. The 5 year old subject with VI was not able to perform any of the leaning tasks. Results for that subject in the quiet standing tasks were successfully completed and included in the analysis.

CONTROL SUBJECTS

Correlation Between Outcome Parameters and Age

A Pearson correlation coefficient was calculated to examine the relation between age and all outcome parameters (Table 2). Values for the outcome parameters of CPx and CPy EO conditions decreased with

Table 2. Pearson correlation coefficients for age and each outcome parameter for control subjects (n = 38).

Parameter	Stance	Vision	r value	p ≤
CPx	Normal	Eyes Open	-.56	.001
		Eyes Closed	-.33	ns
	Foam	Eyes Open	-.58	.001
		Eyes Closed	-.32	ns
CPy	Normal	Eyes Open	-.61	.001
		Eyes Closed	-.42	.01
	Foam	Eyes Open	-.58	.001
		Eyes Closed	-.16	ns
vel	Normal	Eyes Open	-.83	.001
		Eyes Closed	-.75	.001
	Foam	Eyes Open	-.83	.001
		Eyes Closed	-.81	.001
SLlat	Normal	Eyes Open	-.04	ns
		Eyes Closed	-.11	ns
	Foam	Eyes Open	-.12	ns
		Eyes Closed	-.27	ns
SLa-p	Normal	Eyes Open	.01	ns
		Eyes Closed	-.25	ns
	Foam	Eyes Open	-.29	ns
		Eyes Closed	-.11	ns
2(SD of CPx) / SLlat	Normal	Eyes Open	-.63	.001
		Eyes Closed	-.49	.001
	Foam	Eyes Open	-.53	.001
		Eyes Closed	-.32	ns
2(SD of CPy) / SLa-p	Normal	Eyes Open	-.63	.001
		Eyes Closed	-.56	.001
	Foam	Eyes Open	-.62	.001
		Eyes Closed	-.36	ns

an increase in age. For CPy the EC condition also decreased with an increase in age. Velocity was also negatively correlated with age. The SL in the a-p and lat planes were independent of age.

Analysis of Variance

Data were analysed using a three way mixed design ANOVA. Results for the Analysis are summarized in Table 3. The effect of development is of interest in this investigation. Physical changes associated with development could be responsible for differences noted between groups. In order to control for these differences, an ANCOVA was also completed with the data. To determine the appropriate variable to use as the covariate, the Pearson correlation coefficient was calculated to look at the relation between control subjects age, height, weight and foot size (in the a-p and lat planes). Height was chosen as the covariate since it correlated most strongly with age ($r = .9132$, $p = .001$). Results for the ANCOVA analyses are summarized in Table 4. With the variability due to height removed, age remained a significant factor for two of the seven outcome parameters (vel and 2(SD of CPx)/SLlat). Information contained below discusses the results using the ANCOVA procedure.

Table 3. Summary of the main effects and interactions for Analysis of Variance for control subjects.

		CPx	CPy	vel	SLa-p	SLlat	2(SD of CPx)/SLlat	2(SD of CPy)/SLa-p
age	F(3,34)=	5.32	4.38	41.82			9.35	7.18
	P≤	.004	.001	.001			.001	.001
stance	F(1,34)=	36.21	71.61	68.08	22.78		29.56	78.08
	P≤	.001	.001	.001	.001		.001	.001
age by stance	F(3,34)=			6.91				
	P≤			.001				
vision	F(1,34)=	135.14	42.88	25.58	5.46		70.34	50.43
	P≤	.001	.001	.001	.026		.001	.001
age by vision	F=							
	P≤							
stance by vision	F(1,34)=	20.29	12.88	25.47			15.84	16.48
	P≤	.001	.001	.001			.001	.001
age by stance by vision	F=							
	P≤							

Table 4. Summary of the main effects and interactions for Analysis of Covariance for control subjects.

		CPx	CPy	vel	SLa-p	SLlat	2(SD of CPx)/SLlat	2(SD of CPy)/SLa-p
age	F(3,33)=			4.10			3.26	
	P≤			.014			.034	
stance	F(1,34)=	36.21	71.61	68.08	22.78		29.56	78.08
	P≤	.001	.001	.001	.001		.001	.001
age by stance	F(3,34)=			6.91				
	P≤			.001				
vision	F(1,34)=	135.14	42.88	25.58	5.46		70.34	50.43
	P≤	.001	.001	.001	.026		.001	.001
age by vision	F=							
	P≤							
stance by vision	F(1,34)=	20.29	12.88	25.47			15.84	16.48
	P≤	.001	.001	.001			.001	.001
age by stance by vision	F=							
	P≤							

Analysis of Covariance

Quiet standing tasks

The quiet standing tasks were measured using the outcome parameters of CPx, CPy, and vel. For each of these parameters, main effects were noted for stance, and vision with an interaction between stance and vision. For vel, a main effect was noted for age and an interaction was demonstrated between age and stance.

Velocity decreased as subjects age increased. The velocity of the youngest group of subjects (age 4 and 5 years) was greater than the velocity for all other groups of subjects. The velocity for the oldest group of subjects (10 to 12 years) was less than the velocity for all other groups of subjects (Figure 1). For the stance and vision main effects, an increase in variability of the CPx, CPy, and a higher velocity of CP movements was noted when subjects stood on the foam as compared to the force plate alone (for the stance main effects) and when the subjects stood with eyes closed as compared to eyes open (for the vision main effects). For the stance by vision interaction, subjects found standing on foam to be more destabilizing when they were also standing with eyes closed (Table 5). These findings indicate that both the foam and the EC conditions did provide postural challenges for the subjects.

The interaction between age and stance for vel demonstrated

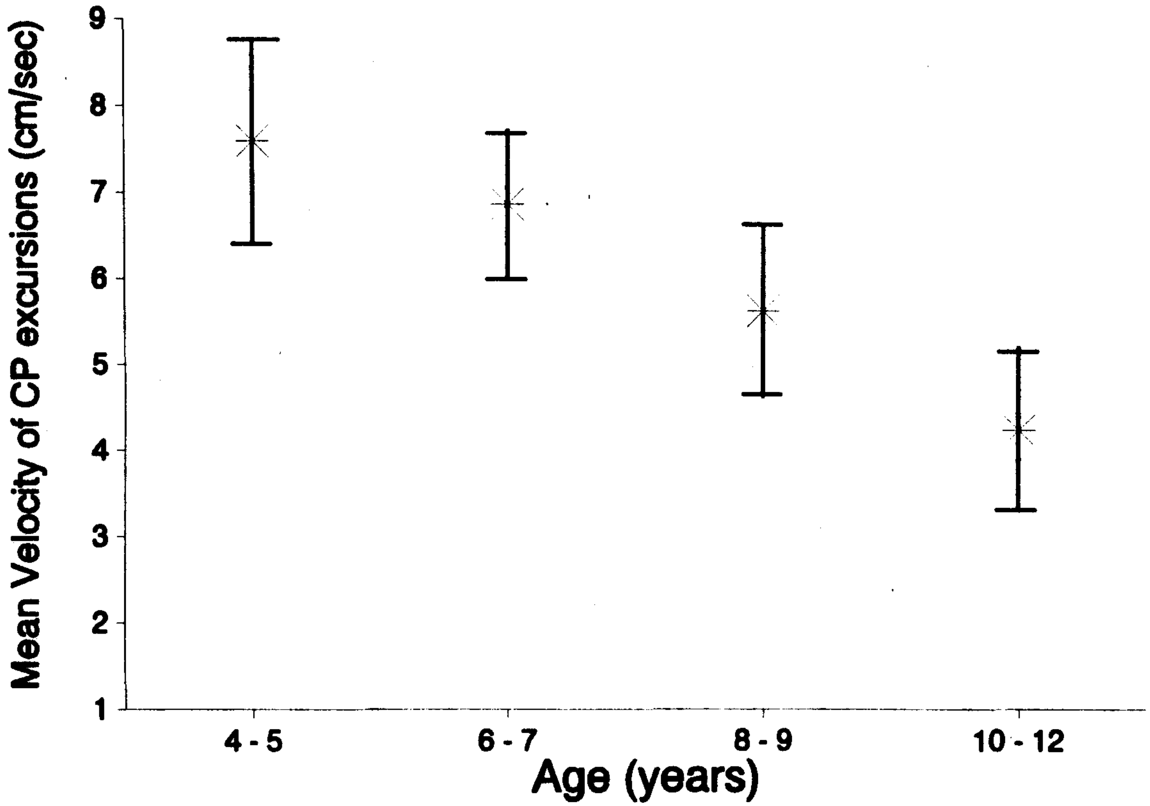


Figure 1. Main effect for age collapsed over stance and vision condition for the outcome parameter of mean velocity of CP excursions for control subjects. Velocity decreased with increased age.

