Université d'Ottawa · University of Ottawa

Feedforward postural adjustments associated with a goal-directed reach produced by infants in the sitting and standing positions

By

Lynn M. Casimiro

Thesis submitted as partial fulfillment of the degree requirements for a Master of Arts

School of Human Kinetics
Faculty of Health Sciences
University of Ottawa
Fall 2000

0-612-58446-1

This thesis would not have been possible without the guidance and encouragement of Dr. Heidi Sveistrup and without the support of my family.

I am indebted to all of you

Table of Contents

List of Figures

List of Tables

Abstract

Two mechanisms of postural control, feedback and feedforward, are implicated for the maintenance of independent sitting and standing postures. More specifically, feedback mechanisms encompass all postural reactions produced to maintain equilibrium in response to an unexpected perturbation. Perturbations induced by a voluntary movement are controlled by feedforward mechanisms. The purpose of this study is to characterize feedforward postural adjustments produced by infants in the sitting and standing positions. Twenty-two infants between the ages of 5 to 18 months were tested using a goal-directed reach paradigm. Infants were separated in two behavioral groups, sitters and creepers. Surface electromyography, center of pressure displacement and video data were collected. Sitters and creepers showed no consistent patterns of postural muscle activation or differences in postural muscle onset latencies. Compared to sitters, creepers showed a greater proportion of trials with more than one postural muscle activated ($p < .05$) and reached more slowly ($p < .05$) in the sitting position. A descriptive analysis of the data revealed a large number of trials with tonic postural muscle activity in both the sitters and creepers group. In the creepers group, however, more phasic postural muscle activity was noted. It is possible that infants initially use tonic postural muscle activity to "stiffen" the body and maintain their balance. As they mature and gain experience in the sitting and standing positions, infants develop more phasic postural muscle activity. The reduction in reaching speed in the creepers group may be an early movement strategy used to minimize the self-induced perturbation caused by goal-directed reaching.

CHAPTER I

Purpose of Study

The purpose of this study was to characterize feedforward postural adjustments produced by infants aged 5 to 18 months. The infants were divided post-hoc based on their score in sitting and standing on the Alberta Infant Motor Scale (AIMS) (Piper and Darrah 1994). This resulted in post-hoc grouping of the infants into two groups: Sitters and Creepers. Characterization of feedforward postural adjustments in infants of these behavioral levels provided the opportunity to identify strategies used as infants attempted to maintain their equilibrium during a goal-directed reach in the sitting and standing positions.

Definitions of Postural Control

How do we avoid falling when our equilibrium is challenged? What are the processes that enable us to keep our balance when we lift a heavy box or when we slip on a patch of ice? An in depth examination of the mechanisms of postural control provides answers to these questions.

Postural control incorporates the concepts of equilibrium and orientation (Horak and Macpherson 1996; Macpherson et al. 1997). Postural equilibrium is the ability to reestablish or maintain the center of mass (CM) over the base of support (Kingma et al.1995), whereas the concept of orientation refers to the position of each body segment with respect to each other and with respect to the environment. For clarification purposes, the center of mass can be defined as the concentration of the entire body's mass in one point (Kingma et al. 1995). Equilibrium and orientation of body segments are therefore central concepts of postural control and must be functional in both static positions and during movement (Hageman et al.1995; Pai and Patton 1997). The act of maintaining equilibrium and orientation is termed "postural adjustment" (PA) (Horak and Macpherson 1996; Macpherson et al. 1997).

PAs are often taken for granted, yet they require complex processes which coordinate the sensory and motor systems (Shumway-Cook and Woollacott 1995; Sveistrup and Woollacott 1996) with the various levels of the central nervous system (CNS) (Hageman et al., 1995). Two categories of PAs are reported (Frank and Earl 1990). The first category encompasses the adjustments controlled by a feedback system called *feedback postural adjustments*. In most instances, they refer to the group of reactions following a sudden unexpected perturbation (Nashner 1976). This is the case when one slips on a patch of ice but manages to avoid falling. The second category uses anticipatory adjustments called *feedforward postural adjustments*. These are functional changes, occurring in a defined time interval, in preparation to the onset of a voluntary movement and accompanying the voluntary movement (Belen'kii et al.1967; Hugon et al. 1982). Therefore, the goal of feedforward postural adjustments is to minimize CM displacement thus allowing the safe completion of a voluntary task. Lifting a load is an example of a voluntary movement eliciting feedforward postural responses.

In both instances, feedforward and feedback, the PAs are triggered by a perturbation. In the case of feedback postural control, the perturbation is often not expected therefore PAs occur several milliseconds after the perturbation. In the case of feedforward postural control, the perturbation is expected. Therefore PAs can start several milliseconds before the voluntary movement and up to a few milliseconds after movement onset. The specific timing of feedback PAs versus feedforward PAs will be discussed in greater depth later in this chapter.

Postural adjustments are recorded and studied using various technical means including electromyography (EMG), force platform and videography. EMG records muscle activity via electrodes positioned on key muscles. This method can be used to identify patterns of postural muscle activity and determine the time interval in milliseconds between the activation of postural muscles and the onset of the perturbation. Consequently, EMG data help to distinguish between feedback and feedforward postural responses.

It has been suggested (Forssberg and Nashner 1982; O'Sullivan 1988; Shumway-Cook and Woollacott 1995), that the patterns of postural muscle activity for feedback and feedforward PAs be termed "synergy". Synergies are defined as a functional arrangement of muscle groups, which causes these muscles to act together. Therefore, instead of activating each muscle independently, the CNS can call upon muscle synergies to simplify the command (Massion, 1994; Massion et al.1992; Shumway-Cook and Woollacott 1995). According to these authors, synergies are not fixed but can be modified by the CNS relative to the afferent information received and the environmental demands imposed.

Force platforms are used to determine center of pressure (COP) displacement. The COP is the location of force reactions in the horizontal planes and approximates CM excursion (Shumway-Cook and Woollacott 1995). The COP can be used as an indication of the spontaneous body displacements (Maki et al.1990). Videography is used for the kinematic analysis of PAs. It allows the study of body segment positions and displacements.

Feedforward Postural Adjustments

The ability to maintain posture is a prerequisite to all coordinated movements (Larish and Stelmach 1982; Lee 1980). Feedforward PAs have been defined in the literature as a compensatory postural muscle activation complex occurring –100ms or less before voluntary movement and extending between 80 to 100ms during voluntary movement (Frank and Earl 1990), as depicted by the left side of Figure I. The purpose of this system is to minimize CM displacements caused by voluntary movements. These PAs do not directly assist the execution of the movement but compensate for the inherent perturbations (Belen'kii et al. 1967; Bouisset and Zattara 1981; Gahéry and Massion 1981).

A number of authors have studied the characteristics of feedforward PAs in the sitting position for infants (van der Fits et al. 1999a,b; Von Hofsten and Woollacott 1989) and adult populations (van der Fits et al.1998). Feedforward PAs have been studied in the standing position in children (McGregor 2000; Riach and Hayes 1990) and adults (Aruin and Latash 1995; Belen'kii et al. 1967; Bouisset and Zattara 1981; Friedli et al.1984; Lee et al.1987). No research was found in the standing position for infants or in the sitting position for children.

In feedforward studies, the infant, child or adult participant is most often required to perform a predetermined voluntary task. For example, a fast pointing movement is frequently chosen. The purpose of this experimental design is to induce an expected perturbation. In this case, lifting the arm to point pulls the subject forward and the PAs act in the opposite direction to try and keep the CM over the base of support. If the feedforward PAs are inappropriate, the subject may fall. Therefore, feedforward PAs are specific to the direction and magnitude of the perturbation.

In order to elicit feedforward PAs in an experimental situation using a designated, voluntary movement, such as described above, the participants must be able to understand and execute the instructions provided by the researcher. The lack of understanding and ability to cooperate in the infant population is one of the reasons very little research has been focused on this age group.

Key Studies of Feedforward Postural Control in Standing Subjects

Belen'kii, Gurfinkel and Pal'tsev (1961) were among the first to test feedforward PAs in a group of normal subjects using a reaching paradigm in the standing position. They reported an anticipatory activation of the lower limb and trunk muscles prior to anterior deltoid muscle onset. Specifically the ipsilateral biceps femoris muscle was activated first followed by the almost simultaneous activation of the sacrolumbar muscle and contralateral biceps femoris muscle. They suggested that the consistency between subjects of the recorded onset latencies were indicative of a stable yet task specific postural muscle activation complex. Using the same research model, Bouisset and Zattara (1981) studied feedforward PAs in standing adults, using a right arm reaching paradigm. They recorded EMG for more of the lower extremity muscle groups than Belen'kii et al. (1961) and identified the following consistent postural muscle synergies. Before the activation of the focal muscles responsible of movement onset (anterior deltoid muscle and pectoralis major muscle), the soleus muscle was inhibited, and the right semitendinosus and right gluteus maximus muscle were activated. The focal muscles were then activated (anterior deltoid and pectoralis major) followed by activation of the left tensor of the fascia lata muscle, the left rectus femoris muscle and the left semitendinosus muscle.

Generally, research in the adult population has shown consistent patterns of postural muscle activity with some variability existing between studies. Most likely, the patterns of postural muscle activity are paradigm specific (Lee et al. 1987).

Riach and Hayes (1990) studied feedforward PAs in standing in a group of 4 to 14 year old children. As in the Bouisset and Zattara (1981) study, the subjects were asked to rapidly point on cue with their right arm towards a target. They recorded center of pressure displacements and noted that most subjects were able to produce feedforward center of pressure displacements. Even the four-year-olds were capable of producing feedforward PAs, however, their center of pressure displacements were inconsistent with regards to direction and timing of the shift. The authors suggested "young children had not yet mastered the ability to reliably anticipate and coordinate balance control with the movement task".

A current study (McGregor 2000) on feedforward PAs in standing looked at children aged between 4 and 5 years and between 10 and 11 years. The same protocol as Riach and Hayes (1990) was used and modified to record EMG data. The results showed that the younger children tended to activate their lumbar extensors more quickly than the older children, however, no differences were reported in the probability of activating postural muscles. The developmental period when feedforward PAs appear in the standing position has therefore not yet been identified.

Key Studies of Feedforward Postural Control in Sitting Subjects

Van der Fits, Klip, van Eykern and Hadders-Algra (1998) studied feedforward PAs in young adults. The investigators placed their participants in standing and in various sitting positions. Feedforward PAs were elicited by instructing the subjects to point on cue at a target. They found that the lumbar extensor muscles were occasionally activated in a feedforward fashion and that the neck extensor muscles and neck flexor muscles were co-activated in all the tested positions but predominantly in the standing position. They proposed that the ensemble of their data supported the idea that feedforward muscle activity was negatively related to the stability of the base of support, for example standing versus sitting.

In a 1989 abstract by Von Hofsten and Woollacott, findings of five infants aged 9 to 10 months in the sitting position were reported. The infants sat on a parent's lap and were presented a toy of interest. The authors recorded feedforward postural activity in the trunk extensor muscles in the majority of the trials. Yet the recorded postural muscle onset latencies of these PAs were not reported. They proposed that the feedforward postural system was functional, but not yet mature.

Van der Fits, Otten, Klip, Van Eykern and Hadders-Algra (1999) conducted a longitudinal study of the development of feedforward PAs during reaching with ten infants between the ages of 6 and 18 months. The infants were placed in a sitting position and were presented an attractive toy to elicit a reach. For the study, a chair was used for support for infants who could not sit independently (less than 8 months). It is important to note that postural muscle activity was only considered feedforward in nature if it occurred prior to deltoid muscle activation. The postural muscle activity that accompanied the voluntary movement was not considered. They reported very little feedforward postural muscle activity prior to 15 months, with activity in one of the postural muscles in only 20% of the trials at six months of age. No statistically significant differences were found in the postural muscle onset latencies between 6 and 18 months of age, but the authors reported that generally the contralateral lumbar extensor muscle tended to be activated earlier than the ipsilateral lumbar extensor muscle in the older infants.

In a second study by Van der Fits. Klip, van Eykern and Hadders-Algra (1999), spontaneous reaching and goal-directed movements in infants between 3 and 6 months of age were examined in the sitting position. They found no significant differences in postural muscle activation between spontaneous reaching and goal-directed reaching. Nonetheless, the authors reported that infants showed a preference for neck muscles during goal-directed reaches. They proposed that infants required increased head stabilization in space during goal-directed movements. They further reported postural muscle activity was present during goal-directed reaching but not before focal muscle activity. Since they defined feedforward postural muscle activity as occurring 200ms prior to anterior deltoid muscle activation, they did not consider postural muscle activity accompanying the focal movement as feedforward in nature.

Feedback Postural Adjustments

The ability to reestablish equilibrium following an unexpected perturbation is necessary to ensure safety and prevent falls. The understanding of the various postural muscle synergies activated by feedback PAs is one of the preoccupations of researchers studying postural adjustments (Shumway-Cook and Woollacott 1995). In order to differentiate between feedforward PAs and feedback PAs, it is generally accepted that feedback PAs occur approximately 60ms to 100ms after an unexpected perturbation in the standing position, as depicted by the right side of figure I. Many researchers have studied feedback PAs in the sitting and the standing positions in infants using varied research paradigms in infants (Hadders-Algra et al.1996a; Harbourne 1993; Hirschfeld and Forssberg 1994; Shumway-Cook and Woollacott 1985; Sveistrup and Woollacott 1996; Woollacott et al. 1987), in children (Forssberg and Nashner 1982; Foster et al. 1996) and in adults (Forssberg and Hirschfeld 1994; Horak et al.1989; Horak and Nashner 1986; Nashner 1976; Prochazka et al. 1997).

Feedback PAs in the sitting and standing positions have often been studied using a moveable force platform, able to produce an unexpected forward or backward translation at a predetermined speed. Other research models have been used but the following information has been obtained from studies using the moveable platform model. Subjects of all age groups can be placed in the position studied, for example standing, on a moveable force platform, which is then unexpectedly translated forward or backward. The subject's lower body follows the direction of the platform more quickly than the upper portion of the body thus causing the body to lean in the opposite direction of the translation. For example, if the platform translates backwards when a subject is in the standing position the legs of the subject move backward with the platform, resulting in a forward lean of the body. Feedback PAs are activated to maintain the CM over the base of support to prevent a fall.

Key Studies of Feedback Postural Control in Standing Subjects

Results of studies on feedback PAs in the standing position suggest the use of muscle synergies to regain postural stability (Haas et al. 1986; Horak et al. 1989; Nashner 1976; Sveistrup and Woollacott 1996). Horak, Diener and Nashner (1989) studied feedback PAs produced by adults using a backward translation of a moveable force platform. The results showed a distal to proximal activation of the agonist postural muscles (gastrocnemius muscle, hamstring muscles, paraspinal muscles). These muscles were activated to pull the body backwards, thus maintaining the CM over the base of support. When a large translation was used to perturb the subjects, the agonist postural muscle activation was also large and needed to be countered by the antagonist muscles (tibialis anterior muscle and quadriceps muscle) thus avoiding an overcorrection by the agonists.