Figure 5. For the stance by vision interactions for control subjects (ANCOVA), this table provides the means and standard deviations (SD) for each outcome parameter in normal and foam stances, eyes open (EO) and eyes closed (EC) conditions.

parameter		Normal Stance EO	Normal Stance EC	Foam Stance EO	Foam Stance EC
CPx	mean	.566	.776	.612	1.047
(cm)	SD	.228	.199	.195	.237
CPy	mean	.549	.644	.686	1.038
(cm)	SD	.171	.217	.238	.370
vel	mean	5.156	5.526	5.558	6.903
(cm/s)	SD	1.690	1.387	1.787	1.869
2(SD of CPx)/SLlat	mean	4.658	6.451	5.176	9.104
	SD	2.328	1.996	2.554	2.800
2(SD of CPy)/SLa-p	mean	4.151	4.871	5.379	8.604
	SD	2.280	1.942	2.392	3.746

that subjects aged 6 and 7 years found standing on foam to be more destabilizing than younger and older subjects (Figure 2).

Leaning tasks

The stability limits were evaluated during leaning tasks. No main effects or interactions were noted for the SLlat outcome parameter. In the a-p plane, however, main effects were noted for stance and for vision conditions. A lower SLa-p was noted when subjects stood on the foam as compared to the force plate alone (for the stance main effects) and when the subjects stood with eyes closed as compared to eyes open (for the vision main effects).

Comparison of the excursions of the CP to SL during quiet stance

Main effects were noted for stance and vision with an interaction between stance and vision. The ratio of the 2(SD of CPx) / SLlat also decreased with an increase in age. The youngest group of subjects used a greater amount of the area available in the lat plane during quiet standing tasks than all other groups of subjects. Additionally, subjects aged 6 and 7 years had a higher ratio than older subjects (Figure 3). A higher ratio of SL used during quiet stance in the a-p and lat planes was noted when subjects stood on the foam as compared to the force plate alone (for the stance main effects) and when the subjects stood with eyes closed as compared to eyes open (for the vision main effects).

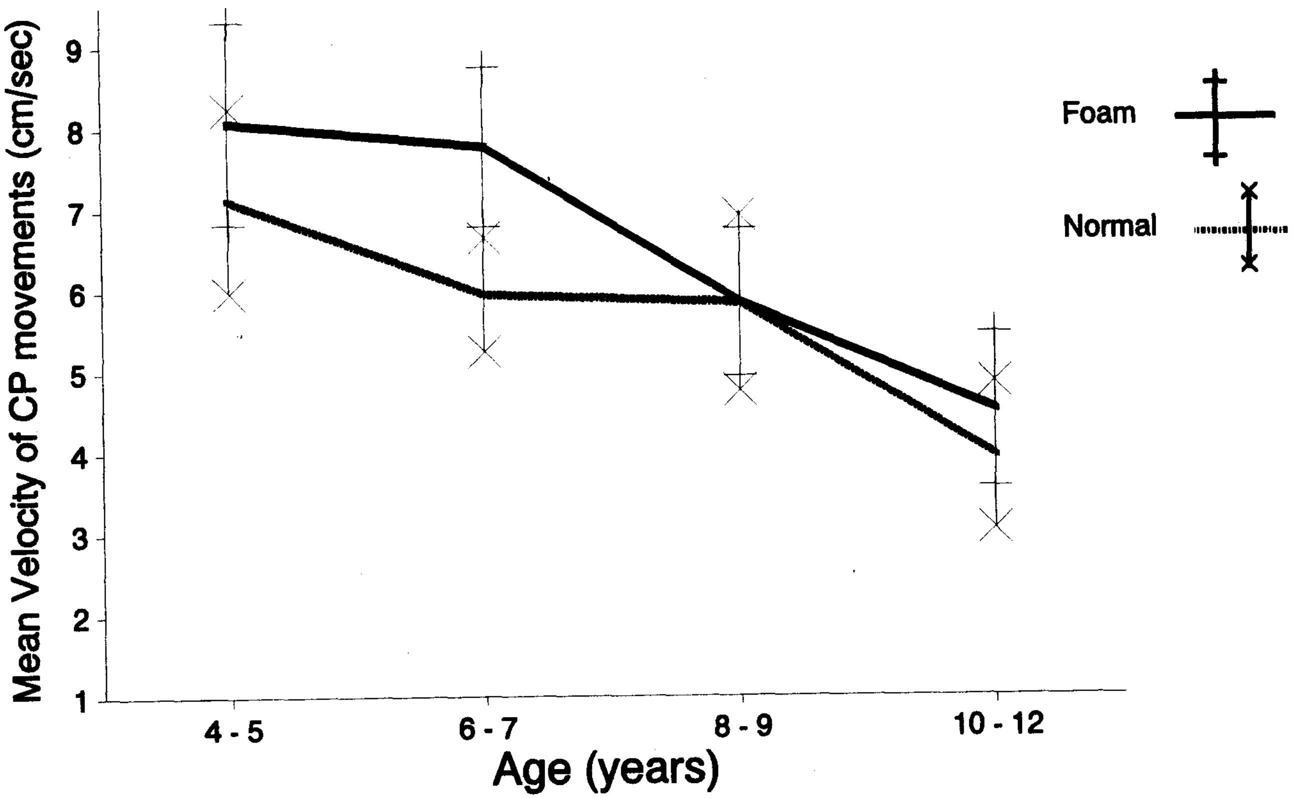


Figure 2. Age by stance interaction collapsed over vision condition for the outcome parameter of mean velocity of CP excursions with control subjects. At age 6 and 7 years, there was a significant difference in velocity of CP excursions between the foam and normal stance conditions.

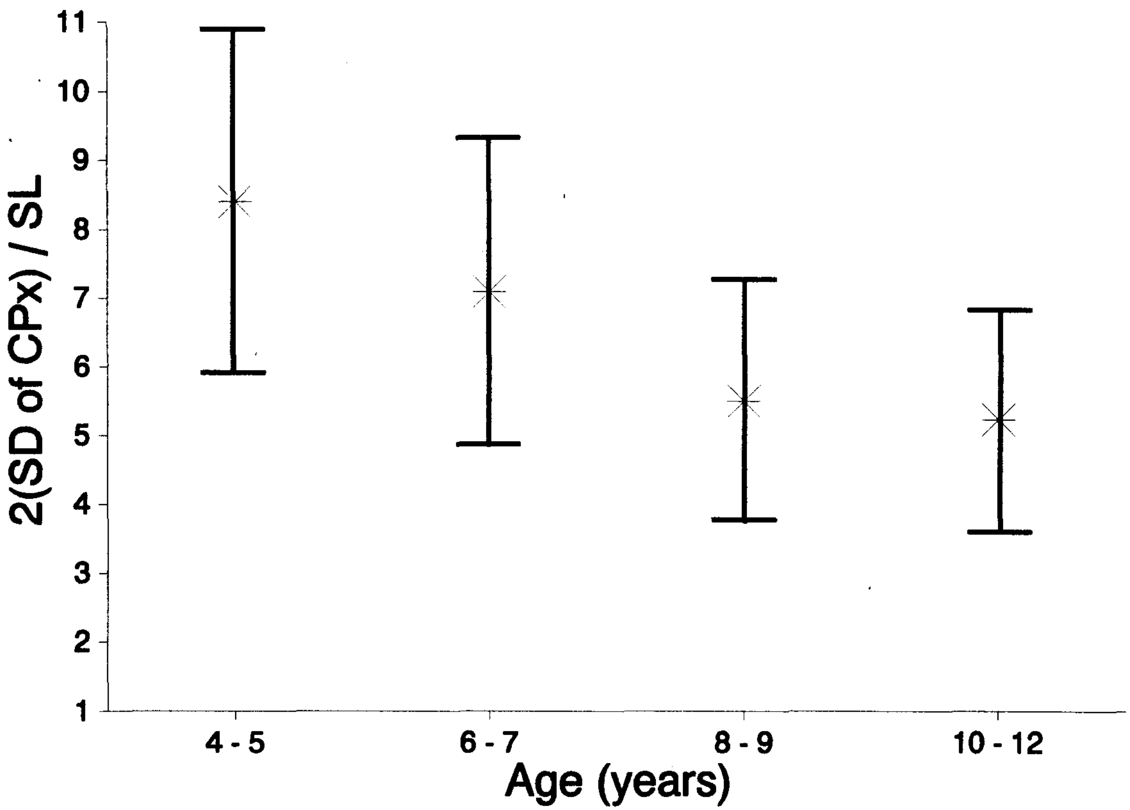


Figure 3. Main effect for age collapsed over stance and vision condition for the outcome parameter of 2 (SD of CPx) / SLlat for control subjects. Ratio decreased with an increase in age.

The stance by vision interactions indicate that the subjects found standing on foam to be more challenging when they also were standing with eyes closed (Table 5).

Comparing the excursions of the CP during quiet stance to the SL, an increase in age was correlated with a decrease in this ratio for EO conditions in the a-p and lat planes. In the a-p and lat planes, the normal stance EC conditions were also negatively correlated with an increase in age.

Subjects with Visual Impairments

Subjects with VI demonstrated similar or worse postural stability compared to the control subjects. Figures 4 to 10 outline the differences between subjects with VI and control subjects in each condition. Each VI subject's results are plotted directly on the graph. This is compared to two standard deviations from the mean result of all control subjects.

Correlation Between Outcome Parameters and Age

No significant correlations using the Pearson correlation coefficient were found between age and any outcome parameter for the subjects with VI.

Quiet Standing Tasks (Figures 4, 5 and 6)

For quiet standing tasks (measured using CPx, CPy and vel), results for subjects with VI fell outside of two standard deviations of the expected values for control subjects more frequently as age increased. This was true in the EO and EC conditions. In the EC foam condition, subjects with VI had results more similar to control subjects than in any of the other conditions, including the EC normal stance condition. For the excursions of the CP, the two groups were most similar in conditions that changed both visual and somatosensory feedback. They were dissimilar in the conditions changing only somatosensory feedback (Figures 4 & 5).

Differences between visual ability groups were most apparent on the outcome parameter of mean velocity of CP movements in the foam stance EO condition, and least apparent in the foam stance EC condition (Figure 6).

Leaning Tasks (Figures 7 and 8)

Fewer differences based on age, stance or vision conditions were noted between control subjects and subjects with VI in the leaning conditions than in the quiet standing conditions. The 5 year old subject with VI was not able to perform the leaning tasks. In the a-p plane, foam conditions, only one subject with VI had results that fell outside of 2 standard deviations of the mean result for the control subjects in both

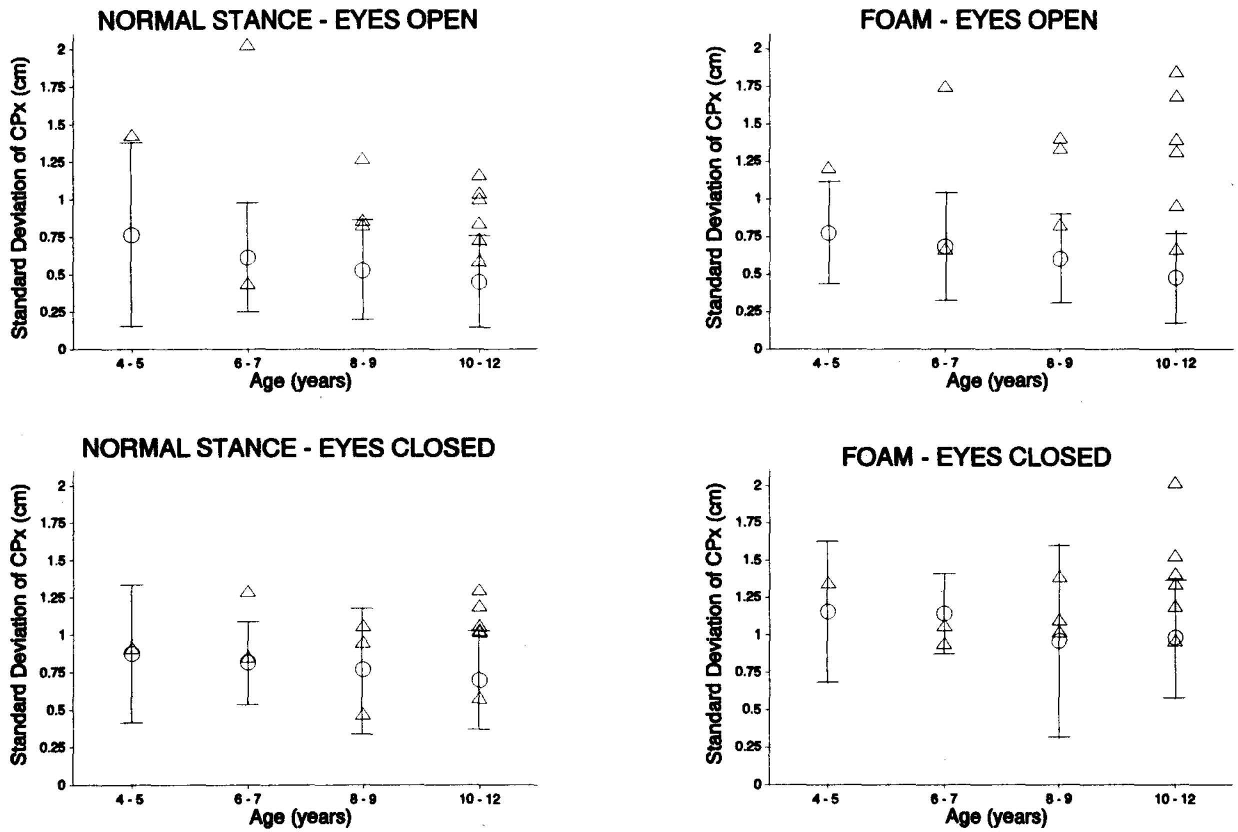


Figure 4. For the outcome parameter of standard deviation of the Centre of Pressure in the x plane (CPx), this figure provides a comparison of the magnitude of CP excursions for control subjects (circles) plus or minus two standard deviations from the mean to individual results for subjects with visual impairments (triangles).

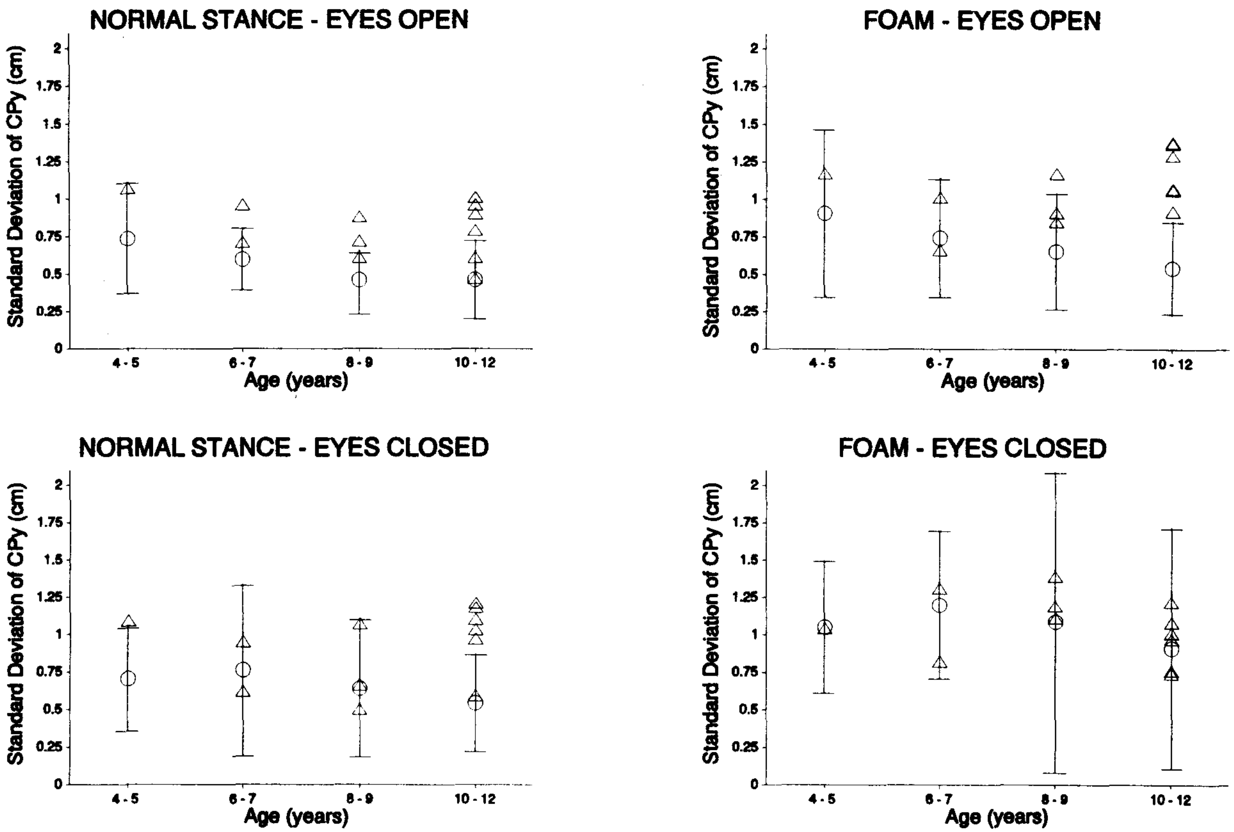


Figure 5. For the outcome parameter of standard deviation of the Centre of Pressure in the y plane (CPy), this figure provides a comparison of the magnitude of CP excursions for control subjects (circles) plus or minus two standard deviations from the mean to individual results for subjects with visual impairments (triangles).