Sveistrup and Woollacott (1996) conducted a longitudinal study of the development of feedback PAs with infants between the ages of 5 and 17 months. Following a forward or backward translation of the force platform, they found that the feedback postural muscle synergies were similar to the adult postural muscle synergies and were activated in a distal-to-proximal order. However, these postural synergies were only consistently present once infants achieved independent stance, ranging between 8 and 15 months of age. Before this behavioral level, the postural muscle activation pattern was not consistent but the authors proposed that the simple presence of grouped feedback postural activity suggested the emergence of postural muscle synergies before the infants were able to stand independently. Furthermore, before infants were able to stand independently, the EMG recordings showed a large quantity of tonic postural muscle activity before and often lasting as long as the duration of the perturbation. The authors further reported that the tonic postural muscle activity was not specific to the direction and amplitude of the perturbation. The authors therefore proposed that the tonic postural muscle activity was an attempt to control posture in the standing position under normal conditions by decreasing mobility at multiple joints. This argument was further supported by the decrease in tonic postural muscle activity and the increase in feedback phasic postural muscle activity as the infants acquired increased maturity and skill in the standing position.

Key Studies of Feedback Postural Control in Sitting Subjects

In the sitting position, the feedback PAs also follow distinct direction specific postural muscle synergies (Forssberg and Hirschfeld 1994; Hirschfeld and Forssberg 1994; Woollacott et al. 1987). Forssberg and Hirschfeld (1994) studied feedback PAs in the sitting position with adults using a forward translation of a force platform. As expected, they noted the activation of the agonist postural muscles (rectus femoris muscle, rectus abdominis muscle and cervical flexor muscles) to pull the body forward and keep the CM over the base of support. Similarly to the standing position, the activation of the agonist postural muscles was followed by the activation of the antagonist postural muscles (gluteus maximus muscle, lumbar extensor muscles, thoracic extensor muscles and cervical extensor muscles). The postural muscle activation sequence for each of the synergies seemed to follow a proximal-to-distal direction, the opposite of the standing data, which showed distal-to-proximal activation.

A second study by Hirschfeld and Forssberg (1994) identified feedback PAs in infants between 5 and 8 months of age in the sitting position. Using a forward translation of the support surface, they noted that the agonist postural muscles were activated first, corresponding to the findings of the adult study. Furthermore, agonist postural muscle activity was recorded in the group of infants not able to sit independently, although consistency of postural muscle activation was notably better (60% vs 25%) in the group of infants able to sit independently. However, antagonist postural muscle activity rarely occurred, and when it did the activity was recorded very late after the agonist postural muscle activity. The authors proposed that the ability to regulate the postural correction initiated by the agonist postural muscles was not yet functional. Moreover, the direction of postural muscle activation did not consistently follow a proximal-to-distal sequence of activation. In addition, tonic postural muscle activity was present and decreased as the infants learned how to sit independently around 7 to 8 months of age, similarly to the study by Sveistrup and Woollacott (1996).

Summary of the Two Types of Postural Adjustments

In order to preserve postural control we rely on postural adjustments (PAs). These PAs occur before, during and after a perturbation. The group of PAs which occur before and during a perturbation induced by a voluntary task, for example lifting a box, is called feedforward postural adjustments. The group of PAs, which occur after an unexpected perturbation, for example, slipping on ice, is called feedback postural adjustments. Feedback PAs are more consistently present once infants are able to sit independently, around 7 to 8 months of age, and when infants are able to stand independently around 8 to 15 months of age. The postural muscle activity patterns of these PAs are similar to the postural muscle activity patterns reported in adults. Feedforward PAs occurring prior to focal movement onset don't appear to be consistent before the age of 15 months in the sitting position. The studies on feedforward PAs have not identified a consistent feedforward postural muscle synergy and have not identified a consistent sequence of activation. Feedforward PAs accompanying the focal movement have not yet been considered in the sitting position or studied in the standing position with an infant population. Therefore, the behavioral level at which feedforward PAs emerge during sitting and standing remains unclear. Consequently, the relationship between feedforward PAs and independent sitting and standing in infants needs to be further investigated.

Review of Literature

Introduction

It is recognized that certain aspects of postural control are present in the early beginnings of human development in the form of primitive postural reflexes (Bly 1980). Even though research on PAs in children (Hirschfeld and Forssberg 1994; Riach and Hayes 1990) and infants (Sveistrup and Woollacott 1996) bring forth evidence for similarities between their postural muscle synergies and those produced by adults

(Bouisset and Zattara 1981; Forssberg and Hirschfeld 1994; Horak et al. 1989), concrete differences do exist. For example, infants produce more variable feedback PAs (Forssberg and Nashner 1982; Hadders-Algra et al. 1994, Hirschfeld and Forssberg 1994; Sveistrup and Woollacott 1996) and lower frequencies of feedforward PAs, with an inconsistent pattern of postural muscle activation (van der Fits et al. 1999a,b).

The Development of Postural Control

How does postural control develop? What is the link between primitive postural reflexes in the newborn, the emergence of functional feedback and feedforward PAs and their evolution into adult forms of PAs? Early studies examined PAs in general. In time, the research models were modified to obtain specific data with regards to feedback and feedforward PAs. Even though both types of PAs are equally important, very little research has focused on feedforward PAs. Therefore, much of the information available on the evolution of postural control has been provided by studies in the area of feedback PAs.

Research shows that infants already display certain aspects of postural control from birth. For example, head righting leads to the development of antigravity extension and weight shifting (Bly 1980). At first glance, the process to postural control acquisition appears rather reflex based. The stereotyped activities, however, quickly adapt to the environment (Harbourne 1993). Infants must therefore coordinate their actions with the desired motor function, an integration that requires the involvement of the superior centers (Forssberg and Wallberg 1980; Sears 1971; von Euler 1981).

Improvement in head control is one of the first steps of motor development (Bly 1980). It is essential to allow the discovery of new motor activities and is a key factor for the development of independent walking (Assaiante 1998). New activities undertaken by infants are the result of unique combinations of learned movements, each presenting its own rate of development (Goldfield 1989). The evolution of new skills depends on the infant's individual characteristics, the kinematic recalibration that occurs with growth (Saltzman and Munhall 1992), the environment (Thelen 1995) and the required motor task (Green et al. 1995).

According to these criteria, one can deduce that the PAs, which coordinate the trunk and the extremities, develop later than the PAs controlling the head. Since the infants' individual characteristics is one of the factors identified in the acquisition of postural control, the ability to produce PAs is dependent on maturity as well as on the strength and coordination of the required muscles. The rate of development for each one of these components is different (Woollacott and Sveistrup 1994).

During the acquisition of a new behavioral skill such as sitting, the infant must not only possess the required motor and neurological characteristics, but must also be able to react to a loss of equilibrium and recover postural control. Based on studies of feedback PAs, it is the activation of postural muscle synergies that is at the root of postural control in new behavioral positions. Even though many factors have a part in the development of new postural muscle synergies, a certain degree of precision is also necessary to properly time postural muscle synergy activation and achieve efficient and functionally appropriate PAs. To gain this precision, infants must rely on the coordination or the association of the sensory and motor processes. This sensory-motor mapping is a central concept of the development of posture control (Berthental et al. 1997; Woollacott and Sveistrup 1994).

Control Mechanisms of Postural Adjustments

Overview

Many studies contribute important information concerning the understanding of PAs (Belen'kii et al. 1967; Woollacott 1985; Keshner et al. 1988; Forssberg and Hirschfeld 1994). Although these studies, amongst many others, provide some insight into what happens at a neurological level, many gaps exist. What are the exact mechanisms of control? Are PAs spinal level reflexes, or movements controlled by the superior centers?

Human neurological models of postural control propose that the activation of antigravity postural muscles to maintain orientation are located at the spinal level and that the superior centers control equilibrium. The cerebral trunk and the cerebellum help to control posture, the vestibular nuclei integrates the different senses and the reticular formation influences postural tone (Horak and Macpherson 1996; Massion 1980,1994).

Human research in the standing position identified that a horizontal displacement of the support surface elicited a stretch response of the gastrocnemius muscle at approximately 90ms. This muscle onset latency is too long for a reflex arc but too short for a voluntary response (Nashner, 1976). Furthermore, the complexity of the postural muscle synergies suggests that PAs are centrally mediated (Forssberg and

Hirschfeld 1994; Goldfield and Michel 1986). It has been proposed that this mechanism of control resides at the level of the superior centers and has been named "central pattern generators" (CPGs) (Forssberg and Hirschfeld 1994).

Central Pattern Generators

Overview

It has been advocated that CPGs are programmed with spatio-temporal information from reliable sensory sources (Forssberg and Hirschfeld 1994). For example, in the sitting position, it appears that the speed and direction of pelvic rotation provide crucial somatosensory information to elicit a CPG triggered response (Forssberg and Hirschfeld 1994). In the standing position, ankle rotation has been suggested as the trigger (Shumway-Cook and Woollacott 1995).

Two levels of CPGs are proposed (Forssberg and Hirschfeld 1994). A first simple level is triggered by spatio-temporal information, as stated above, and takes care of assembling the motor reactions. This level chooses the most appropriate PA. A second level delineates the order in which the postural muscles are to be activated and the quantity of postural muscle activation needed. This level is dependent on the information received from the sensory system and is responsible for the quality of the PA. The CNS most likely takes advantage of a few CPGs that can be modulated as needed by the superior centers (Forssberg and Hirschfeld 1994; Gahéry and Massion 1981; Gurfinkel et al.1995; Ledebt et al. 1995; Shumway-Cook and Woollacott 1985). The main advantage of CPGs is the increase in PA speed of activation.

Feedback Postural Adjustments

In 1993, Harbourne studied PAs elicited in sitting in infants aged 2 to 5 months. The goal of the study was to observe the feedback strategies manifested by infants during two behavioral stages of the sitting position. The first stage corresponded to sitting with external support and the second stage corresponded to sitting with the infants supporting themselves with their arms. For this study, infants in both behavioral stages of sitting were provided with external support. Harbourne created a natural perturbation by releasing the external support. The feedback PAs produced were recorded with EMG and videography. The results of this study suggested that feedback PAs in sitting were linked to the emergence of preferential activation of the following synergies, the paraspinal-hamstring postural muscle synergy and the paraspinal-quadriceps postural muscle synergy. Clearly, these postural muscle synergies were more often activated than other combinations as the infant's ability in sitting improved. Harbourne proposed that the more successful postural synergies were gradually selected by a trial and error phenomenon. Harbourne further argued that the limited number of postural muscle combinations recorded compared to all the calculated possibilities indicated that a selection process occurred early in the infant's development. This process would generally determine or anticipate what could be a functionally appropriate PA, essentially, the proposed role of a first level CPG.

The infant study of Hirschfeld and Forssberg (1994) on feedback PA in the sitting position demonstrated the presence of PAs functioning before the acquisition of independent sitting or standing. They concluded that infants were able to modulate their

PAs in the sitting and standing positions before being able to maintain their equilibrium independently. Other researchers also arrived at the same conclusion (Berthental et al. 1997; Hadders-Algra et al. 1994,1996a). Hirschfeld and Forssberg (1994) further suggested that these early PAs were produced by CPGs.

If feedback PAs are already functional, why can't infants maintain independent sitting? A recap of the concepts discussed in the section on development of postural control, brings forth the idea that PAs require more than just the activation of a postural muscle synergy. PAs require a certain level of motor and neurological maturity, appropriate sensory-motor mapping and an adequate internal representation of the body.

Feedforward Postural Adjustments

The innovative study of Belen'kii et al. (1967) on feedforward PAs with adults in the standing position, recorded postural muscle activity in the lower extremities and the trunk before focal arm movement onset. They deduced that the response was preprogrammed. These findings are supported by the work of other researchers with adults (Benvenuti et al. 1997; Bouisset and Zattara 1981; Friedli et al. 1984; Larish and Stelmach 1982). A feedforward PA study by Benvenuti, Stanhope, Thomas, Panza and Hallett (1997), with adults in the standing position used a different methodology. They asked their participants to flex their elbow as quickly as possible using two behavioral conditions, a self-paced task and a reaction-time task. They reported that the behavioral conditions affected the order and duration of feedforward postural muscle activity. The authors proposed that this finding suggested remarkable versatility and adaptability of the feedforward PAs. Consequently, the authors argued that feedforward PAs were under the control of central mechanisms capable of detailed planning.

The Effects of Training on Postural Adjustments

Overview

When studying the development of feedforward and feedback PAs, it is always a dilemma to determine whether reported evolution changes are a result of experience or maturity. Massion et al. (1992) propose that mapping the body plays an important part in the development of PAs. The authors explain that experience most likely contributes to the evolution of the central processing of pertinent afferent information thus creating a better internal image of the body. Moreover, Forssberg and Hirschfeld (1994) state that this process includes the orientation of the vertical axis as well as the relationship between the CM and the base of support. A process based on the continual influx of sensory information and requiring progressive adaptation like many other learning processes.

Other authors propose that the selections of functionally appropriate postural strategies are based on the maturation of the CNS, the changes in biomechanical constraints and muscle strength (Harbourne 1993; Hirschfeld and Forssberg 1994; Horak and Nashner 1986; Kokubun et al.1997).

Training studies help to differentiate between developmental changes that are linked to experience and developmental changes that are linked to maturity. Specifically, if training affects certain aspects of PAs such as frequency of postural muscle activity, then it can be deduced that the reported changes in the stated variable are linked to experience. In contrast, aspects of PAs, which are not affected by training, are most likely linked to the maturation process.

Feedback Postural Adjustments

A number of authors have studied the effects of training on feedforward PAs (Hadders-Algra et al.1996b; Mouchnino et al.1992; Sveistrup and Wollacott 1997). The study by Hadders-Algra, Brogren and Forssberg (1996) looked at the effect of training on feedback PAs with infants in the sitting position. These infants were separated into two groups matched for age and gender. The experimental group was trained for a period of 3 to 3.5 months, whereby parents were instructed to present a toy within the limits of sitting stability, for a few minutes a day. They found that training increased the frequency with which the same postural muscle synergies were triggered. They concluded that training affected the first level of CPGs. Sveistrup and Wollacott (1997) also studied feedback PAs. Infants between the ages of 36 and 48 weeks were tested in the standing position with a moveable platform paradigm and trained over the course of three consecutive days. A total of 300 perturbations were administered in a block format on the same platform where the tests were performed. The results showed that training increased the probability of activating functionally appropriate muscles within a same trial. However, there was no difference in the agonist postural muscle onset latencies. They concluded that, for the tested variables, experience seemed to be coupled to maturation during the development of feedback PAs.

Feedforward Postural Adjustments

In 1992, Mouchino, Aurenty, Massion and Pedotti reported their findings from a study on feedforward PAs in unipedal stance. They compared adults from the general population with adult dancers. They discovered that subjects from the general public produced a greater variety of postural muscular synergies and were less efficient at adjusting the position of their CM than the dancers. They concluded that long-term training, such as dancing, seemed to contribute to the identification of the most efficient postural muscle synergies.

Sensory Influences on Postural Adjustments

Overview

It is well known that the somatosensory, vestibular and visual systems are important for the maintenance of independent stance (Forssberg and Hirschfeld 1994; Gurfinkel et al. 1995; Hadders-Algra et al. 1996a). These systems are already structurally present and mature in infants (Hirschfeld and Forssberg 1994). Although the required sensory tools for the production of PAs are present at birth, they are not necessarily functional. For example the ability to couple sensory information to the motor task is not ready at birth (Portfors-Yeomans and Riach, 1995). It has also been suggested that visual information helps to calibrate the other sensory systems linked to postural control (Woollacott et al.1987).

Feedback Postural Adjustments

Using a moveable room paradigm, Foster, Sveistrup and Woollacott (1996) studied feedback PAs in the standing position with infants and children between the ages of 5 months and 10 years. Subjects stood inside a fair sized box comprised of three sides and a roof. The construction of the box was such that it resembled a small room and was painted with continuous stripes of two contrasting colors on all sides. The room, which was set on casters, could be moved backward or forward. The subjects interpreted the visual information provided by the room's translation as if they were moving, thus causing the subjects to produce a direction specific feedback PA. For example if the room was moved forward, the subjects felt they were moving backward and activated the ventral postural muscles. Feedback PAs were recorded in subjects as young as five months and before the infants could stand without support. Infants just learning how to walk produced a higher rate of feedback PAs, which later decreased in older children. The authors concluded that the youngest participants experienced difficulty in identifying the less reliable sensory sources or had difficulty in modulating their feedback PAs.