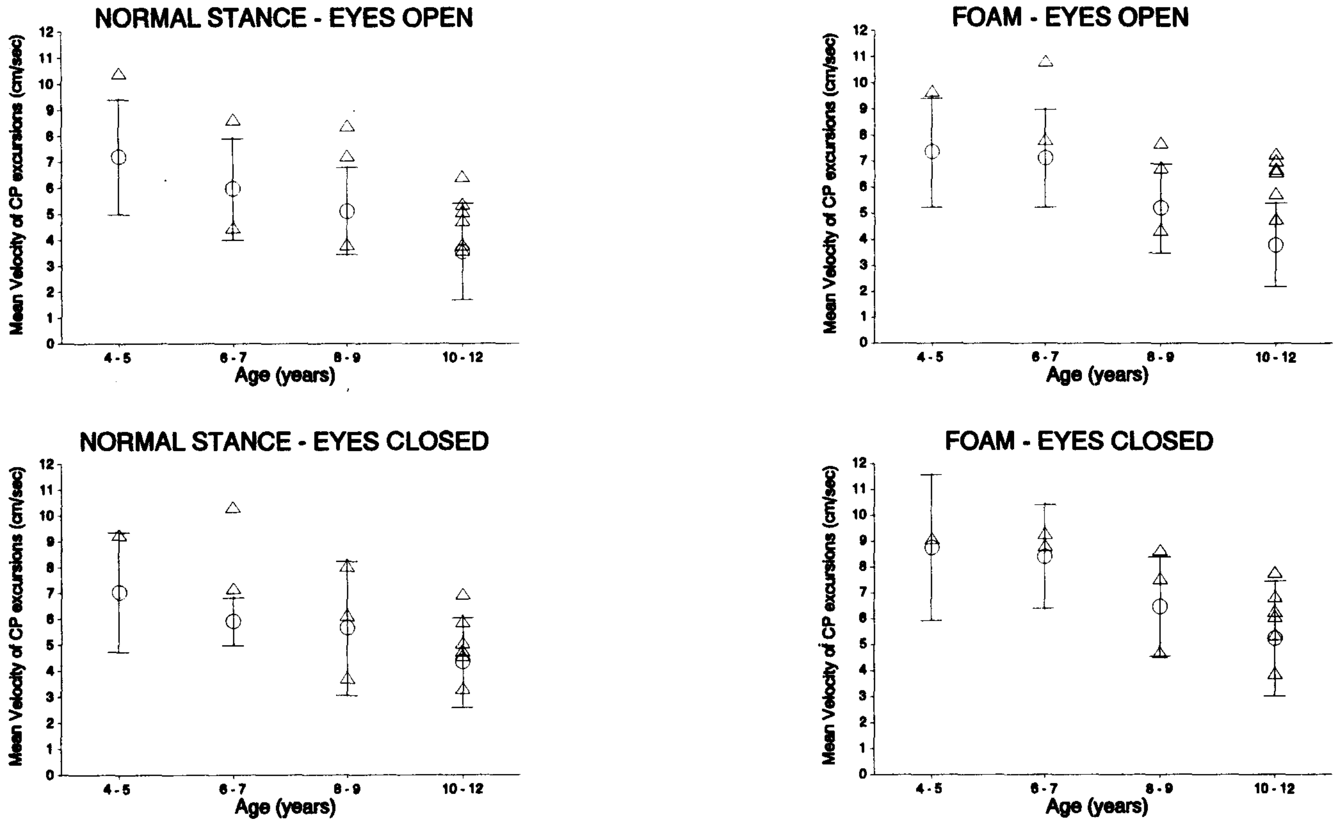


Figure 6. Mean velocity of CP excursions for control subjects (circles) plus or minus two standard deviations from the mean compared to individual results for subjects with visual impairments (triangles).

EO and EC conditions. For the EO condition, the subject was in the 8 - 9 year old group. In the EC condition, the subject was in the 10 - 12 year old group. In the normal stance conditions, 4 and 5 subjects fell outside of 2 standard deviations of the mean result for control subjects in the EO and EC conditions respectively. All subjects were in the 8 - 12 year old groups (Figure 7).

In the lat plane, normal stance conditions, 3 subjects fell outside of the expected range for both the EO and EC conditions. In the foam condition, 2 subjects fell outside in the EO condition (8 - 9 year old group), while all subjects were within the expected range for the EC condition (Figure 8).

Comparison of the excursions of the CP to SL during quiet stance (Figures 9 and 10)

Results for subjects with visual impairments fell outside of two standard deviations of the mean for control subjects more frequently as age increased. This difference was noted most strongly in the foam EO conditions in the lat and a-p planes. The two groups were most similar in the condition limiting both visual and somatosensory feedback (foam EC condition).

Figure 11 provides a comparison of the excursions of CP during quiet stance to the SL and to the anatomical base of support for

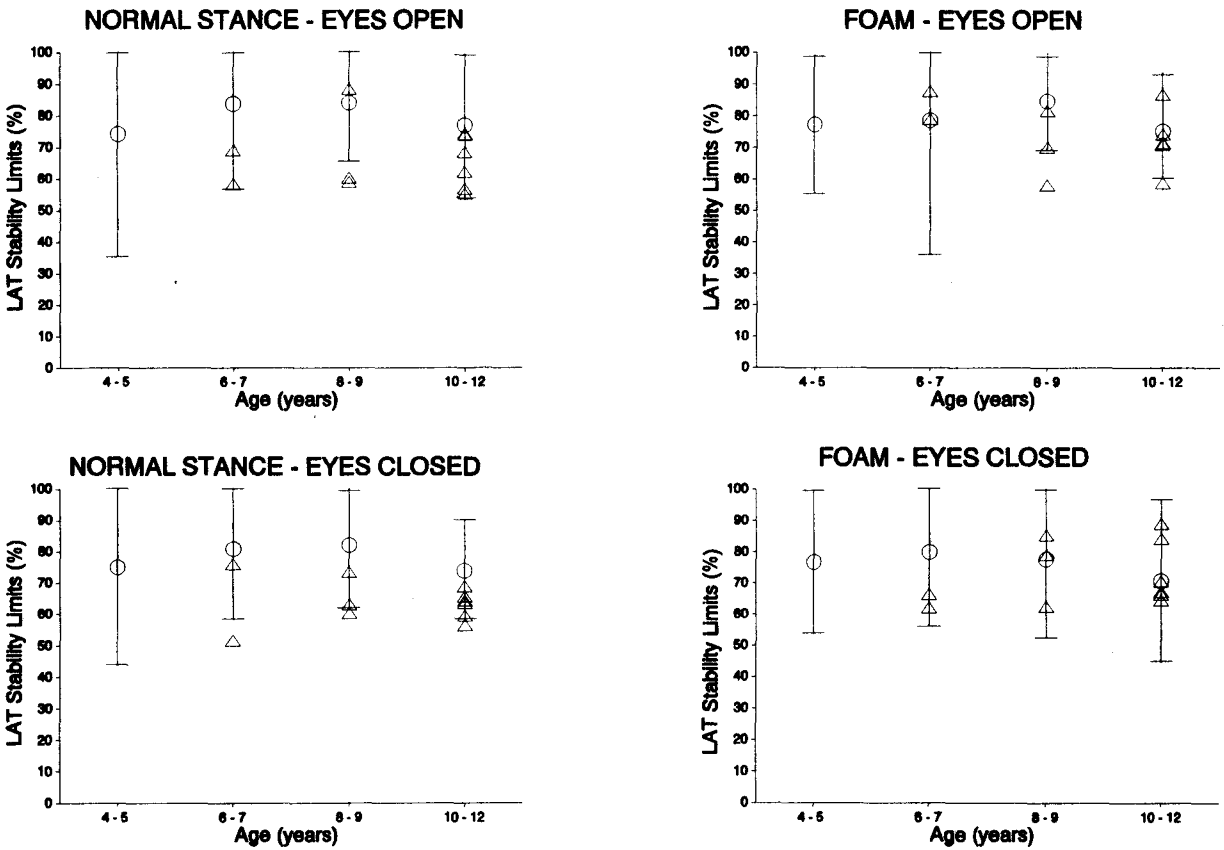
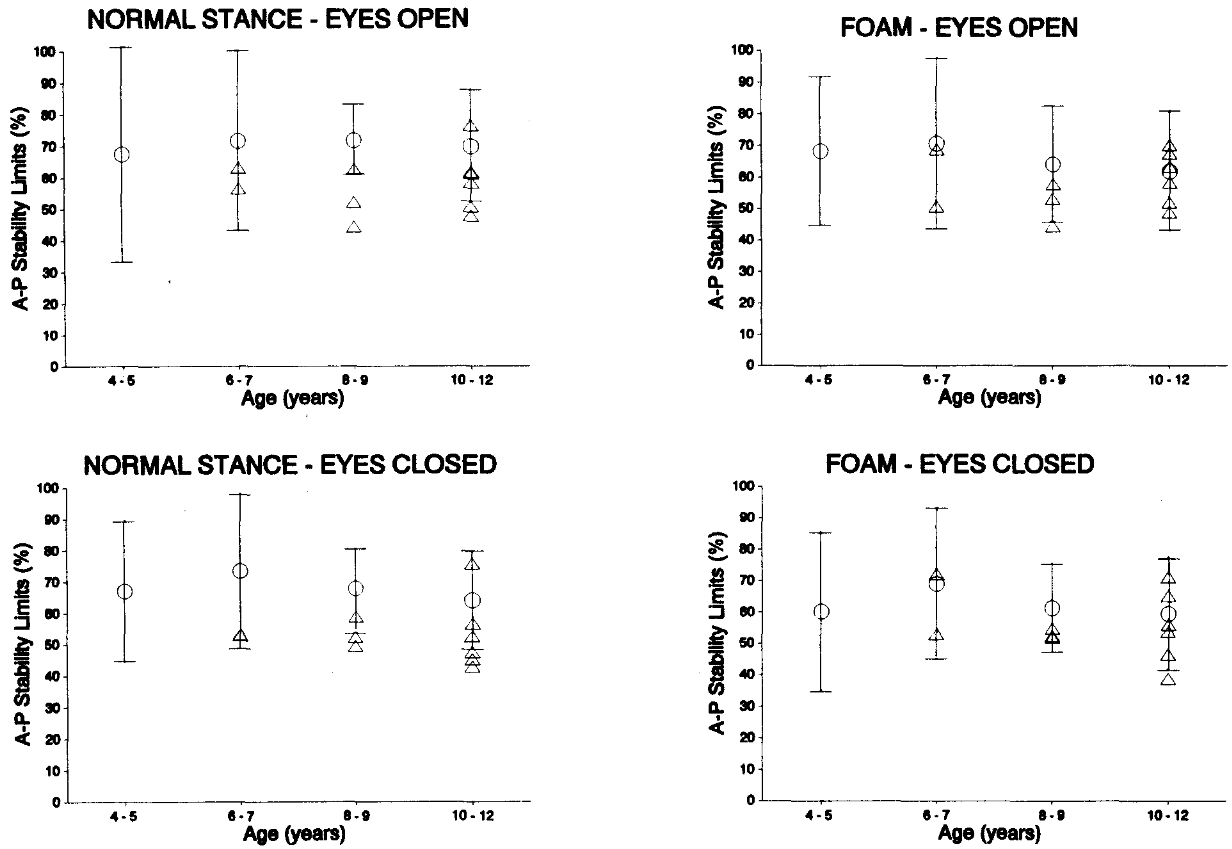