Berthental, Rose and Bai (1997) used the same research model to study feedback PAs with infants in the sitting position. The authors reported that infants produced feedback PAs in response to the translation of the room before being able to sit without support. The authors therefore suggested that vision was important for the production of feedback PAs in infants.

Feedforward Postural Adjustments

The following studies focused on the effects of sensory information on gait. Even though the primary research objective of these experiments was not the study of feedforward PAs, the PAs that were reported occurred in anticipation of specific gait events.

Ledebt et al. (1995) studied young children during independent walking without support in the 10 to 15 weeks following the acquisition of the ability. The authors reported very little trunk and head oscillations in the early stages of independent walking. This oscillation increased with experience with independent walking. They suggested that the decreased trunk and head movements provided the early stabilization required during the evolution of independent walking. Assaiante and Amblard (1996) studied gait in children between the ages of 3 to 6 years. Various experimental conditions were provided, such as eyes open or closed, or walking on a narrow surface. They noted that children could selectively use the visual information during the production of feedforward segmental adjustments, such as a contralateral trunk lean prior to the initiation of the step, by the age of four years old.

Hageman, Leibowitz and Blanke (1995) studied gait in adults. They determined that vision played an important role in reducing angular oscillations of the head during gait. However, Riach and Hayes (1987) found that children between 2 and 14 years of age used very little visual information to control head oscillations. This finding fits with the suggestion of Assaiante and Amblard (1996) that head stabilization appears to be dependent on vestibular stimuli rather than vision in children. Alternatively, Riach and Hayes (1987) argue that the difference in the use of visual information for head stabilization between children and adults could be attributed to the children's inability to fixate their gaze. Nonetheless, the differences in the role of vision between infants and adults indicate that most likely the sensory mechanisms involved in postural control, such as vision, progressively evolve into adult form (Riach and Hayes 1987).

Theoretical Model of Postural Control

Many schools of thought exist on the control of PAs. For example, one school purports the concept of auto-organization. According to Bouisset and Zattara (1981), PAs can be reduced to a system of forces provoking moments of force around the CM. Specifically, a voluntary movement such as arm elevation, induces a moment of force around the CM which is thwarted by an inverse moment of force created through feedforward PAs. This is also the case of the dynamical systems approach. Proponents of this school of thought are mostly concerned by the constraints caused by the musculo-skeletal system and by the environment on the production of PAs. They are less concerned with the internal control mechanisms governing PAs (Kelso and Schöner 1988; Schöner et al. 1992; Thelen et al.1993; Thelen and Spencer 1998; Zanone and Kelso 1992).

This study is based on the systems theory (figure II). It is a holistic model, which associates, among other components, the influences of the CNS with the musculoskeletal characteristics as well as the environmental factors. The superposition of the circles reflects the interdependence of the various systems.

Importance of the Study

Research must focus on feedforward PAs since they constitute an important part of postural control. This study is interested in the characterization of feedforward PAs in sitting and standing with an infant population.

Both positions, sitting and standing, are important behavioral milestones in human development. During the acquisition of sitting, infants start to demonstrate the independent control of an observable posture. It is a crucial step in development, whereby, for the first time, infants independently regulate their CM while it is suspended over the base of support. In the standing position, the element of weight bearing is added on the lower extremities. This is a crucial step in infant development that precedes walking. These new skills require a certain level of stability to maintain the CM within the limits of the base of support (Berthental et al. 1997). Consequently they also require efficient PAs. We already know that feedback PAs are elicited by a platform perturbation in infants able to independently sit or stand (Hirschfeld and Forssberg 1994; Sveistrup and Woollacott 1996). The role of feedforward PAs during independent sitting and standing in infants, however, is not as clearly defined. Three studies have reported on feedforward PAs with infants in the sitting position (van der Fits et al. 1999a,b; Von Hofsten and Woollacott 1989) but none considered the postural muscle activity that occurs during focal movement onset. In addition, none of the studies investigated feedforward PAs with infants in the standing position. This study addresses these gaps in the literature.

Research focusing on feedforward PAs in sitting and standing infants could therefore provide insight on the influences of this group of PAs on the development of independence in the two studied positions.

Definition of the Research Problem

Are feedforward PAs elicited during a goal-directed reach different in infants aged 5 to 18 months when studied in the sitting and supported standing positions? Post-hoc grouping of the infants based on their scores in sitting and standing on the Alberta Infant Motor Scale (AIMS) (Piper and Darrah 1994) resulted in two groups: Sitters and Creepers. The following hypotheses reflect the post-hoc organization of the infants based on skill level.

Hypotheses

1. There will be a significant difference in the timing of changes in center of pressure displacement or postural muscle onset latencies, within the defined feedforward period, between infant sitters and infant creepers, in both the sitting and the standing positions.
2. Infant creepers will have an increased probability of activating postural muscles and displacing the center of pressure, before and during focal movement onset, within the defined feedforward period, in both the sitting and the standing positions than the sitters.
3. Infant creepers will display more consistent patterns of feedforward postural muscle activity in both the sitting and standing positions than the sitters.

CHAPTER II

The following manuscript has been prepared using author guidelines from *The Journal of Experimental Brain Research*. It describes the methodology, reports the pertinent results and is followed by a specific discussion. Even though all the results are discussed, not all are visually represented. Figures, which complement the manuscript but have not been included with the manuscript, have been placed in appendix I at the end of the thesis. In addition to the figures already mentioned in Chapter I, the following figures can be found:

Feedforward postural adjustments associated with a goal-directed reach produced by infants in the sitting and standing positions

Running title: Feedforward postural adjustments in infants

Key words: feedforward, feedback, postural adjustments, motor control, equilibrium, goal-directed reach, sitting, standing

Authors: Lynn Casimiro, MA, PT, is Clinical Training Advisor with the National Centre of Education for Francophones in Health Sciences.

Heidi Sveistrup, PhD, is a Career Scientist with the Ministry of Health and Long-Term Care of Ontario.

Address: Lynn Casimiro,
School of Rehabilitation Sciences,
Faculty of Health Sciences,
University of Ottawa,
451 Smyth Rd.
Ottawa, Ontario
K1H 8M5
Email: **casimiro@uottawa.ca**

Acknowledgements: This work was funded in part by the Physiotherapy Foundation of Canada

Abstract

Feedforward postural adjustments were studied in 22 infants between the ages of 5 to 18 months using a goal-directed reach paradigm. Infants were separated in two behavioral groups, sitters and creepers and were encouraged to reach for an object of interest without support in the sitting position and with minimal external support in the standing position. Surface electromyographies, center of pressure displacements and video data were collected. Three trials in each position were selected based on the video recordings and coded for further analysis. Feedforward postural muscle activity was recorded in both sitters and creepers. The infants in the two groups showed no clear pattern of postural muscle activation or differences in postural muscle onset latencies. Compared to sitters, creepers showed a greater proportion of trials with more than one postural muscle activated ($p < .05$) and reached more slowly ($p < .05$) in the sitting position. A descriptive analysis of the data revealed a large proportion of trials with tonic postural muscle activity in both the sitters and creepers group. In the creepers group more phasic postural muscle activity was noted. It is possible that infants initially use tonic muscle activity to "stiffen" the body to maintain postural stability and develop more phasic postural muscle activity as they mature and gain experience in the sitting and standing positions. During this time evidence of feedforward postural synergies emerge since more than one muscle group are activated. The reduction in reaching speed in the creepers group may be an early movement strategy used to minimize the self-induced perturbation caused by a goal-directed reach.

Introduction

Two mechanisms of postural control, feedback and feedforward, are used in the maintenance of independent sitting and standing postures. More specifically, feedback postural adjustments (PAs) encompass all postural reactions produced to maintain equilibrium in response to an unexpected perturbation (Nashner 1976). When the perturbation is expected, feedforward postural adjustments (PAs) are elicited. Feedforward PAs can be defined as functional changes, which occur in a particular time interval in preparation to the start of a voluntary movement, or as an accompaniment to voluntary movement (Belen'kii et al. 1967; Frank and Earl 1990; Hugon et al. 1982). These two periods of feedforward PAs are often termed preparatory PAs and accompanying PAs respectively. Taken together, PAs, which occur in the preparatory and accompaniment periods, form the feedforward period (Frank and Earl 1990).

Although PAs are often taken for granted, it has been proposed that their production demands complex processes that coordinate biomechanical, sensory and motor systems with the various levels of the central nervous system (CNS) (Hageman et al. 1995; Sveistrup and Woollacott 1996). As suggested by Sveistrup and Woollacott (1996), postural control is a prerequisite of coordinated movement and the development of new motor skills. Consequently, posture control has been found to play an important part in the development of abilities such as reaching (Kaminski et al. 1995; Rochat 1992,1995) and walking (Assaiante 1998; Goldfield 1989). Studies focusing on feedforward PAs in the independently sitting and standing infant provide important information on the development and regulation of this postural mechanism. In addition, research delving into the development of a feedforward postural adjustment mechanism improves our understanding of the relationship between voluntary movement and the clinical presentation of various infant pathologies affecting motor or neurological development (Berger 1998; Hadders-Algra et al.1999; van der Fits et al.1999a).

Presently there are no data characterizing the development and regulation of feedforward postural adjustments in the standing infant and only a few studies have examined the sitting infant (Thelen and Spencer 1998; van der Fits et al.1999a,b; Von Hofsten and Woollacott 1989). Studies of infant feedforward behavior in the sitting and standing positions will be discussed separately.

Thelen and Spencer (1998) used a dynamical systems approach to conceptualize the coordinated development of posture and reaching. Specific to feedforward PAs, the authors reported that the head, with upper and lower body activity combined to produce successful reaching.

In a 1989 abstract by Von Hofsten and Woollacott, findings of feedforward PAs in the sitting position from five infants aged 9 to 10 months were reported. The authors recorded feedforward trunk extensor muscle activity in the in the majority of the trials. Other postural muscles were only inconsistently activated. They proposed that the feedforward postural system was present but not yet mature.

Moreover, in a first study by van der Fits, Klip, van Eykern and Hadders-Algra (1999a) spontaneous reaching and goal-directed reaching in infants between 3 and 6 months of age were examined in the sitting position. The authors found no significant differences in postural muscle activity between spontaneous reaching and goal-directed reaching. Nonetheless, the authors reported that infants showed a preference for neck muscles during goal-directed reaches. They proposed that infants required increased head stabilization in space during goal-directed movements. In the group of infants tested they found that goal-directed reaching occurred between four to five months and was accompanied by a significant amount of postural muscle activity. The authors also reported that postural muscle activity decreased as goal-directed reaching improved with infants in the sitting position. The authors suggested that infants required less joint stiffness to perform a voluntary movement as they became more experienced. It is important to note that the authors stated that the postural muscle activity did not occur before the activity of the prime mover. Since they defined feedforward postural muscle activity as occurring prior to the anterior deltoid muscle activity, they did not consider postural muscle activity accompanying the focal movement as feedforward in nature.

In a second study, van der Fits, Otten, Klip, van Eykern and Hadders-Algra (1999b) used a longitudinal research paradigm to examine the development of feedforward postural adjustments during reaching with ten infants between the ages of 6 to 18 months. The infants were placed in a sitting position and were presented an attractive toy to elicit a reach. The authors reported very little feedforward postural muscle activity prior to fifteen months. As in their first study, the authors considered postural muscle activity to be feedforward in nature only if it occurred prior to deltoid muscle activation. Postural muscle activity accompanying the movement was not considered feedforward in nature. No statistically significant differences were found in the postural muscle onset latencies between infants when grouped by age categories. They also examined global patterns of muscle activation regardless of their category, feedback or feedforward. They found that an increase in the most complete postural response patterns as defined by their onset latencies corresponded with the emergence of standing without support, the side step and independent walking. They further reported a decrease in postural muscle activity between the ages of 6 to 8 months. They proposed that this period of low postural muscle activity was used to reorganize the postural adjustments from a simple form to a more complex form. The former could not be fine-tuned to task-specific conditions whereas the latter could be adapted to task-specific constraints. These authors, however, do not provide data to support their proposal.

All the aforementioned studies used a reaching paradigm, but most had a different definition of the time interval at which the functional changes occurred relative to movement onset, or did not report a definition at all. The literature, however, clearly demonstrates that feedforward postural adjustments can be recorded as early as 100ms prior to the activation of the prime mover (Frank and Earl 1990). Postural reactions recorded earlier can be caused by a voluntary activity. It is also clear in the literature that feedback PAs have been recorded in the standing position as early as 60ms after activation of the prime mover in the adult population (Forssberg and Hirschfeld 1994) and 90ms in the infant population (Sveistrup and Woollacott 1996). Therefore PAs recorded between 100ms prior to activity of the prime mover and 70ms after activity of the prime mover is a conservative window of time to define feedforward PAs, and it is a window that includes preparatory feedforward PAs and their accompanying feedforward PAs. This window also reduces the risk of including voluntary and feedback postural muscle activity when reporting on feedforward PAs.

In the present study, a goal-directed reaching paradigm was used to examine feedforward postural adjustments in two groups of infants, independent sitters and reciprocal creepers. Surface electromyography of the quadriceps muscle, hamstring muscles, lumbar extensor muscles and right deltoid muscle, changes in center of pressure displacement and body kinematics were analyzed for both the preparatory and accompanying periods of feedforward postural control. These data were used to identify differences between groups in order to characterize the feedforward postural adjustments used.

Subjects and Method

Subjects

Twenty-two infants between the ages of 5 and 18 months were recruited through local parenting groups. Informed consent was obtained from a parent prior to the testing session. Infants did not present any systemic illnesses or orthopedic disorders at the time of assessment. The data from two infants were not included in the analysis due to data acquisition problems (electrode malfunction).

All infants were able to sit without support for 10 seconds or more but none were able to walk independently. The infants were divided post-hoc based on their score in sitting and standing on the Alberta Infant Motor Scale (AIMS) (Piper and Darrah 1994). These resulted in post-hoc grouping of the infants into two groups: (a)

Sitters (n = 10), and (b) Creepers (n = 10). The infants in the "Sitters Group" were able to reach while sitting without support but were unable to achieve four point kneeling or reciprocal creeping (see Table 1 for subject characteristics). The "Creepers Group" encompassed infants able to perform reciprocal creeping and in some trials, standing without support (C6, C9 and C10). Clearly, these infants were not skilled in the independent standing position. In the "Creepers Group", C1 developed an alternative form of creeping in comparison to the AIMS criteria, yet her data appeared no different than the other infants of her group.

Procedure

A goal-directed reaching task was used to elicit right arm reaches from infants while they were in the sitting and standing positions. Surface electromyography (EMG) and force platform data were recorded at 600Hz using the Ariel Performance Analysis System (APAS) (Trabuco Canyon, California).

Seven pre-amplified surface electrodes (Neuromuscular Research Center, Boston, Massachusetts) were used to record electromyography (EMG) data from one voluntary muscle, the right anterior deltoid muscle (RDelt), and three pairs of postural muscles, right and left lumbar extensors (Rext & Lext), right and left hamstrings (Rhams & Lhams) and right and left quadriceps (Rquad & Lquad). The deltoid muscle is not always the prime mover during reaching tasks in the adult population (Layne and Abraham 1991; van der Fits et al. 1998), it is often preceded by the biceps brachii muscle. In the infant population however, van der Fits et al. (1999) reported no statistical differences between the onset latencies of the deltoid muscle and the biceps brachii muscle as prime movers. Therefore, the deltoid muscle was chosen for this study.

Force data was collected with infants in the sitting and standing positions using a type 9281B DelSys KISTLER force plate (Kistler Instrument Corporation, Amherst New York). The force data was then processed post hoc to yield center of pressure displacement data.

Body kinematics were recorded using one camera positioned perpendicular to the plane of motion. The infants were dressed in a dark form-fitting suit to which eight reflective markers were attached on the right side of the body over the: (1) styloid process; (2) lateral epicondyle; (3) acromion process; (4) posterior superior iliac spine; (5) greater trochanter; (6) lateral border of the tibial plateau; (7) lateral maleoli and the (8) head of the fifth metatarsal.

Infants were tested in two positions. In the first position the infants sat without support on the force platform with the lower extremities semi-flexed. An experimenter was positioned behind the infant to help maintain balance between reaches. The parent was in front of the infant and was instructed to rapidly present a small object such as a rattle, teether, wooden puzzle pieces or a key chain to the infant, in line with the right shoulder. Only reaches performed with the right arm were recorded. Infants S1, S4 and C2 showed a preference for using the left hand to reach. For these infants, the toy was presented slightly lateral to the right shoulder to encourage a right-handed reach.

In the second position, the infants were placed in an upright position with their feet placed approximately shoulder width apart. Because most infants were only willing to participate when a parent supported them in the standing position, the parent kneeled behind the infant to help support them in the standing position while the experimenter presented the toy. Every effort was made to avoid a forward or a backward lean of the trunk. The parent's hands were positioned slightly above the reflective marker placed on the posterior superior iliac spine and he or she was instructed to offer a minimal amount of support to the infant. It was difficult to standardize the amount of support provided. In one case, the infant produced reaching behaviors only if the parent presented the toy and in two cases, both parents had to share the assigned positions since the infants would not participate if the experimenter was in close proximity. When infants became fussy, parents were allowed to attend to their needs and were asked if they wished to continue. Infant C1 was not able to complete the standing trials. therefore, only sitting data was obtained.

Reduction and Analysis of Data

Data Coding

Up to ten reaches were recorded in each position. The data for three reaches in each position were selected by viewing each infant's video. The criteria for selection of the three trials for analysis in each of the positions included: (1) the infant was not performing gross movements prior to reach; (2) there was no loss of equilibrium during the reach; (3) the infant was positioned properly with feet resting on the force plate; (4) the infant completed the reach which included grasping the toy; (5) no support was provided in sitting and (6) a minimal amount of support was provided in standing.

Center of pressure displacement and muscle activity was coded for the selected reaches. The videotapes were also digitized to determine the reaching speed of each chosen trial.

EMG and force plate data for each of the three trials were analyzed using BIOPROC (Robertson, Marcoux, Bradley, and Lamontagne, 1999). In order to analyze the data with BIOPROC, a window of time (ms) corresponding to feedforward postural muscle activity and center of pressure displacement was established based on previous research. It has been reported that feedforward postural responses in the standing position can both precede and accompany voluntary movement. The range of feedforward PA onset latency is from 100ms prior to reach onset, to 100ms after reach onset (Belen'kii et al. 1967; Bouisset and Zattara 1981; Cordo and Nashner 1982; Forssberg and Hirschfeld 1994; Frank and Earl 1990; Layne and Abraham 1991). However, an overlap exists between feedforward and feedback postural responses, the latter starting as early as 60ms in adults and 90 ms in infants after the perturbation (Forssberg and Hirschfeld 1994; Forssberg and Nashner 1982; Sveistrup and Woollacott 1996).

To ensure that the coded data would be feedforward in nature, the analysis window was set a priori from –100ms to 70ms. Thus, in this study, postural activity was separated into three periods. The "Feedforward Period" encompassed any postural adjustments from -100ms to 70ms. This period included postural activity that occurred before and during the voluntary movement. The "Preparatory Period", which referred to any postural adjustment between -100ms and 0ms, considered only the postural activity that occurred before the voluntary movement. Finally, the "Accompanying Period" which took into account postural adjustments between 0ms and 70ms, which corresponded to postural activity that occurred after the voluntary movement.

Muscle activity onsets were identified as activity of more than two standard deviations above baseline, and lasting more than 50ms (De Wolf et al.1998; Foster et al. 1996). Each of the six postural muscles was coded relative to deltoid muscle activity onset (0ms). The same procedure was followed for center of pressure displacement. Ten infants were randomly chosen and their EMG data recoded after a three-month period had elapsed. Intra-evaluator consistency was calculated at 0.93 $p < .01$.

Individual data from three trials for each infant were averaged to provide a mean value for each infant. The infant means were used in statistical tests of group differences.

Statistics

The decision to use one statistical test over another was difficult to set a priori. A review of other studies on feedback (Sveistrup and Woollacott 1996) and feedforward (van der Fits et al. 1999c) postural responses in infants to determine and anticipate which statistical test would be most appropriate. For example, the aforementioned studies found no differences in onset latencies between behavioral groups and age groups. Therefore, we relied on the descriptive analysis of the data to decide whether a multiple analysis of variance (MANOVA), was warranted to calculate the differences in onset latencies of postural muscle activity and center of pressure displacement between sitters and creepers in the sitting and standing positions. Based on the descriptive analysis of our data that showed no identifiable differences in the patterns of postural muscle activity or postural muscle onset latencies, MANOVAs were not indicated.

We also relied on the qualitative analysis to compare the data when the infants were divided equally into two age groups, younger and older infants versus with the infants divided based on behavior into two groups. No differences were found between organizing the group by age level or by behavioral characteristics.

Non-parametric tests, set at a Significance of $p < .05$ (Chi-square with Yates correction), were used to analyze the differences in the proportion of trials with postural muscle activity or center of pressure displacement in the preparatory period, the accompanying period, as well as the entire feedforward period between sitters and creepers in both sitting and standing positions. Another Chi-square was also used to calculate the differences in the proportion of trials with no postural muscle activity, one active postural muscle and more than one active postural muscle between sitters and creepers, in both sitting and standing positions. Finally, a t-test was used to analyze the differences in reaching speeds between sitters and creepers in both sitting and standing positions.

Results

Descriptive Analysis

Postural Muscle Activity

Sitting position

Visual representation of the mean onset latency of postural muscles activated in the sitting position (left side of Figure 1) for each infant revealed the presence of feedforward postural muscle activity in both behavioral groups. However, a noticeable inter-subject variability was apparent. For example, the mean onset latencies of each infant for the Lext muscle ranged from -100ms to 32ms for the sitters and –77ms to 30ms for the creepers. Although no clear pattern of feedforward muscle activity emerged, the creepers showed a tendency to activate a larger number of postural muscles within the feedforward period when compared to the sitters, in the sitting position.

Examples of three trials of processed EMG recordings from four infants in the sitting position (S3, S6, C4 and C10) are depicted in figures 2 (a). These infants were chosen to represent the qualitative similarities and differences in EMG recordings between the two behavioral groups. Both sitters and creepers presented tonic postural muscle activity throughout the three trials. In the sitters group, Infant S6 showed a phasic feedforward postural muscle burst of the Rext muscle in trial one which seemed to emerge out of the tonic postural muscle activity. In the creepers group, infant C4 activated the Lext muscle within the feedforward window in two out of the three trials while tonic postural muscle activity was less apparent in the remainder of the muscles. Finally, infant C10 activated the Rext and Lext muscles within the feedforward window, in trial three. In summary, the EMG illustrated tonic postural muscle activity for the sitters and creepers. Greater phasic feedforward postural muscle activity, however, was noted for the creepers. Furthermore, the EMG recordings demonstrated great intra subject variability when comparing the consistency of feedforward postural muscle activity between the three trials.

Standing position

An observation of the right side of figure 1 revealed very little feedforward postural muscle activity in the feedforward period for both sitters and creepers in the standing position. Specifically, seven infants in the sitters group and five infants in the creepers group showed no feedforward postural muscle activity. The infants who did activate postural muscles in a feedforward manner demonstrated variable postural muscle onset latencies. Therefore, no clear pattern of postural muscle activation was apparent in either group.

Figure 2 (b) shows tonic postural muscle activity in most muscle groups in all three trials for all of the infants. Only infant C10 produced phasic feedforward postural muscle activity, although these bursts were difficult to discern from the background tonic activity. The phasic postural muscle activity was recorded in the Lhams muscle in trial two and the Rext and Lext muscles in trial three.

Center of Pressure

Feedforward displacement of the center of pressure occurred in both groups and in both test positions (Table 2). The onset latencies of center of pressure displacement, however, were quite variable as confirmed by the large standard deviations. Furthermore, no feedforward center of pressure displacement was recorded for the creepers group in the preparatory period, for the standing position.

Quantitative Analysis

Since no clear pattern of postural muscle activation or differences in postural muscle onset latencies were found during the descriptive analysis, the quantitative analysis was focused on determining significant differences in the proportion of trials with postural muscle activity and center of pressure displacement between sitters and creepers. Proportions of postural muscle activity and center of pressure displacement were calculated on three trials and one value was used to reflect each infant.

Proportion of Trials with Feedforward Postural Muscle Activity

Sitting position

Figure 3 illustrates the mean proportions of trials with postural muscle activity. Only the data recorded in the sitting position are included. The information was divided by behavioral level and by feedforward period. In the preparatory period, sitters produced feedforward postural muscle activity in a proportion of 0.13 of trials, compared to 0.33 of trials for the creepers. In the accompanying period, sitters produced feedforward postural muscle activity in a proportion of 0.20 of trials, compared to 0.33 of trials for the creepers. Finally, in the feedforward period, sitters produced postural muscle activity in a proportion of 0.33 of trials compared to a proportion of 0.53 of trials for the creepers.

Chi-squares analyses were used to determine whether the differences in proportions of trials with postural muscle activity between the sitters and the creepers for the preparatory, accompanying and feedforward periods. The results were significant ($p < .05$). Although creepers tended to activate a larger proportion of postural muscles in all three of the periods in the sitting position, the differences between the two groups were not statistically significant.

In order to complete the analysis of the proportions of trials with postural muscle activity in the sitting position, two additional variables were assessed. First, the number of postural muscles that were activated in any given trial was determined to provide insight into the development of synergies. Creepers activated significantly more than one postural muscle in a higher proportion of trials (0.30) than sitters (0.07) (Chi-square = 8.94 $p < .05$). Second, Chi-squares were used to determine whether a statistically significant difference existed with regards to the proportions of trials with specific postural muscle activity between the creepers and the sitters in the sitting position. For example, a chi-square was calculated to determine whether the creepers activated their Lext muscle more often than the sitters. None of the differences in specific postural muscle activity between sitters and creepers reached statistical significance.

Standing position

The proportion of trials with postural muscle activity was very low. The preparatory period showed proportions of feedforward postural muscle activity in 0.07 of trials for the sitters and in 0.22 of trials for the creepers. In the accompanying period, sitters produced feedforward postural muscle activity in a proportion of 0.10 of trials and creepers in a proportion of 0.07 of trials. Finally, in the feedforward period, sitters produced feedforward postural muscle activity in a proportion of 0.13 of trials and creepers in a proportion of 0.22 of trials. None of these differences were statistically significant.

The proportion of trials in which more that one postural muscle was activated were very low in the standing position, 0.03 of trials for the sitters and 0.07 of trials for the creepers. The proportion of trials with specific postural muscle activity was not statistically different between the sitters and the creepers.

Proportion of Trials with Feedforward Center of Pressure Displacement

Sitting position

Although creepers tended to display feedforward center of pressure displacement in the sitting position more often than the sitters, the differences in feedforward center of pressure displacement between the two behavioral groups did not reach statistical significance (Chi-Square=1.63 $p > .05$). The proportions of trials with feedforward center of pressure displacement in the preparatory period were 0.07 for the sitters and 0.13 for the creepers. In the accompanying period, the proportions of trials with feedforward center of pressure displacement were 0.10 for the sitters and 0.17 for the creepers. In the feedforward period, the proportions of trials with center of pressure displacement were 0.17 for the sitters and 0.30 for the creepers.

Standing position

Low proportions of trials with feedforward center of pressure displacement were noted for both the sitters and the creepers in the standing position. The proportions of trials with feedforward center of pressure displacement in the preparatory period were 0.10 for the sitters and none for the creepers. In the accompanying period, the proportions of trials with feedforward center of pressure displacement were equal for both the sitters and the creepers at 0.07. In the feedforward period, the proportions of trials with center of pressure displacement were 0.17 for the sitters and 0.07 for the creepers. No statistically significant differences were found in feedforward center of pressure displacement between the sitters and the creepers.

Reaching speed

Individual infant reaching speeds were extracted from the video data. Figure 4 represents the reaching speed mean and standard deviations for each behavioral group in both the sitting and standing positions. The results clearly demonstrate that the sitters reached more quickly than the creepers in the sitting position (66.40cm/sec $\pm$ 32.25 compared to 48.4 cm/sec $\pm$ 27.11) and in the standing position (93.99cm/sec $\pm$ 74.31 compared to 55.16cm/sec $\pm$ 16.39). A t-test revealed statistically significant differences in reaching speeds between sitters and creepers ($p < .021$) in the sitting position but not in the standing position.

Discussion

The purpose of this study was to characterize feedforward postural adjustments in sitting and standing in infants. Three main questions emerge from our data. First, what are the postural strategies used by infants during a goal-directed reach? Second, why are feedforward postural adjustments not consistently the main stabilizers in early sitting and standing? Finally, is the modulation of reaching speed a feedforward strategy?

What are the Postural Strategies Used by Infants during a Goal-Directed Reach?

Young adult data suggests that consistent patterns of feedforward postural muscle synergies and center of pressure displacement are used to counteract the perturbation induced by the voluntary movement such as the one used in this study (Belen'kii et al. 1967; Bouisset and Zattara 1981; De Wolf et al. 1998; Friedli et al. 1984). In contrast, even though every infant in this study was able to sit independently and perform a goal-directed reach without losing their equilibrium, neither sitters nor creepers consistently produced feedforward PAs. The highest and lowest proportions of trials with feedforward postural muscle activity were recorded for the creepers in the sitting position (0.53) and for the sitters in the standing position (0.07), respectively. Moreover, the highest and lowest proportions of trials with feedforward center of pressure displacement were recorded for the creepers in the sitting position (0.30) and the standing position (0.07), respectively. Furthermore, patterns of postural muscle activity were not consistent between individual trials, between each infant and between the two behavioral groups, concurring with the reported results of studies on the development of feedforward PAs (van der Fits et al. 1999c; Von Hofsten and Woollacott 1989).

Then how did these infants maintain postural control during a goal-directed reach if they didn't consistently use feedforward PAs? As previously suggested, the tonic postural muscle activity that was observed in sitters and in creepers is an early adaptive mechanism to stiffen the body and maintain postural stability (Hirschfeld and

Forssberg 1994; Sveistrup and Woollacott 1996 and Van der Fits et al. 1999). Hence, in this study, the self-induced body sway caused by the goal-directed reach might have been prevented by the observed tonic muscle activity. This proposed strategy of early postural control might explain the minimal amount of trials with recorded center of pressure displacement.

Compared to sitters, why is there more phasic postural muscle activity in creepers? A possible explanation is that tonic postural muscle activity limits the infants' motor abilities by decreasing the degrees of freedom of movement available (Thelen and Spencer 1998). More precisely, the stiffened body may have difficulty dissociating the various segments to allow infants to move each segment independently, for example, to perform a forward trunk lean. Therefore it may be necessary for infants to slowly introduce phasic postural muscle activity as they mature or gain experience in a new postural position such as sitting, in order develop new motor skills such as reciprocal creeping.