Figure 7. Mean SLlat for control subjects (circles) plus or minus two standard deviations from the mean compared to individual results for subjects with visual impairments (triangles). Results are normalized to foot size.



<u>Figure 8.</u> Mean SLa-p for control subjects (circles) plus or minus two standard deviations from the mean compared to individual results for subjects with visual impairments subjects (triangles). Results are normalized to subjects foot size.

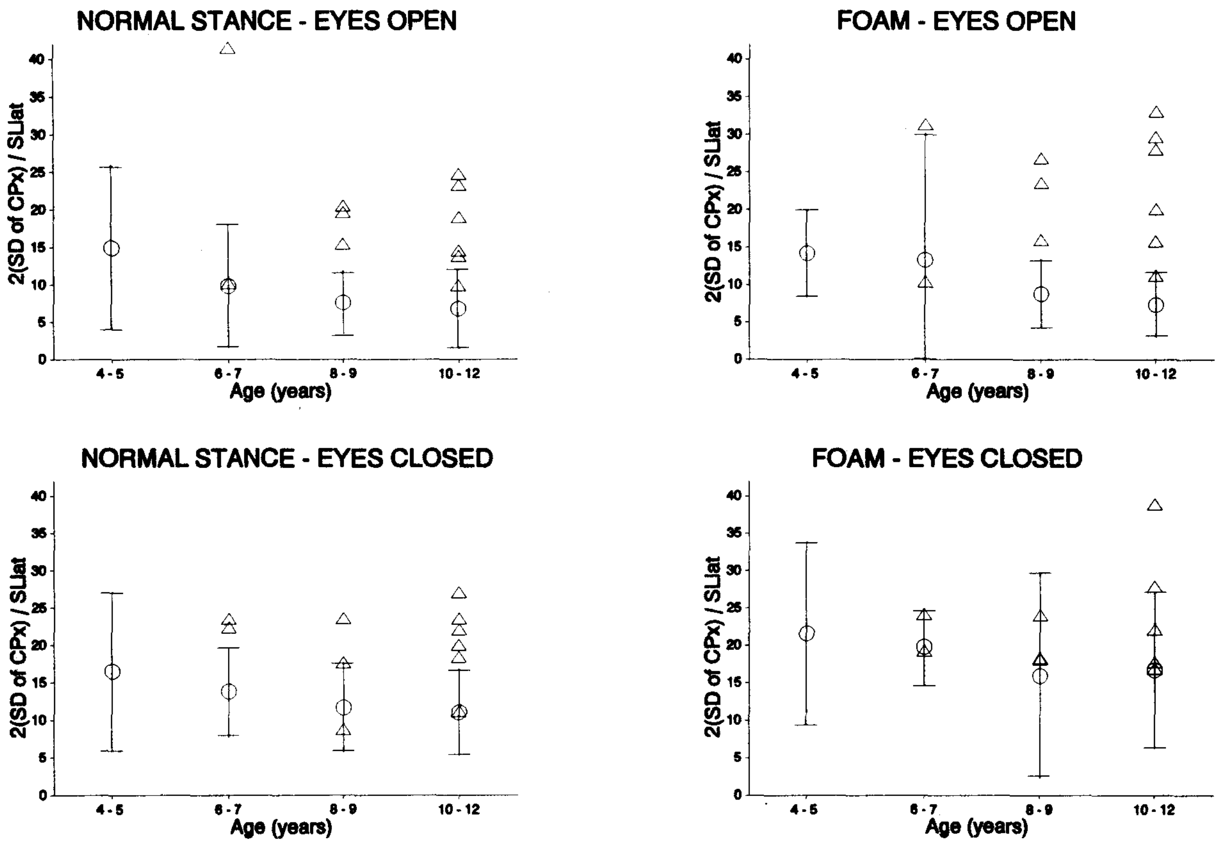
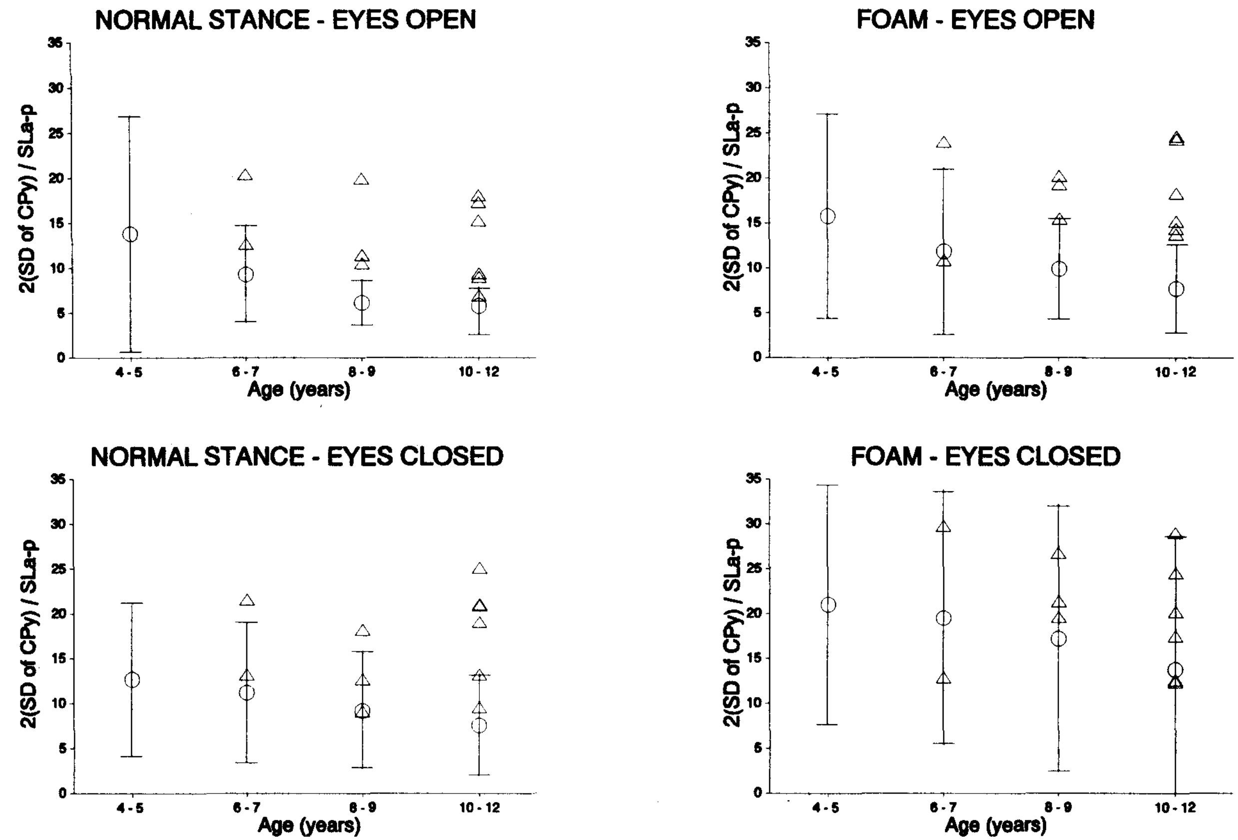
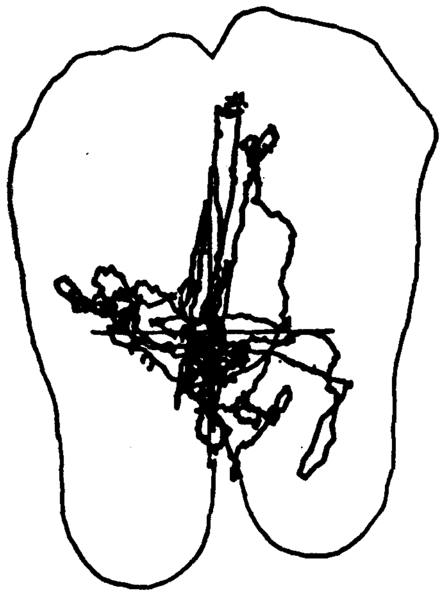


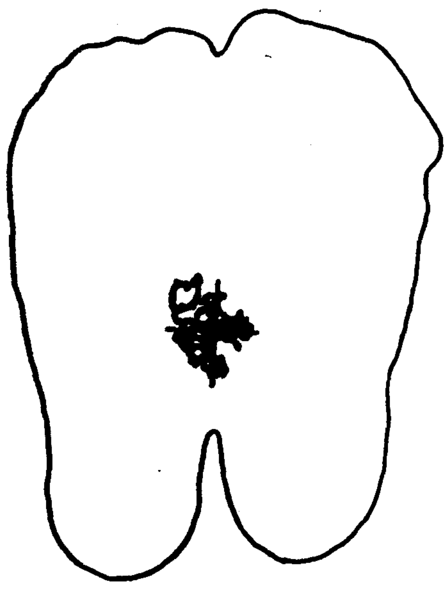
Figure 9. Mean ratio of SL used during quiet stance (lat) for control subjects (circles) plus or minus two standard deviations from the mean compared to individual results for subjects with visual impairments (triangles).