The standing data from this study seems to support this argument. None of the infants were skilled in independent standing, which may explain why no differences were found in the number of muscles or number of trials with phasic postural muscle activity between sitters and creepers. Perhaps differences would emerge with increased experience as supported by training studies conducted on feedback PAs with infants in sitting (see Hadders-Algra et al. 1996) and standing (see Sveistrup and Wollacott 1997) positions.

In summary, creepers seem to use more phasic postural muscle activity than sitters to maintain postural stability in the sitting positions. The tonic postural muscle activity appears to counteract the inherent unstable nature of the sitting position. This may serve to prepare the body to counteract a self-induced perturbation as well. As infants become more experienced (Berthental and Von Hofsten 1998; Gramsbergen and Hadders-Algra 1998; Hirschfeld and Forssberg 1994) and as they mature (van der Fits et al. 1999a) phasic postural muscle activity seems to emerge to maintain equilibrium thus allowing infants more freedom of movement.

Why are Feedforward Postural Adjustments not consistently the Main Stabilizers in Early Sitting and Standing?

A review of the key studies on feedback postural adjustments in sitting, concurrent with the result of the present study, offers some insight into the development of feedforward PAs.

Sitting Position

Hirschfeld and Forssberg (1994) identified feedback PAs in infants between five and eight months of age in the sitting position. Using a forward translation of the support surface, they noted that the agonist postural muscles (neck and trunk flexor muscle groups) were activated first, corresponding to their findings with adult subjects (Forssberg and Hirschfeld, 1994). Furthermore, the agonist postural muscle activity was recorded in the group of infants not able to sit independently (25% of trials), although consistency of postural muscle activation was notably better in the infant group able to sit independently (60% of trials). In contrast to the adult data, the antagonist postural muscles were rarely activated. The authors proposed that the infant's ability to regulate the postural correction initiated by the agonist postural muscles was not yet functional. Furthermore, the temporal sequence of postural muscle activity was not consistently proximal-to-distal. It is important to note that the authors also reported tonic postural muscle activity, which decreased as the infants learned to sit independently around seven to eight months of age.

In the current study, no consistent pattern of feedforward postural muscle activation was evident, even though every infant was able to sit independently. Therefore, the relationship between agonist and antagonist feedforward postural muscle groups and temporal sequence of feedforward postural muscle activity, as reported in adult studies (Belen'kii et al. 1967; Lee et al. 1987; van der Fits et al. 1998), cannot yet be identified in infants at the behavioral levels of sitting and creeping. However, similar to the findings in feedback PAs with sitting infants (Hirschfeld and Forssberg 1994), phasic postural muscle activity occurred more often in the more behaviorally advanced infants in the creepers group. Moreover, our study showed an increased proportion of trials where infant creepers activated more than one postural muscle in the feedforward period. One could argue that the increase in phasic postural muscle activity and the number of postural muscles activated between sitters and creepers, suggests the emergence of functionally appropriate postural muscle synergies, or patterns of postural muscle activation (Harbourne, 1993) to increase the level of feedforward control. Through maturation and experience, these synergies probably continue to develop into adult form.

Standing Position

Sveistrup and Woollacott (1996) conducted a longitudinal study of the development of feedback PAs in the standing position with infants between the ages of 5 and 17 months. Following a forward or backward translation of the force platform, they found that feedback postural muscle synergies were similar to the adult pattern and that sequential timing of the postural muscle activity within the synergies was most often distal-to-proximal. These postural synergies, however, were only consistently present once infants achieved independent stance, ranging between 8 and 15 months of age. Before this behavioral level, the muscle activation pattern was not consistent, but the authors proposed that the simple presence of grouped feedback postural muscle activity suggested that postural muscle synergies emerged before the infants were able to stand independently. Furthermore, the large quantity of tonic postural muscle activity was present before and often lasting as long as the duration of the perturbation before infants were able to stand independently. As the infants matured, or became more skilled in the standing position, the authors noted increased phasic postural muscle activity.

The infants in our study were unskilled in the standing position, and did not present any differences in postural muscle activity between the sitters and creepers. Postural muscle synergies were not identified and postural muscle activity was not consistent. In fact, the infants in our study displayed very little feedforward postural muscle activity, specifically in a proportion of 0.13 of trials for the sitters and 0.22 of trials for the creepers in the standing position. This finding apparently differs from the development of feedback PAs where Sveistrup and Woollacott (1996) reported the emergence of patterns of postural muscle activity. This PA feedback pattern seemed to follow a distal-to-proximal sequence of activation prior to the infant's ability to stand independently. In this study, no feedforward synergies appeared to emerge before the infants acquired skill in independent standing. Similarly to feedback PAs in infants, tonic postural muscle activity was present in the EMG recordings.

Overall Significance

The comparison of studies of feedback and feedforward postural adjustments may suggest a sequential developmental strategy. Feedback PAs seem functional and used in an appropriate manner before infants are able to sit and stand independently. However, the consistency of these postural adjustments only appears to be present once infants have achieved independent sitting and standing. In contrast, feedforward postural adjustments are not adult-like, in terms of postural muscle synergies and sequence of activation, even after the acquisition of independent sitting. The creepers group in this study showed signs of emerging postural muscle synergies in the sitting position, but these infants were skilled in independent sitting at the time of the study.

When infants first begin to move independently, their movements can result in losses of balance. A possible three-step developmental sequence is proposed. First, a repeated loss of balance with the same movement provides the infant with the opportunity to map the destabilization to an appropriate synergy of postural muscle activity that will prevent a complete loss of balance. Second, once this relationship has been developed, infants may begin to use tonic muscle activity or a "stiffening" strategy in order to prevent the anticipated loss of balance. Finally, phasic bursts of the postural muscles characterized as feedforward postural adjustments will be added to the motor repertoire in order to permit an increasingly efficient postural regulation with different movement demands.

It seems that the emergence of phasic postural activity follows the same developmental process in both feedback and feedforward postural adjustments. In fact, phasic postural muscle activity was recorded in the sitting position more often in the creepers than in the sitters. It is likely that the tendency for an increase in the probability of postural muscle activation would continue as infants became skilled in independent standing. An additional explanation may be that the older infants and children will display an increased probability of postural muscle activity.

In summary, age and accumulated experiences in compensating for externally induced and self-induced perturbations seem to shape the evolution of new muscle synergies. Sensory-motor mapping of the afferent information completes the picture by helping infants choose functionally appropriate synergies for the type of perturbation. While feedback postural adjustments appear to develop before feedforward postural adjustments, the emergence of phasic postural muscle activity seems to follow the same timeline.

Is the Modulation of Reaching Speed a Feedforward Strategy?

Compared to sitters, creepers reached more slowly in sitting and in standing. The difference in reaching speed between sitters and creepers was statistically significant ($p < .05$) in sitting and a trend was noted in standing. We suggest that this phenomenon represents one way for infants to make the self-induced perturbation more manageable. This would imply that infants in the creepers group can anticipate the threat that reaching can pose to their equilibrium.

This finding is supported by Thelen et al.'s work with infants (Thelen et al.1996; Thelen and Spencer 1998). They reported that stable reaching emerged as infants learned to slow down their movement while they developed strategies to preserve good trajectories at different speeds. They further discovered that infants had difficulty maintaining equilibrium when perturbations were generated by fast movements. The same findings were reported in a study on feedforward and feedback postural control in adults in the standing position (Nouillot et al. 2000). Young adults decreased the velocity of reaching by as much as 40% when standing on one leg, an unstable position. The authors suggested that the reduction of the velocity was an attempt to reduce the associated postural perturbation.

It is therefore possible that sensory-motor mapping of the perturbation caused by a goal-directed reach develops with maturity and or experience in the sitting and standing positions and infants respond to the information provided by the mapping to decrease the self-induced perturbation. One of the feedforward strategies used by infants in this study appears to be a decrease in reaching speed.

Conclusion

Infants in this study seem to use tonic muscle activity to maintain equilibrium in the sitting and standing position. With experience and/or maturity, more than one postural muscles are activated in a feedforward manner in the sitting position, which may represent the emergence of postural synergies. During this period, infants appear to learn to reduce the impact of the self-induced perturbation by decreasing their reaching speeds.

References (specific to manuscript –Chapter II)

Assaiante, C. (1998) Development of locomotor balance in healthy children. Neurosci Biobehav Rev 22:527-532

Belen'kii, V. Y., Gurfinkel, V. S., Pal'tsev, Y. I. (1967) Elements of control of voluntary movements. Biophysics 12:154-160

Berger, W. (1998) Characteristics of locomotor control in children with cerebral palsy. Neurosci Biobehav Rev 22:579-582

Berthental, B., Von Hofsten, C. (1998) Eye, head and trunk control: the foundation for manual development. Neuroscience & Biobehavioral Reviews 22:515-520

Bouisset, S. (1991) [Relationship between postural support and intentional movement: biomehcanical approach] [French article]. Arch Int Physiol Biophys 99:A77-A92

Bouisset, S., Zattara, M. (1981) A sequence of postural movements preceeds voluntary movement. Neurosci Lett 22:263-270

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

Cordo, P. J., Nashner, L. M. (1982) Properties of postural adjustments associated with rapid arm movements. J Neurophysiol 47:287-302

De Wolf, S., Slijper, H., Latash, M. L. (1998) Anticipatory postural adjustments during self-paced and reaction-time movements. Exp Brain Res 121:7-19

Forssberg, H., Hirschfeld, H. (1994) Postural adjustments in sitting humans following external perturbations: muscle activity and kinematics. Experimental Brain Research 97:515-527

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

Foster, E. C., Sveistrup, H., Woollacott, M. H. (1996) Transition in visual proprioception: A cross-sectional developmental study of the effect of visual flow on postural control. J Mot Behav 28:101-112

Frank, S. F., Earl, M. (1990) Coordination of posture and movement. Phys Ther 70:855-863

Friedli, W. G., Hallett, M., Simon, S. R. (1984) Postural adjustments asociated with rapid voluntary arm movements I. Electromyographic data. J Neurol Neurosurg Psychiatry 47:611-622

Goldfield, E. C. (1989) Transition from rocking to crawling: postural constraints on infant movement. Dev Psych 25:913-919

Gramsbergen, A., Hadders-Algra, M. (1998) Development of postural control, a basic aspect of neuro-ontogeny. Neuroscience and Behavioral Reviews 22:463-464

Hadders-Algra, M., Brogren, E., Forssberg, H. (1996) Training effects the development of postural adjustments in sitting infants. Journal of Physiology 493:289-298

Hadders-Algra, M., Brogren, E., Forssberg, H. (1998) Postural adjustments during sitting at preschool age: presence of a transient toddling phase. Dev Med Child Neurol 40:436-447

Hadders-Algra, M., van der Fits, I. B., Stremmelaar, E. F., Touwen, B. C. (1999) Development of postural adjustments during reaching in infants with CP. Dev Med Child Neurol 41:766-76

Hageman, P. A., Leibowitz, J. M., Blanke, D. (1995) Age and gender effects on postural control measures. Arch Phys Med Rehab 76:961-965

Harbourne, R. T. (1993) A kinematic and electromyographic analysis of the development of sitting posture in infants. Developmental Psychobiology 26:51-64

Hirschfeld, E., Forssberg, H. (1994) Epigenetic development of postural response for sitting during infancy. Exp Brain Res 97:528-540

Hugon, M., Massion, J., Wiesendanger, H. (1982) Anticipatory postural changes induced by active unloading and comparison with passive unloading in man. Pflügers Archives 393:292-296

Kaminski, T. R., Bock, C., Gentile, A. M. (1995) The coordination between trunk and arm motion during pointing movements. Exp Brain Res 106:457-466

Layne, C. S., Abraham, L. D. (1991) Interactions between automatic postural adjustments and anticipatory postural patterns accompanying voluntary movements. Int J Neurosci 61:241-254

Lee, W.A., Buchanan, T.S., Rogers, M.W. (1987) Effects of arm acceleration and behavioral conditions on the organization of postural adjustments during arm flexion. Exp Brain Res 66:257-270

Nashner, L. M. (1976) Adapting reflexes controlling the human posture. Exp Brain Res 26:59-72

Nouillot, P., Do, M., Bouisset, S. (2000) Are there anticipatory segmental adjustments associated with lower limb flexions when balance is poor in humans? Neurosci Lett 279:77-80

Piper, M. C., Darrah, J. (1994). Motor assessment of the developing infant,Vol. W.B. Saunders Company, Montréal

Robertson, D., Marcoux, M., Bradley, D., Lamontagne, M. (1999). Bioproc: Biomechanical Data Processing. School of Human Kinetics, University of Ottawa, Ottawa.

Rochat, P. (1992) Self-sitting and reaching in 5- to 8-month-old infants: the impact on posture and its development on early eye-hand coordination. J Mot Behav 24:210-220

Rochat, P. (1995) Development of sitting and reaching in 5- to 6-month-old infants. Infant Behv Dev 18:53-68

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

Sveistrup, H., Woollacott, M. H. (1996) Longitudinal development of the automatic postural response in infants. J Mot Behav 28:58-70

Thelen, E., Corbetta, D., Spencer, J. P. (1996) Development of reaching during the first year: role of movement speed. J Exp Psych 22:1059-1076

Thelen, E., Spencer, J. P. (1998) Postural control during reaching in young infants: a dynamic systems approach. Neuroscience Biobehavioral Reviews 22:507-514

van der Fits, I. B., Flikweert, E. R., Stremmelaar, E. F., Martijn, A. (1999a) Development of postural adjustments during reaching in preterm infants. Ped Res 46:1-7

van der Fits, I. B., Klip, A. W., van Eykern, L. A., Hadders-Algra, M. (1999b) Postural adjustments during spontaneous and goal-directed arm movements in the first half year of life. Behavioural Brain Research 106:75-90

van der Fits, I. B. M., Klip, A. W. J., Van Eykern, L. A., Hadders-Algra, M. (1998) Postural adjustments accompanying fast pointing movements in standing, sitting and lying adults. Exp Brain Res 120:202-216

van der Fits, I. B. M., Otten, E., Klip, A. W. J., Van Eykern, L. A., Hadders-Algra, M. (1999c) The development of postural adjustments during reaching in 6- to 18-month-old infants. Exp Brain Res 126:517-528

Von Hofsten, C., Woollacott, M. (1989) Anticipatory postural adjustments during infant reaching. Soc Neurosci Abstr 15:1199

Figure Captions

Figure 1: Mean onset latencies (ms) of feedforward postural muscle activity for individual infants. Each line represents a time continuum ranging from –100ms to 70ms. The X indicates deltoid muscle onset and represents 0ms. Note that no data were recorded in standing for infant C1.

Figure 2: Electromyography (EMG) recordings from two infants in each behavioral group (infants S3, S6 = sitters and infants C4, C10 = creepers), (a) in sitting and (b) in standing. The EMG recordings illustrate postural muscle activity associated with a self-induced perturbation caused by a goal-directed reach. A 300ms window of EMG recordings for the right anterior deltoid, the left and right quadriceps muscle, the left and right lumbar extensor muscles and the left and right hamstring muscles, is depicted from top to bottom. An arrowhead identifies feedforward postural muscle activity. The coded EMG window is delineated by the vertical lines at —100ms and 70ms. Zero milliseconds (0ms) represents onset of right anterior deltoid muscle activity.

Figure 3: Proportion of trials with feedforward postural muscle activity recorded in one, two, three, four or five postural muscles for both behavioral groups in the sitting position. Values represent group means and have been separated into the preparatory period, the accompanying period and the feedforward period. The height of each bar indicates the total proportion of muscle activation for the period indicated. Each section of the bars delineates the proportion by number of muscles activated.

Figure 4: Reaching speed of infant sitters and creepers in the sitting and standing positions. Bars represent infant group means $\pm$ SD, which were calculated from each infant's mean of three trials. The asterisk* indicates that statistical significance ($p = .02$) was reached in the sitting position between the two behavioral groups.

Figure 1

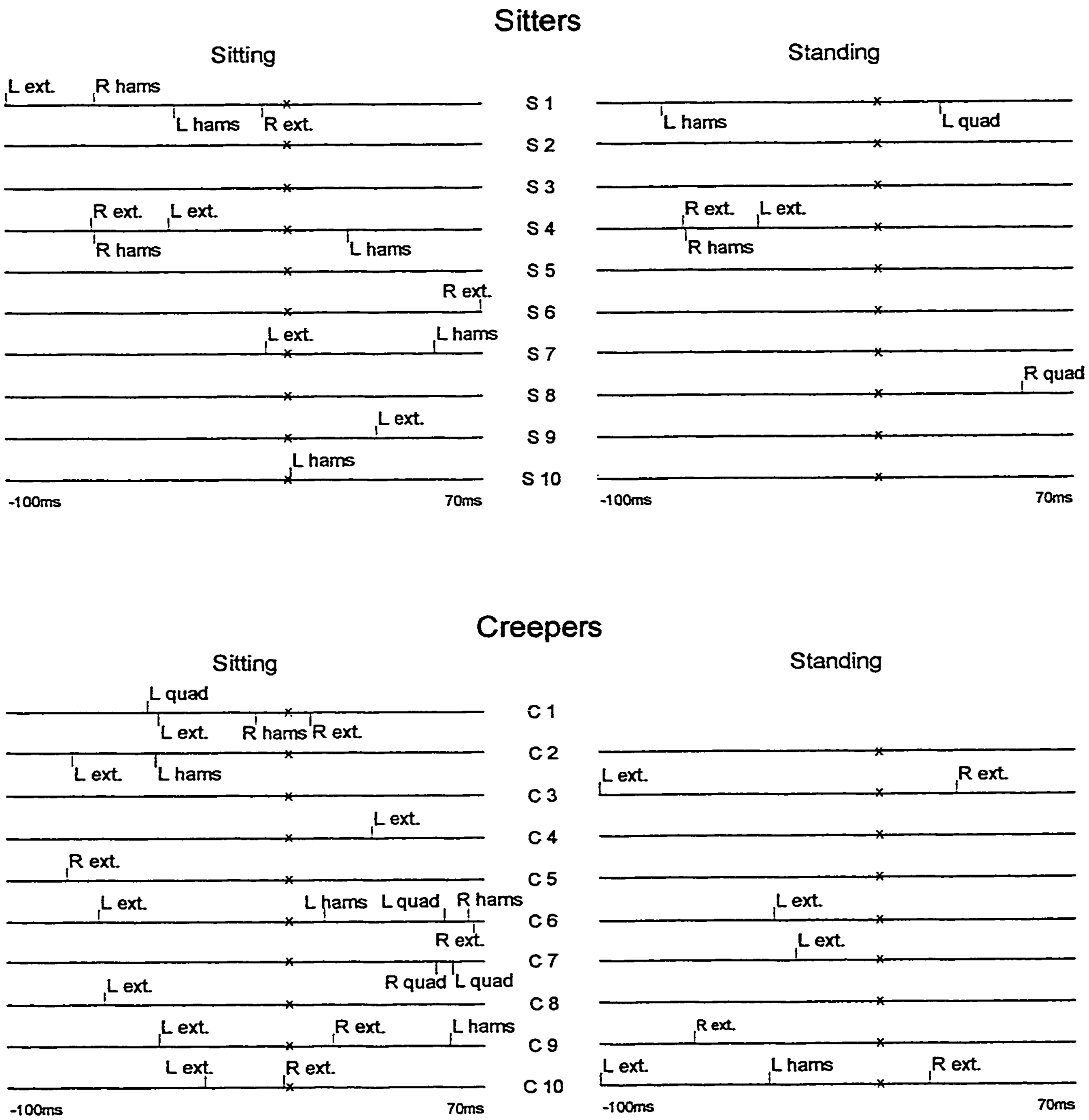
Sitters
Sitting
Standing
L ext.
R hams
L hams
R ext.
L quad
R ext.
L ext.
R hams
L hams
R ext.
L ext.
L hams
R quad
L ext.
L hams
S 1
S 2
S 3
S 4
S 5
S 6
S 7
S 8
S 9
S 10
-100ms
70ms
Creepers
Sitting
Standing
L quad
L ext.
R hams
R ext.
L ext.
L hams
R ext.
L ext.
R ext.
L ext.
L hams
L quad
R hams
R ext.
R quad
L quad
L ext.
L ext.
R ext.
L hams
L ext.
R ext.
L ext.
L hams
R ext.
C 1
C 2
C 3
C 4
C 5
C 6
C 7
C 8
C 9
C 10
-100ms
70ms

Figure 2 (a): Sitting

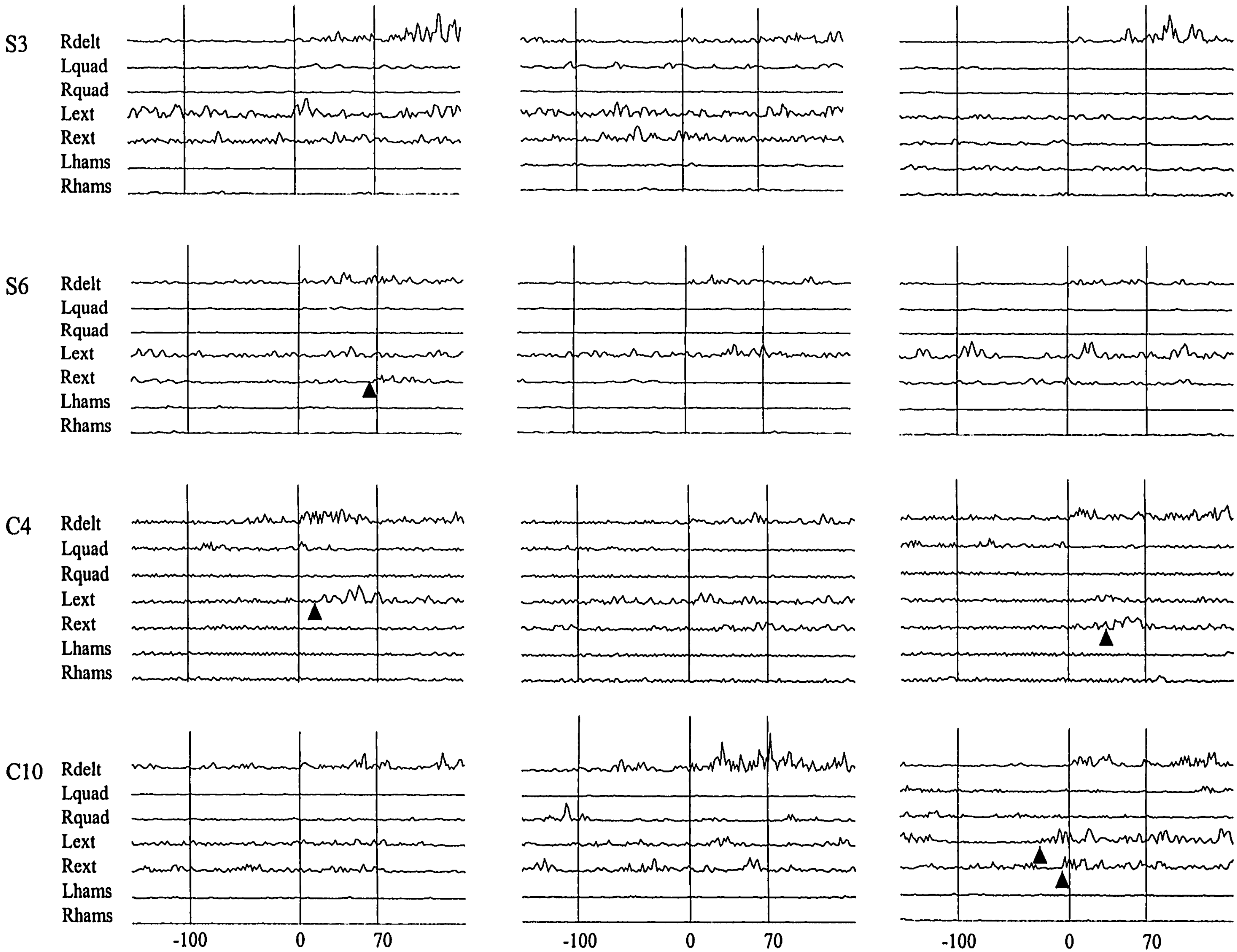

Figure 2 (b): Standing

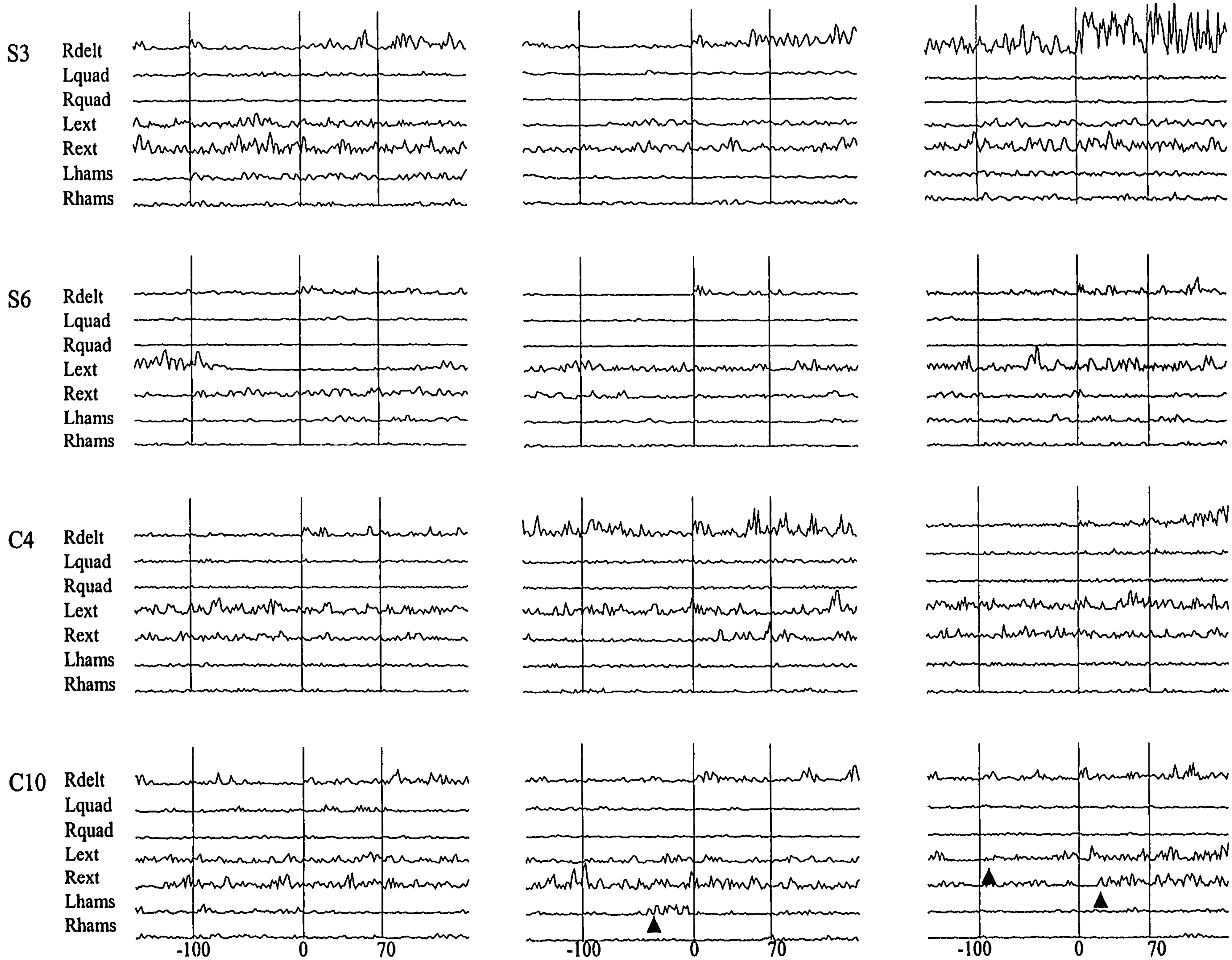

Figure 3

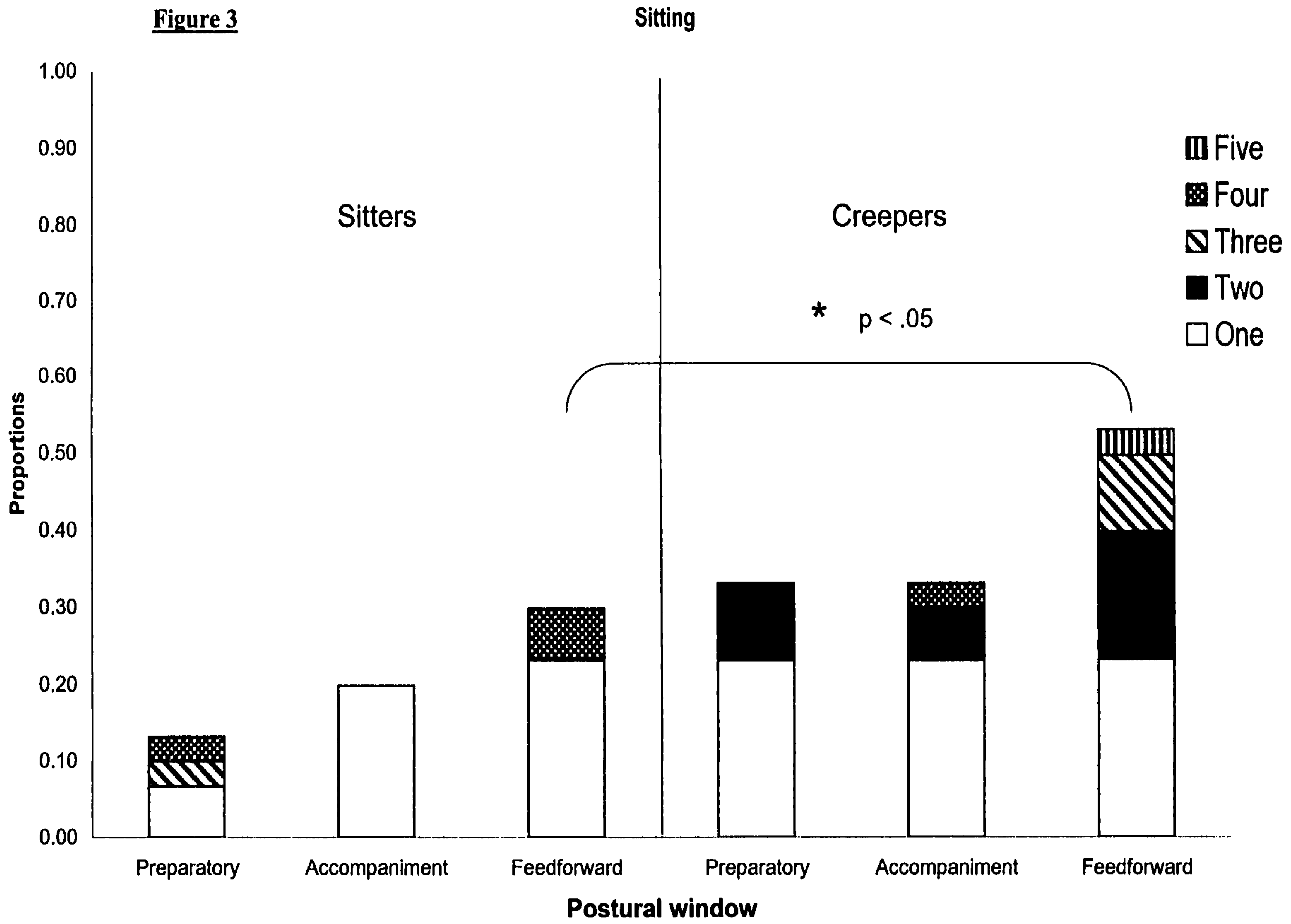
Sitting
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Proportions
Sitters
Creepers
* p < .05
Five
Four
Three
Two
One
Preparatory
Accompaniment
Feedforward
Preparatory
Accompaniment
Feedforward
Postural window