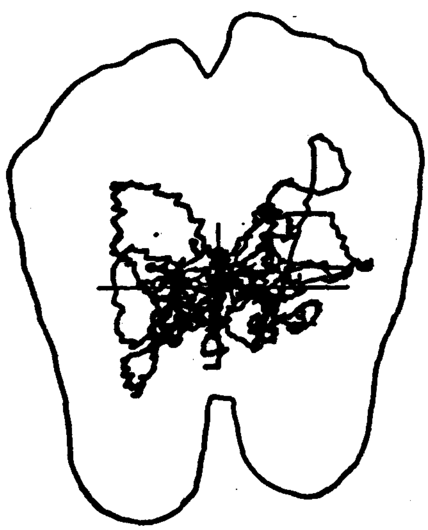
<u>Figure 10.</u> Mean ratio of SL used during quiet stance (a-p) for control subjects (circles) plus or minus two standard deviations from the mean compared to individual results for subjects with visual impairments (triangles).



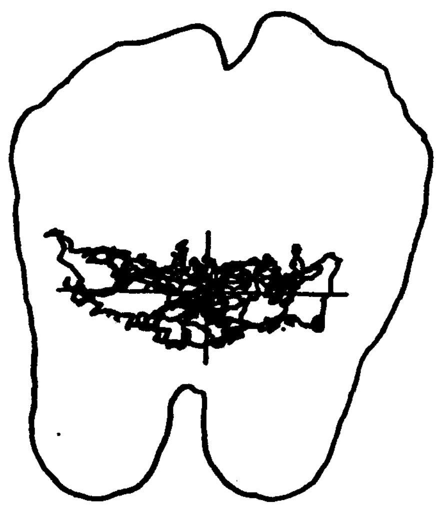
7 year old Control subject - Leaning Task



7 year old Control Subject - Quiet Standing

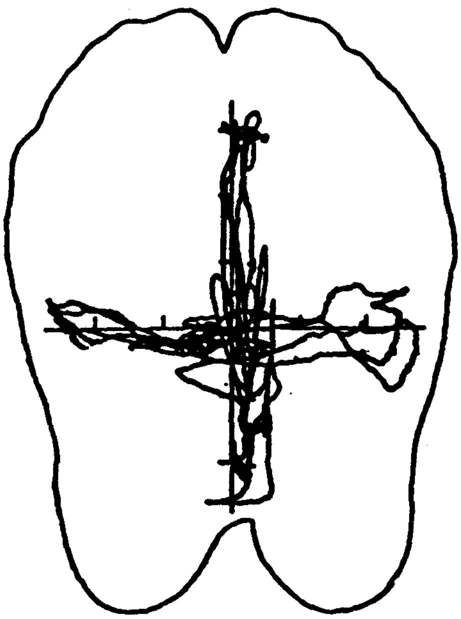


7 year old subject with VI - Leaning Task

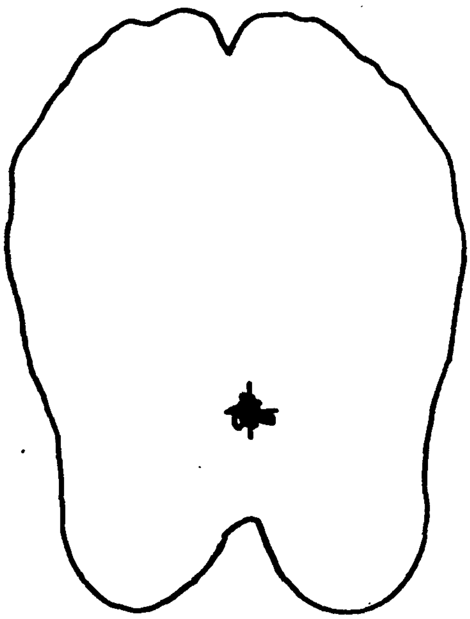


7 year old subject with VI - Quiet Standing

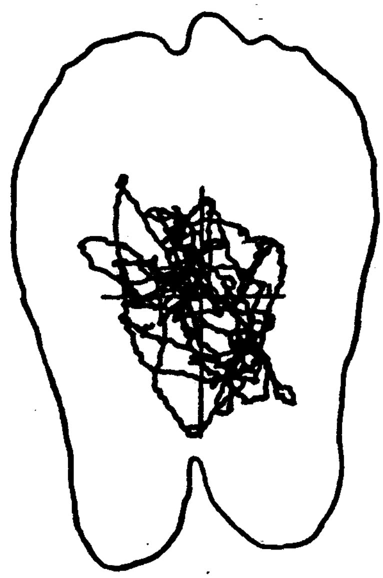
Figure 11. Diagram to illustrate the proportional areas of CP excursions (during quiet stance, eyes open), stability limits (during leaning task, eyes open), compared to an outline of the subjects feet for 7 year old and 12 year old subjects with and without visual impairments.



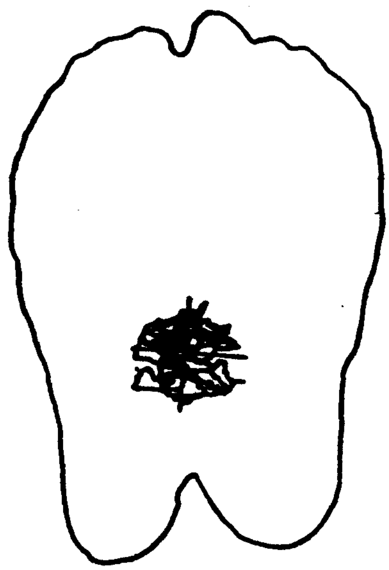
12 year old Control subject - Leaning Task



12 year old Control Subject
- Quiet Standing



12 year old subject with VI - Leaning Task



12 year old subject with VI
- Quiet Standing

subjects with and without visual impairments. It demonstrates that the differences between the groups were greater with older subjects than with younger subjects. Control subjects pictured at 7 and at 12 years were more stable in quiet standing tasks than subjects with visual impairments, and they had larger stability limits than subjects with visual impairments at the same age.

Chapter 5

DISCUSSION

The development of postural control in children with and without visual impairments was investigated in this study. Because a small number of subjects with visual impairments within each age group were available for this study, a qualitative comparison between the groups was made.

Control Subjects

Quiet standing tasks

In quiet standing conditions, control subjects found the EC condition and the foam stance to be more challenging than the EO and normal stance conditions. Additionally, subjects found that they were less stable in conditions in which they faced two postural challenges (foam and EC) than when only one challenge was present. These findings are consistent with the current understanding of postural control (Diener et al., 1986; Lee & Lishman, 1975).

Changes due to development were found with the outcome parameter of velocity. Velocity of the movement of centre of pressure decreased with age. Subjects who were 4 and 5 years old had a higher velocity than subjects in the older age groups, while subjects who were in the oldest age group had a lower velocity than younger subjects. A similar change in the velocity of CP movements has been noted in previous work (Starkes et al. 1992). It has been attributed to a change in the strategy used to control posture. A high velocity of CP movements has been thought to indicate a ballistic control strategy. A lower velocity of CP movements may reflect a more sensory guided approach to the control of posture.

Transition periods in which a subject's ability to control their posture changes have been described in the past. These are periods in which children appear to become temporarily less stable. They are thought to be using the time to reorganize or integrate the information that they receive from their sensory inputs in order to use it more effectively (Woollacott, Debu, & Shumway-Cook, 1987). In this investigation, an interaction was found between age and stance for the control subjects. The transition period described by Woollacott, Debu and Shumway-Cook (1987) occurs between the ages of 4 and 6 years. In this investigation, a similar transition occurred using the outcome parameter of velocity of CP movements.

Leaning Tasks

Quiet standing tasks are used to measure postural stability under normal conditions. In these conditions, subjects use a very small proportion of the area available to them (the area beneath their feet). The CP is, by definition, located beneath the feet. It is moved to keep the CG within a stable position. In the leaning tasks, subjects are asked to move their CG as far forward, backward, left or right as possible without falling. The CP is moved forward, backward, left or right in order to ensure that the subject does not loose balance. Developmental changes have been noted with SL (Starkes et al., 1992). Children under 7 years were noted to have smaller stability limits than older children.