Figure 4

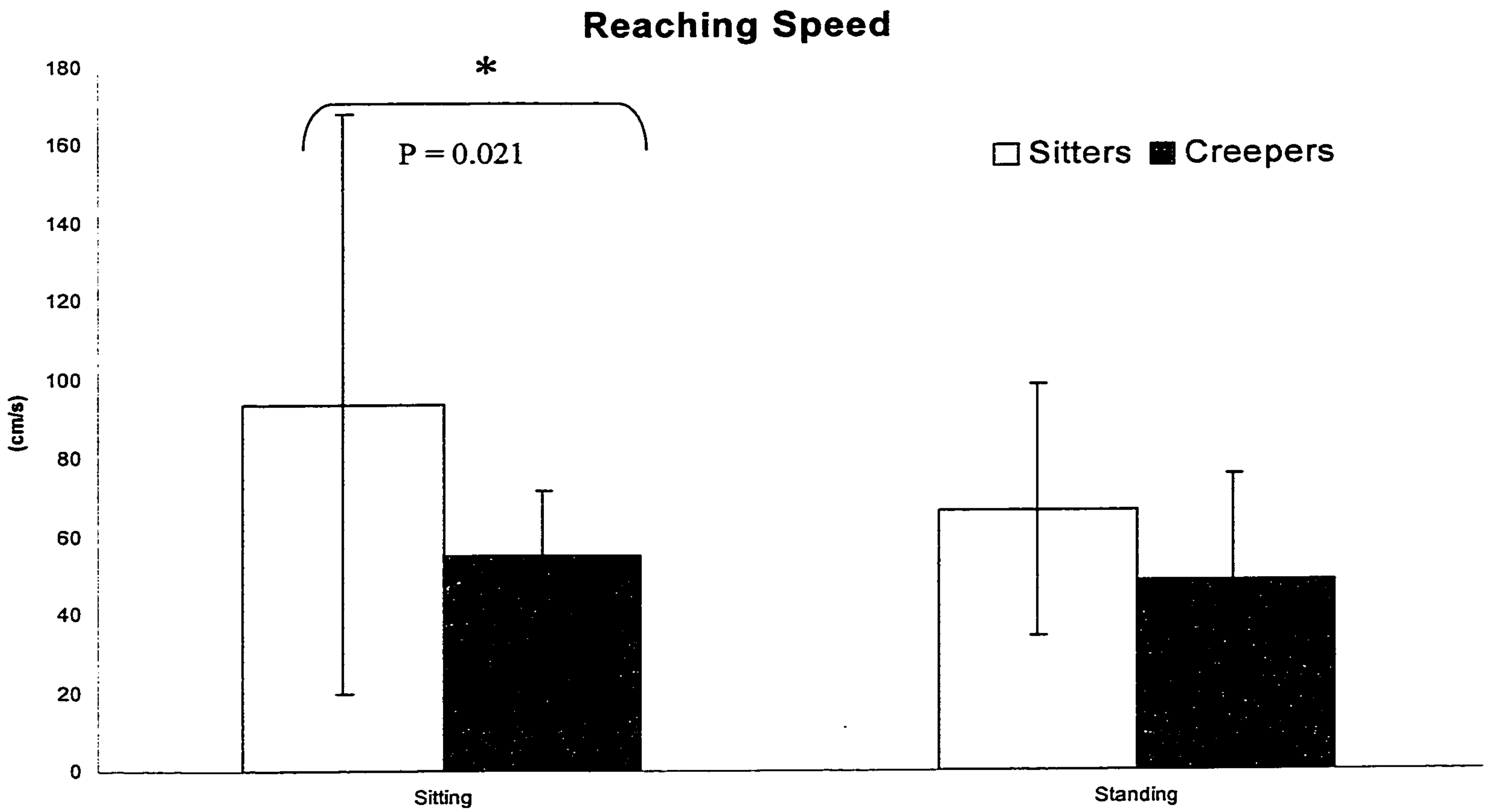
Reaching Speed
*
P = 0.021
Sitters
Creepers
180
160
140
120
100
80
60
40
20
0
(cm/s)
Sitting
Standing

Table 1

Subject characteristics with infants ranked by AIMS score

Infant	Sex	Chronological Age (months)	Corrected Age (months)	AIMS Score	Weight (kg)	Height (cm)
			Sitters			
S1	F	6.77	6.77	29	7.50	68.00
S2	M	7.65	7.65	29	10.00	74.00
S3	M	6.84	5.94	30	8.20	66.50
S4	M	8.29	7.87	31	9.10	70.00
S5	F	6.61	6.97	31	9.80	69.50
S6	F	8.39	8.39	32	7.50	68.00
S7	M	8.43	8.43	32	7.40	69.00
S8	M	6.87	6.1	33	7.30	66.00
S9	F	7.78	7.71	34	7.40	66.50
S10	F	8.13	8.13	34	9.10	69.50
Mean± SD		7.48±0.89	7.40±1.00	31.50±1.84	8.33±1.07	68.70±2.34
			Creepers			
C1	F	10.45	10.74	37	8.60	67.00
C2	F	10.50	10.50	38	8.20	69.00
C3	M	10.87	10.87	42	8.10	73.00
C4	F	10.52	10.32	43	9.70	70.50
C5	M	10.03	9.29	45	8.20	69.50
C6	F	11.10	11.33	47	10.40	70.50
C7	F	11.90	11.70	49	10.40	78.50
C8	M	8.74	8.29	50	11.40	78.00
C9	M	11.33	11.33	52	9.50	73.50
C10	F	10.50	10.27	54	9.00	70.50
Mean± SD		10.59±0.84	10.46±1.02	45.70±5.74	9.35±1.13	72.00±3.78

Note : F = female, M = male. Corrected age refers to the infant's post gestational age, for example infant S4 was born at 38 weeks gestation therefore his chronological age was corrected accordingly. None of the infants had a gestational age less than 36 weeks.

Table 2

Mean ± SD onset latencies for feedforward center of pressure displacement

	Sitters		Creepers	
	Sitting position	Standing position	Sitting position	Standing position
Preparatory	-58.50	-43.67 ± 40.65	-44.75 ± 27.83	------------------
Accompaniment	15.75 ± 8.13	54.50 ± 21.92	47.33 ± 9.45	28.50 ± 16.26
Feedforward	-9.00 ± 43.25	-4.40 ± 61.95	-2.42 ± 42.14	28.50 ± 16.26

Note: no center of pressure displacement was recorded in the preparatory period for the creepers group in standing

CHAPTER III

General Discussion

Outcome of Hypotheses

The results of this research study do not support the first hypothesis. No differences were found in feedforward postural muscle onset latencies between sitters and creepers, in both the sitting and standing positions ($P < .05$). This finding concurs with the results of the longitudinal and training studies on feedback PAs by Sveistrup and Woollacott (1996,1997). In both studies, these authors found no differences in postural muscle onset latencies. Their data on feedback PAs in infants support the idea that developmental changes in postural muscle onset latencies are potentially dependent on maturation processes. Our results on feedforward PAs in infants are not conclusive on the issue of maturity due the small age span included in the study.

Secondly, we hypothesized that the probability of producing feedforward PAs would follow the same trend as feedback PAs. Specifically, that feedforward PAs would not only be present but would occur more often in creepers in the sitting and standing position than sitters.

Wollacott, Debû and Mowatt (1987) examined feedback postural responses in the supported sitting position with infants of less than five months. Although the patterns of feedback postural muscle activity were inconsistent, feedback PAs were still present, although not functional, before the infants had the experience of independently stabilizing their CM over the base of support. Similarly, Hirschfeld and Forssberg (1994) clearly demonstrated that infants aged five months or more produced functional feedback postural responses once they had mastered independent sitting. Two main studies pertaining to feedforward PAs in infants (van der Fits et al. 1999b; Von Hofsten and Woollacott 1989) suggested that consistent activation of postural muscles only occurred after 15 months. However, the authors only considered the preparatory period of feedforward PAs.

Even though we included the accompaniment period of feedforward PAs, the second hypothesis was not supported. Our findings therefore concur with the findings of van der Fits et al. 1999b and Von Hofsten and Woollacott 1989. Creepers did not record higher probabilities of feedforward activation of their postural muscles when compared to sitters. Had the age and/or behavioral range been larger, perhaps increased probability of feedforward postural muscle activity would have been observed.

In the third hypothesis we proposed that patterns of postural muscle activity would be more consistently present in infant creepers when compared to infant sitters. In accordance with von Hofsten and Woollacott (1989) and van der Fits et al. (1999) we found no clear pattern of feedforward postural muscle activity. Again, we feel that a specific look at both preparatory and accompanying feedforward PAs in a larger age and/or behavioral range might have revealed patterns of postural muscle activity. However, our study provided evidence that creepers activated more than one postural muscle in a larger proportion of trials (Chi-square = 8.94 $p < .05$). Even though the third hypothesis was rejected, we suggest that creepers presented early signs of developing feedforward patterns of postural muscle activity, more so than sitters.

What is the link with the systems theory?

This study has shown that infants in the creepers group reached at a slower speed than the infants in the sitters group when tested in the sitting position. Based on the systems theory model, the slower reaching speed results in modification of the task. This ultimately has an impact on the postural adjustments that would be necessary to maintain equilibrium. Specifically, a decreased reaching speed would result in less postural destabilization and would require less postural muscle activity.

The infants were divided post-hoc into sitters and creepers based on skill level. This difference in skill level may be due to developmental changes in the musculoskeletal system, motor strategies or the anthropometry of the infant. Based on systems theory, any of these or other changes may impact the postural adjustment produced.

Limitations of the study

1. The external support provided to most infants in the standing position is a limitation of this study. The amount of external support provided could not be quantified within the context of this study. Therefore the results obtained in the standing position must be carefully interpreted.
2. A second limitation is the number of infants tested in this study. Although the number of participants (n=20) is comparable to that of similar studies in this field (Hadders-Algra et al. 1994; Hirshfeld and Forssberg 1994, Sveistrup and Woollacott 1996; van der Fits et al. 1999b), the results yielded must be interpreted with caution.

Suggestions for Future Research

Two main questions have arisen from this study. What is the developmental course of feedforward PAs ranging from early infancy until the production of adult-like feedforward postural responses? What is the relative importance of maturation versus experience during the development of feedforward PAs?

To answer the first question, a longitudinal study or a cross-sectional study over a broad period, extending well into the independent walking phase, would provide additional information on the evolution of feedforward PAs.

For the second question, a training study is suggested in order to adequately differentiate between the effects of maturation and experience. To control for the effects of maturation, the infants would be exposed to a short duration (for example one week) of PA training program. Comparing changes in pre- and post-training PAs would provide evidence regarding the importance of experience on the development of feedforward PAs.

Conclusion

We hypothesized that infant feedforward PAs would evolve between the sitters and the creepers. Evolution was measured in terms of consistency of postural muscle synergies, probability of feedforward PAs and changes in onset latencies of postural muscle activity and center of pressure displacement. We found little evidence of evolution of feedforward PAs in the population studied, a reasonable outcome in light of the small behavioral and age range chosen. Three main findings on the evolution of feedforward PAs were discussed. First, we suggested that infants initially use tonic postural muscle activity to maintain equilibrium in the sitting and the standing positions. With experience and maturity, creepers showed signs of emerging phasic postural muscle activity in the sitting position. Second, creepers significantly activated more than one postural muscle in a feedforward manner, probably representing the beginnings of feedforward postural muscle synergies. Third, compared to sitters, creepers decreased their reaching speed in the sitting position, which most likely indicated that speed reduction was a feedforward strategy to minimize the self-induced perturbation.

Interestingly, when our results were compared with other studies on feedback PAs in infants, we discovered that feedback and feedforward PAs most likely developed sequentially, with feedback PAs appearing first. Specifically, signs of feedback postural muscle synergies are present prior to the infants' ability to sit or stand independently whereas feedforward postural synergies don't seem to emerge until well after the ability to sit or stand independently.

References (specific to thesis – Chapters I & III)

Aruin, A. S., Latash, M. L. (1995) Direction specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. Exp Brain Res 103:323-332

Assaiante, C., Amblard B. (1996) Visual factors in the child's gait: effects on local motor skills. Percep Mot Skills 83:1019-1041

Assaiante, C. (1998) Development of locomotor balance in healthy children. Neurosci Biobehav Rev 22:527-532

Belen'kii, V. Y., Gurfinkel, V. S., Pal'tsev, Y. I. (1967) Elements of control of voluntary movements. Biophysics 12:154-160

Benvenuti, F., Stanhope, S. J., Thomas, S. L., Panzer, V. P., Hallett, M. (1997) Flexibility of anticipatory postural adjustments revealed by self-paced and reaction-time arm movements. Brain Res 761:59-67

Berthental, B. I., Rose, J. L., Bai, D. L. (1997) Perception-action coupling in the development of visual control of posture. J Exp Psych 23:1631-1642

Bly, L. (1980). The components of normal movement during the first year of life. *In* D. Slaton (Ed.), *Development of Movement in Infancy*, pp. 81-123. University of North Carolina, Chapel Hill.

Bouisset, S., Zattara, M. (1981) A sequence of postural movements preceeds voluntary movement. Neurosci Lett 22:263-270

Forssberg, H., Hirschfeld, H. (1994) Postural adjustments in sitting humans following external perturbations: muscle activity and kinematics. Exp Brain Res 97:515-527

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

Forssberg, H., Wallberg, H. (1980). Infant locomotion: A preliminary movement and electromyographic study. *In* K. Berg and B. Eriksson (Eds.), *Children and exercise IX*, pp. 32-41. University Park Press, Baltimore.