In this investigation, no developmental changes were noted in SL (when variability due to height was removed), and no effects for visual or stance conditions with the SL in the lateral plane. In the a-p plane, subjects had a lower SL for conditions with foam or with EC. The foot, anatomically is larger in the a-p plane than in the lat plane. The subjects therefore had more opportunity for variability in this plane than in the lateral plane. Differences in variability between groups would be more easily seen simply because the scale of possible differences was larger.

Comparison of the excursions of the CP to SL during quiet stance

This measure compares the amount of area beneath their feet that a subject can possibly use to maintain stability (SL (cm)) to the amount that they normally make use of during quiet standing (CP). If subjects use most of the area that they have available to maintain stability in a quiet condition, they do not have much more to use if they are faced with a challenge to their stability. They may be less stable under challenging conditions compared to subjects who use a small proportion of their SL during quiet standing. Two explanations for a high ratio are that the subject has a small SL or that there are large excursions of CP in quiet stance. This may be the most important functional reason for younger children to experience less stability than older children.

The amount of area beneath their feet that subjects can comfortably use to be stable within (SL) was not shown to change with an increase in age when SL was normalized to foot size. Developmental changes were noted in the lat plane when CP was compared to SL. In this plane, 4 and 5 year old subjects used a larger proportion of the area available to maintain stability in quiet tasks than did older subjects. Also, 6 and 7 year old subjects used a larger amount of the total area available to maintain stability in quiet tasks compared to older and younger subjects. In conditions that subjects found more challenging (Foam and EC conditions as well as the foam EC condition), they used a larger proportion of the available space to maintain postural control. The anatomical base of support is smaller in the lat plane than in the a-p plane. A smaller surface is available to move within.

Subjects with Visual Impairments

Subjects with visual impairments demonstrated similar or worse postural stability compared to the control subjects. When subjects with VI fell outside of two standard deviations of the mean of the control subjects, they demonstrated greater postural instability.

Quiet Standing Tasks

Higher SD of the movement of the CP in a-p and lat planes and in the average velocity of CP movements were noted in subjects with VI in the quiet standing tasks. Differences between the two visual ability groups were more apparent as age increased. Within the population of subjects without VI, a decrease in overall variability in CP is seen with an increase in age (Forssberg & Nashner, 1982). The differences between the two groups may be more noticeable as age increases because of this decrease in variability in the results of the control subjects. A similar decrease in variability may not be seen in subjects with visual impairments. These subjects do not appear to improve their ability to maintain postural stability at the same rate as subjects without visual impairments.

Control subjects are expected to have postural control abilities similar to those of an adult by 7 - 10 years of age (Shumway-Cook & Woollacott, 1985). Some lags in motor development have been noted in subjects with VI (Adelson & Fraiberg, 1974). The differences between the two groups may decrease as subjects with VI become adults (i.e. beyond 12 years).

Subjects without visual impairments are noted to become less stable during periods when they are learning to use different sensory feedback systems together to control posture (Woollacott, Debu, & Mowatt, 1987). This period of transition, or of sensory integration, may be occurring later in subjects with VI. Additionally, some children with VI have some residual vision available. If this vision provides them with distorted or inaccurate information, they may find it particularly destabilizing during this time. This would exaggerate any differences between the groups.

Pyykko, Vesikivi, Ishizaki, Magnusson, and Juhola (1991) evaluated the postural control of adults (16 to 28 years old) who were blind or had Ushers Syndrome (a syndrome associated with the loss of vestibular function, retinal degeneration and sensorineural deafness) compared to control subjects. They noted that blind subjects were more stable than subjects without visual impairments. The differences were only noted when postural challenges were present (standing on foam, or having calf muscles vibrated). This investigation of the postural stability of adults with VI would support the hypothesis that by the time subjects with VI reached

16 years, they had improved their ability to control their posture to that of an adult.

In the experimental tasks, having a visual impairment did not have the same effect as a control subject closing their eyes. With the outcome measures used to evaluate the quiet standing tasks, the results for the two visual ability groups were different for both EC and EO conditions. Differences between the visual ability groups were however, more apparent when subjects had their eyes open as compared with when they had their eyes closed. Subjectively, children with VI, even those described as totally blind, reported feeling less stable in conditions when they had their eyes closed, particularly when they were challenged by the foam, or leaning tasks.

Based on the research of Paulus et al. (1984) it was expected that a visual impairment would affect stability in the a-p plane to a greater extent than in the lat plane. This was not observed in quiet standing tasks. Paulus et al. (1984) used a series of fixation targets, and decreased visual acuity across the subjects entire visual field. One reason for the difference between the two results could be that no fixation target was used with the subjects of this investigation. Visual acuity varied between subjects in this investigation. Some subjects with VI may have developed the ability to utilize information from their peripheral visual fields to a greater extent than their central visual fields.

Leaning Tasks

Stability limits were smaller in both the a-p and lat planes for the subjects with VI as compared to control subjects. Results often fell within 2 SD above and below the mean value for control subjects (p = .046). This would mean that when compared to children without VI, children with VI have less area available to make use of in maintaining postural stability. This could be a functional effect or reflect a more cautious approach to postural control. No significant differences were noted between results in the a-p and lat planes.

The 5 year old subject with VI was unable to complete the leaning tasks. This subject may have used most of the available base of support in maintaining stability during quiet tasks, and therefore not had sufficient additional base available when asked to lean. This would support the hypothesis that differences between the two groups are due to a slower course of development of the skills needed to maintain postural stability in subjects with VI.

Comparison of the excursions of the CP to SL during quiet stance

Subjects with VI used more of their available base of support during quiet tasks compared with control subjects. The differences between the groups was more apparent as age increased. Figure 11 illustrates the differences between age and visual ability groups. The differences could reflect a decrease in the variability of results for control subjects as age increased, while the variability of results for subjects with VI either stayed the same or became more variable. It could indicate a slower course of development of postural control mechanisms in children with VI. It could also indicate a different period of transition for the group, where an increase in instability would be expected temporarily while the subject learned how to more effectively use sensory feedback systems together to maintain stability.

Children with VI between the ages of 5 and 12 years do not learn to compensate for the lack of vision. They do not, as often suggested, heighten their remaining senses to counter the lack of vision. This compensation may happen in adults beyond 16 years (Pyykko et al, 1991), but in children, postural control does not improve at the same rate in children with VI as in children without VI. One possible reason is that children without VI between 4 and 6 years do not rely on vision to as great an extent as older children (Riach & Hayes, 1987, Odenrick & Sandstedt, 1984).

Chapter 6

SUMMARY AND CONCLUSIONS

For control subjects, vel of CP movements decreased with an increase in age, as did the proportion of the excursions of the CPx compared to SLlat. These findings indicate an increase in stability with age. A change in velocity may indicate a change in postural control strategy from a ballistic to a sensory guided approach.

In quiet standing tasks, subjects with VI generally demonstrated a higher magnitude of CP movements than control subjects in the same conditions. Differences between the two groups generally increased with an increase in age. Subjects with VI were relatively more affected by postural challenges than control subjects when both groups had EO. The two groups were most similar in the foam stance EC quiet standing condition. No relative difference between results for the a-p and lat planes were noted for subjects with VI.

In the control subjects, stance and vision main effects were noted for SL in the a-p plane but not in the lat plane. Differences in the lat plane may have been masked by the comparative small size of the foot in the lat plane compared to the a-p plane. Subjects with VI generally had smaller SL than control subjects, however, results were commonly within

2 standard deviations above or below the mean for control subjects.

Differences between the subjects with VI and the control subjects increase with an increase in age. This could indicate that although the subjects with VI experience a similar pattern of development in postural control skills as control subjects, the pattern is occurring more slowly. Pyykko et al. (1991) reported that adults with visual impairments are more stable than adults without visual impairments in conditions that present postural challenges.

In children without visual impairments between the ages of 4 and 6 years, vision is not as useful in maintaining postural stability as in older children. Differences between groups may have been more apparent in the older groups since vision is more important to children with vision as they become older (to 12 years).

REFERENCES

Adelson, E., & Fraiberg, S. (1974). Gross motor development in infants blind from birth. Child Development, 45, 114-126.

Allen, H. (1957). Testing the visual acuity in preschool children. Pediatrics, 19, 1093-1100.

Amblard, B., Assainte, C., Cremieux, J., & Marchand, A. R. (1990). From posture to gait: which sensory input for which function. In T. Brandt, W. Paulus, W. Bles, M. Dietrich, S. Krafczyk, & A. Straube (Eds.), Disorders of posture and gait (pp. 168-176). New York: Georg Thime Verlag Stuttgart.

Barrows, H. S. (1980). Guide to neurological assessment. Toronto: J. B. Lippincott Company.

Black, F. O., Shupert, C. L., Peterka, R. J., & Nashner, L. M. (1989). Effects of unilateral loss of vestibular function on the vestibulo-ocular reflex and postural control. Annals of Otology, Rhinology, & Laryngology, 98, 884-889.

Bles, W. (1990). Examination of vestibular function in postural control. In T. Brandt, W. Paulus, W. Bles, M. Dietrich, S. Krafczyk, & A. Straube (Eds.), Disorders of posture and gait (pp. 164-167). New York: Georg Thime Verlag Stuttgart.

Brandt, T. (1988). Sensory function and posture. In B. Amblard, A. Berthoz, & R. Clarac (Eds.), Posture and gait: Development, adaptation and modulation (pp. 127-136). Amsterdam, North Holland: Elsevier Science Publishers B.V.(Biomedical Division).

Colton, T. (1974). Statistics in medicine. Boston: Little, Brown, & Company.

Cummings, M. F., van Hof-van Duin, J., Mayer, D. L., Hansen, R. M., & Fulton, A. B. (1988). Visual fields of young children. Behavioural Brain Research, 29, 7-16.

Diener, H. C., Dichgans, J., Guschlbauer, B., & Bacher, M. (1986). Role of visual and static vestibular influences on dynamic posture control. Human Neurobiology, 5, 105-113.

Edwards, A. S. (1946). Body sway and vision. Journal of Experimental Psychology, 35, 526-535.

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

Goldie, P. A., Bach, P. M., & Evans, O. M. (1989). Force platform measures for evaluating postural control: Reliability and validity. Archives of Physical Medicine and Rehabilitation, 70, 510-517.

Haas, G., & Diener, H. C. (1988). Development of stance control in children. In B. Amblard, A. Berthos, & F. Clarac (Eds.). Posture and gait: Development, adaptation and modulation (pp. 49-65). Amsterdam, North Holland: Elsevier Science Publishers B. V. (Biomedical Division).

Harrison, A. (1975). Methods of assessing visual acuity in young children. American Orthoptics Journal, 25, 109-114.

Hayes, K. C. (1982). Biomechanics of Postural Control. In: Exercise and Sport Sciences Reviews (pp. 363-391). Philadelphia: Franklin Institute Press.

Jensen, R. K. (1986). Body segment mass, radius and radius of gyration proportions of children. Journal of Biomechanics, 19, 359-368.

Johansson, R., Magnusson, M., & Akesson, M. (1988). Identification of human postural dynamics. IEEE Transactions on Biomedical Engineering, 35(10), 858-869.

Kollegger, H., Wober, C., Baumgartener, C., & Deecke, L. (1989). Stabilizing and destabilizing effects of vision and foot position on body sway of healthy young subjects: A posturographic study. European Neurology, 29, 241-245.

Koozekanani, S. H., Stockwell, C. W., McGhee, R. B., & Firoozmand, F. (1980). On the role of dynamic models in quantitative posturography. IEEE Transactions on Biomedical Engineering, BME-27, 10, 605-609.

LeClair, K. L., & Riach, C. L. (1992). Postural stability measurement: Test duration and outcome parameters. In M. Woollacott & F. Horak (Eds.), Posture and gait: Control mechanisms, Volume 1, XIth International Symposium of the Society for Posture and Gait Research (pp 400-403). Portland Oregon: University of Oregon Books.

Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. Perception and Psychophysics, 15(3), 529-532.

Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. Journal of Human Movement Studies, 1, 87-95.

Lucy, S. D. & Hayes, K. C. (1985). Postural sway profiles: Normal subjects and subjects with cerebellar ataxia. Physiotherapy Canada, 37(3), 140-148.

Magnusson, M., Enbom, H., Johansson, R., & Pyykko, I. (1990). The importance of somatosensory information from the feet in postural control in man. In T. Brandt, W. Paulus, W. Bles, M.

Dietrich, S. Krafczyk, & A. Straube (Eds.), Disorders of posture and gait (pp. 190-193). New York: Georg Thime Verlag Stuttgart.

Magnusson, M., & Johansson, R. (1988). Characteristic parameters of anterio-posterior body sway in normal subjects. In B. Amblard, A. Berthos, & F. Clarac (Eds.). Posture and gait: Development, adaptation and modulation (pp. 177-186). Amsterdam, North Holland: Elsevier Science Publishers B. V. (Biomedical Division).

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

McClenaghan, B., & Williams, H. (1991). Sensory regulation of postural control in normal children. North American Society for the Psychology of Sport and Physical Activity. Monterey, California.

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

Nashner, L. M. (1985). Strategies for organization of human posture. In M. Igarashi, & F. O. Black (Eds.), Vestibular and Visual

Control on Posture and Locomotor Equilibrium. International Symposium for the International Society of Posturography, (pp. 1-8). Houston, Texas: Karger, Basel.

Nashner, L. M., Shupert, C. L., Horak, F. B., & Black, F. O. (1989). Organization of posture controls: An analysis of sensory and mechanical constraints. Progress in Brain Research, 80, 411-418.

Njiokiktjien, C., & van Parys, J. (1976). Romberg's sign expressed in a quotient II - pathology. Agressologie, 17D, 19-24.

Odenrick, P., & Sandstedt, P. (1984). Development of postural sway in the normal child. Human Neurobiology, 3, 241-244.

Ohashi, N., Asai, M., Nakagawa, H., & Mizukoshi, K. (1990). Visual feedback on the stabilization of body sway in normal subjects. In T. Brandt, W. Paulus, W. Bles, M. Dietrich, S. Krafczyk, & A. Straube (Eds.), Disorders of posture and gait (pp. 265-267). New York: Georg Thime Verlag Stuttgart.

Ornitz, E. M. (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.

Paulus, W. M., Hawken, M., Quintern, J., Straube, A., Krafczyk, S., Botzel, K., & Brandt, Th. (1988). Multisensory versus monosensory stabilization of posture. Agressologie, 29, 699-703.

Paulus, W. M., Straube, A., & Brandt, Th. (1984). Visual stabilization of posture: Physiological stimulus characteristics and clinical aspects. Brain, 107, 1143-1163.

Paulus, W., Straube, A., Quintern, J., & Brandt, T. (1989). Visual postural performance in Ameotropia and with optical distortion produced by bifocals and multifocals. Acta Otolaryngology (Stockholm) Supplemental., 468, 243-246.

Pyykko, I., Vesikivi, M., Ishizaki, H., Magnusson, M., & Juholta, M. (1991). Postural control in blinds and in Usher's syndrome. Acta Otolaryngol (Stockholm) Supplemental, 481, 603-606.

Reed, E. S. (1989). Changing theories of postural development. In M. H. Woollacott, & A. Shumway-Cook (Eds.), Development of posture and gait across the life span (pp. 3-24). Columbia, South Carolina: University of South Carolina Press.

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

Sonksen, P. M., Levitt, S., & Kitsinger, M. (1984). Identification of constraints acting on motor development in young visually disabled children and principles of remediation. Child: Care, Health and Development, 10, 273-386.

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

Starkes, J., Riach, C. & Clarke, B. (1992). The effect of eye closure on sway: Converging evidence from children and a parkinson patient. In L. Proteau and D. Elliott (Eds.), Vision and motor control (pp 353-373). Amsterdam, North Holland: Elsevier Science Publishers B.V..

Stockwell, C. W. (1985). Conceptual models of human postural control. In M. Igarashi, & F. O. Black (Eds.), Vestibular and Visual Control on Posture and Locomotor Equilibrium. International Symposium of the International Society of Posturography (pp. 22-28). Houston, Texas: Karger, Basel.

Swearingen, J. J., Badgley, J. M., Braden, G. E., & Wallace, T. F. (1969). Determination of centers of gravity of infants (Report No. AM 69-22). Federal Aviation Administration; Department of

Transportation, Office of Aviation Medicine.

Taguchi, K., & Tada, C. (1988). Changes of body sway with growth of children. In B. Amblard, A. Berthos, & F. Clarac (Eds.). Posture and gait: Development, adaptation and modulation Amsterdam, North Holland: Elsevier Science Publishers B. V. (Biomedical Division).

Toole, T., McColskey, D., & Rider, R. A. (1984). Retention of movement cues by visually impaired persons. Journal of Visual Impairment and Blindness, December, 487-490.

Woollacott, M. H. (1988). Posture and gait from newborn to elderly. In B. Amblard, A. Berthos, & F. Clarac (Eds.). Posture and gait: Development, adaptation and modulation (p. 3-12). Amsterdam, North Holland: Elsevier Science Publishers B. V. (Biomedical Division).

Woollacott, M., 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., Debu, B., & Shumway-Cook, A. (1987). Children's development of posture and balance control: Changes in motor coordination and sensory integration. In D.Gould & M. Wein (Eds.),. Advances in pediatric sport sciences: Volume 2

Behavioral issues (pp. 211-233). Champaign, Illinois: Human Kinetic Publishers

Woollacott, M. H., Shumway-Cook, A., & Williams, H. G. (1989). The development of posture and balance control in children. In M. H. Woollacott, & A. Shumway-Cook (Eds.), Development of posture and gait across the lifespan (pp. 77 - 96). Colombia, South Carolina: University of South Carolina Press.

Worchel, P., & Dallenbach, K. M. (1948). The vestibular sensitivity of deaf-blind subjects. American Journal of Psychology, 61, 94-99.

Zernicke, R. F., Gregor, R. J., & Cratty, B. J. (1982). Balance and visual proprioception in children. Journal of Human Movement Studies, 8, 1-13.