Foster, E. C., Sveistrup, H., Woollacott, M. H. (1996) Transition in visual proprioception: A cross-sectional developmental study of the effect of visual flow on postural control. J Mot Behav 28:101-112

Frank, S. F., Earl, M. (1990) Coordination of posture and movement. Phys Ther 70:855-863

Friedli, W. G., Hallett, M., Simon, S. R. (1984) Postural adjustments associated with rapid voluntary arm movements I. Electromyographic data. J Neurol Neurosurg Psychiatry 47:611-622

Gahéry, Y., Massion, J. (1981) Co-ordination between posture and movement. Trends Neurosci 4:199-202

Goldfield, E. C. (1989) Transition from rocking to crawling: postural constraints on infant movement. Dev Psych 25:913-919

Goldfield, E. C., Michel, G. F. (1986) Spatiotemporal linkage in infant interlimb coordination. Dev Psychobiol19:259-264

Green, E. M., Mulcahy, C. M., Pountney, T. E. (1995) An investigation into the development of early postural control. Dev Med Child Neurol 37:437-448

Gurfinkel, V. H., Ivannenko, Y. P., Levik, Y. S., Babakova, I. A. (1995) Kinesthetic reference for human orthograde posture. Neurosci 68:229-243

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

Hadders-Algra, M., Brogren, E., Apel, I., Forssberg, H. (1994) Development of postural response during sitting in healthy infants: effect of maturation and training. J Physiol 479:32P

Hadders-Algra, M., Brogren, E., Forssberg, H. (1996a) Ontogeny of postural adjustments during sitting in infancy: variation, selection and modulation. J Physiol 493:273-288

Hadders-Algra, M., Brogren, E., Forssberg, H. (1996b) Training effects the development of postural adjustments in sitting infants. J Physiol 493:289-298

Hageman, P. A., Leibowitz, J. M., Blanke, D. (1995) Age and gender effects on postural control measures. Arch Phys Med Rehab 76:961-965

Harbourne, R. T. (1993) A kinematic and electromyographic analysis of the development of sitting posture in infants. Dev Psychobiol 26:51-64

Hirschfeld, E., Forssberg, H. (1994) Epigenetic development of postural response for sitting during infancy. Exp Brain Res 97:528-540

Horak, F. B., Diener, H. C., Nashner, L. M. (1989) Influence of central set on human postural responses. J Neurophysiol 62:841-853

Horak, F. B., Macpherson, J. M. (1996). Postural orientation and equilibrium, *Handbook of Physiology*.

Horak, F. B., Nashner, L. M. (1986) Central programming of postural movements: adaptation to alter support-services configurations. J Neurophysiol 55:1370-1381

Hugon, M., Massion, J., Wiesendanger, H. (1982) Anticipatory postural changes induced by active unloading and comparison with passive unloading in man. Pflügers Arch 393:292-296

Kelso, J. A. S., Schöner, G. (1988) Self-organization of coordinative movement patterns. Hum Mov Sciences 7:27-46

Keshner, E. A., Woollacott, M. H., Debu, B. (1988) Neck, trunk and limb muscle responses during postural perturbation in humans. Exp Brain Res 71:455-466

Kingma, J., Toussaint, H. M., Commissaris, D. A., Hoozemans, M. J., Ober, M. J. (1995) Optimizing the determination of the body center of mass. J Biomech 28:1137-1142

Kokubun, M., Shinmyo, T., Ogita, M., Morita, K., Furuta, M., Haishi, K., Okuzumi, H, Koike, T. (1997) Comparison of postural control of children with Down syndrome and those with other forms of mental retardation. Percep Mot Skills 84:499-504

Larish, D. D., Stelmach, G. E. (1982) Preprogramming, programming and reprogramming of aimed hand movements as a function of age. J Mot Behav 14:322-340

Ledebt, A., Bril, A., Wiener-Vacher, S. (1995) Trunk and head stabilization during the first month of independent walking. Neuroreport 6:1737-1740

Lee, W. A., Buchanan, T. S., Rogers, M. W. (1987) Effects of arm acceleration and behavioral conditions on the organization of postural adjustments during arm flexion. Exp Brain Res 66:257-270

Macpherson, J. M., Fung, J., Jacobs, R. (1997) Postural orientation, equilibrium, and the spinal cord. Adv Neurol 72:227-232

Maki, B., Holliday, P., Fernie, G. (1990) Aging and postural control: a comparison of spontaneous and induced-sway balance tests. J Am Ger Soc38:1-9

Massion, J. (1980) Organisation générale de la motricité. Neurologie- La Revue du Praticien 30:4133-4147

Massion, J. (1994) Postural control system. Cur Opinion in Neurobiol 4:877-887

Massion, J., Gurfinkel, V., Lipshits, M., Obadia, A., Popov, K. (1992) Stratégie: deux niveau de contrôle de l'équilibre au cours du mouvement. Effets de la microgravité. C.R. Acad. Sci. Paris 314 (série III):87-92

McGregor, J. (2000) Feedforward postural control development associated with unilateral rapid arm motion in children aged 4- to 5- years and 10- to 11- years. Master's thesis, University of Ottawa

Mouchnino, L., Aurenty, R., Massion, J., Pedotti, A. (1992) Coordination between equilibrium and head-trunk orientation during leg movement: a new strategy build up by training. J Neurophysiol 67:1587-1598

Nashner, L. M. (1976) Adapting reflexes controlling the human posture. Exp Brain Res 26:59-72

O'Sullivan, S. B. (1988). Strategies to improve motor control. *In* S. B. O'Sullivan and T. J. Schmitz (Eds.), *Physical rehabilitation: assessment and treatment*, pp. 253-280. F.A. Davis Company, Philadelphia.

Pai, Y. C., Patton, J. (1997) Center of mass velocity-position predictions for balance control. J Biomech 30:347-354

Portfors-Yeomans, C. V., Riach, C. L. (1995) Frequency characteristics of postural control of children with and without visual impairment. Dev Med Child Neurol 37:456-463

Prochazka, A., Gillard, D., Bennett, D. J. (1997) Positive force feedback control of muscles. J Neurophysiol 77:3226-3236

Riach, C. L.,Hayes, K. C. (1987) Maturation of postural sway in young children. Dev Med Child Neurol 29:650-658

Riach, C. L., Hayes, K. C. (1990) Anticipatory postural control in children. J Mot Behav 22:250-266

Saltzman, E. L., Munhall, K. G. (1992) Skilled acquisition and development: the roles of state-,parameter-, and graph- dynamics. J Mot Behav 24:49-57

Schöner, G., Zanone, P. G., Kelso, J. A. S. (1992) Learning as change of coordination dynamics: theory and experiment. J Mot Behav 24:29-48

Sears, T. A. (1971) Breathing: A sensory-motor act. Science Basis & Medical Annual Review 48:129-147

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

Shumway-Cook, A., Woollacott, M. H. (1995). Motor Control: Theory and practical applications,Vol. Williams & Wilkins, Baltimore

Sveistrup, H., Wollacott, M. H. (1997) Practice modifies the developing postural response. Exp Brain Res 114:33-43

Sveistrup, H., Woollacott, M. H. (1996) Longitudinal development of the automatic postural response in infants. J Mot Behav 28:58-70

Thelen, E. (1995) Origins of origins of motor control. Behav Brain Sci 18:780-783

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P. (1993) The transition to reaching: mapping intention and intrinsic dynamics. Child Development 64:1058-1098

Thelen, E., Spencer, J. P. (1998) Postural control during reaching in young infants: a dynamic systems approach. Neurosci Biobehav Rev 22:507-514

van der Fits, I. B., Klip, A. W., van Eykern, L. A., Hadders-Algra, M. (1999a) Postural adjustments during spontaneous and goal-directed arm movements in the first half year of life. Behav Brain Res 106:75-90 van der Fits, I. B. M., Klip, A. W. J., Van Eykern, L. A., Hadders-Algra, M. (1998) Postural adjustments accompanying fast pointing movements in standing, sitting and lying adults. Exp Brain Res 120:202-216

van der Fits, I. B. M., Otten, E., Klip, A. W. J., Van Eykern, L. A., Hadders-Algra, M. (1999b) The development of postural adjustments during reaching in 6- to 18-month-old infants. Exp Brain Res 126:517-528

von Euler, C. (1981). Some aspects on speech breathing physiology. *In* S. Grillner, A. Person, B. Lindblom, and J. Lubker (Eds.), *The motor control of speech*, pp. 545-552. Pergamon Press, New York.

Von Hofsten, C., Woollacott, M. (1989) Anticipatory postural adjustments during infant reaching. Soc Neurosci Abstr 15:1199

Woollacott, M., Debû, B., Mowatt, M. (1987) Neuromuscular control of posture in the infant and child: is vision dominant? J Mot Behav 19:167-186

Woollacott, M. H., Sveistrup, H. (1994). The development of sensorimotor integration underlying posture control in infants during the transition to independent stance. *In* S. P. Swinnem, J. Massion, and H. Heuer (Eds.), *Interlimb coordination: neural, dynamical and cognitive constraints*, pp. 371-389. Academic Press, San Diego.

Zanone, P. G., Kelso, J. A. S. (1992) Evolution of behavioral attractors with learning: non equilibrium phase transitions. J Exp Psych 18:403-421

Appendix I

Figures

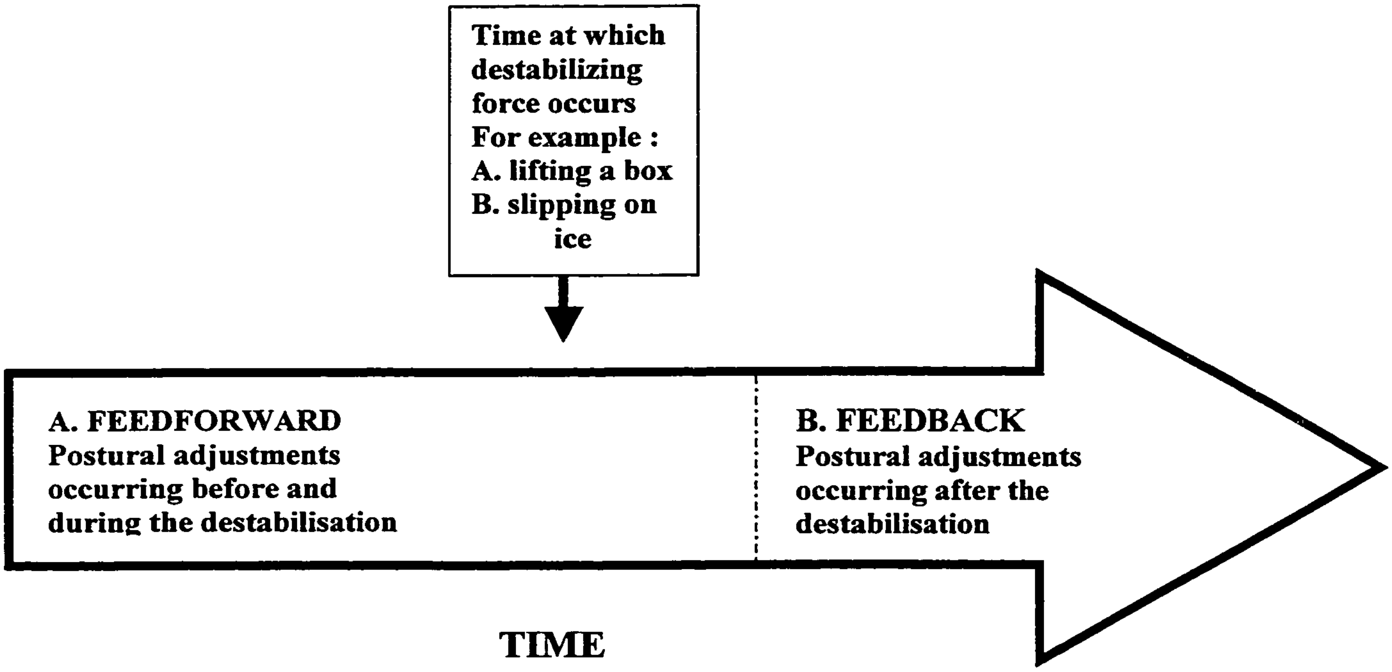

Figure I. Relative timing of feedforward and feedback postural adjustments.

A. When a person performs a voluntary movement, feedforward postural adjustments are used in an anticipatory manner to steady the execution of the movement. For example, when lifting a box, activity of the postural muscles (legs and trunk) may be recorded as early as 100ms before activity of the muscles that would be used to perform the lift (arm).

B. When a person's equilibrium is disturbed unexpectedly, such as slipping on ice, feedback postural mechanisms are used to regain equilibrium. Activity of the postural muscles (legs and trunk) is recorded approximately 80ms to 100ms or more following the unexpected loss of equilibrium.

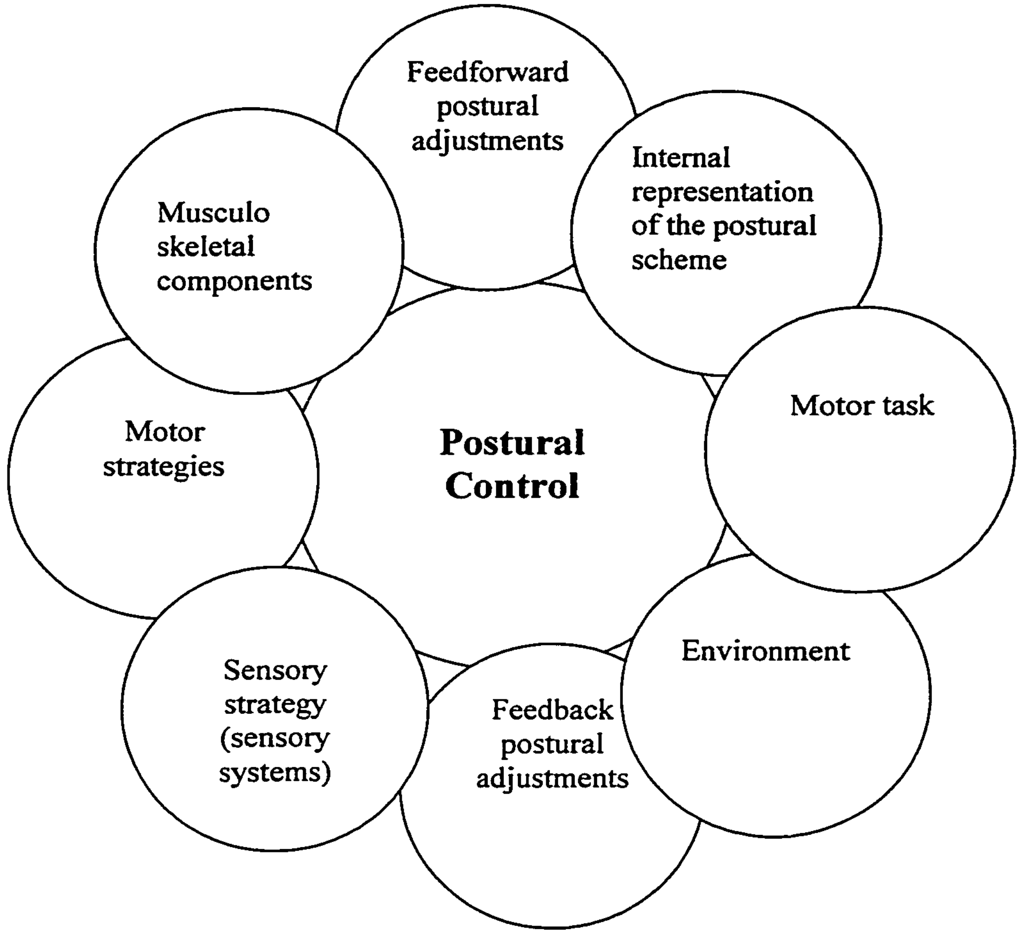

Figure II. Conceptual model representing the systems and components contributing to postural control.

According to this model, each system plays a role in the production of postural adjustments (PA). For example, the sensory systems help to activate and calibrate central pattern generators; the expressed synergies dictate the quality of the PAs; the musculoskeletal system determines whether the individual is capable of completing a PAs; the internal representation of the postural scheme helps with PA precision; the motor task triggers the appropriate type of PAs; the environment, such as an icy surface, can increase the level of difficulty to adapt; and finally, an expected or unexpected perturbation will impact on the type of PAs required. Adapted from Shumway-Cook and Woollacott (1995).

(a)

(b)

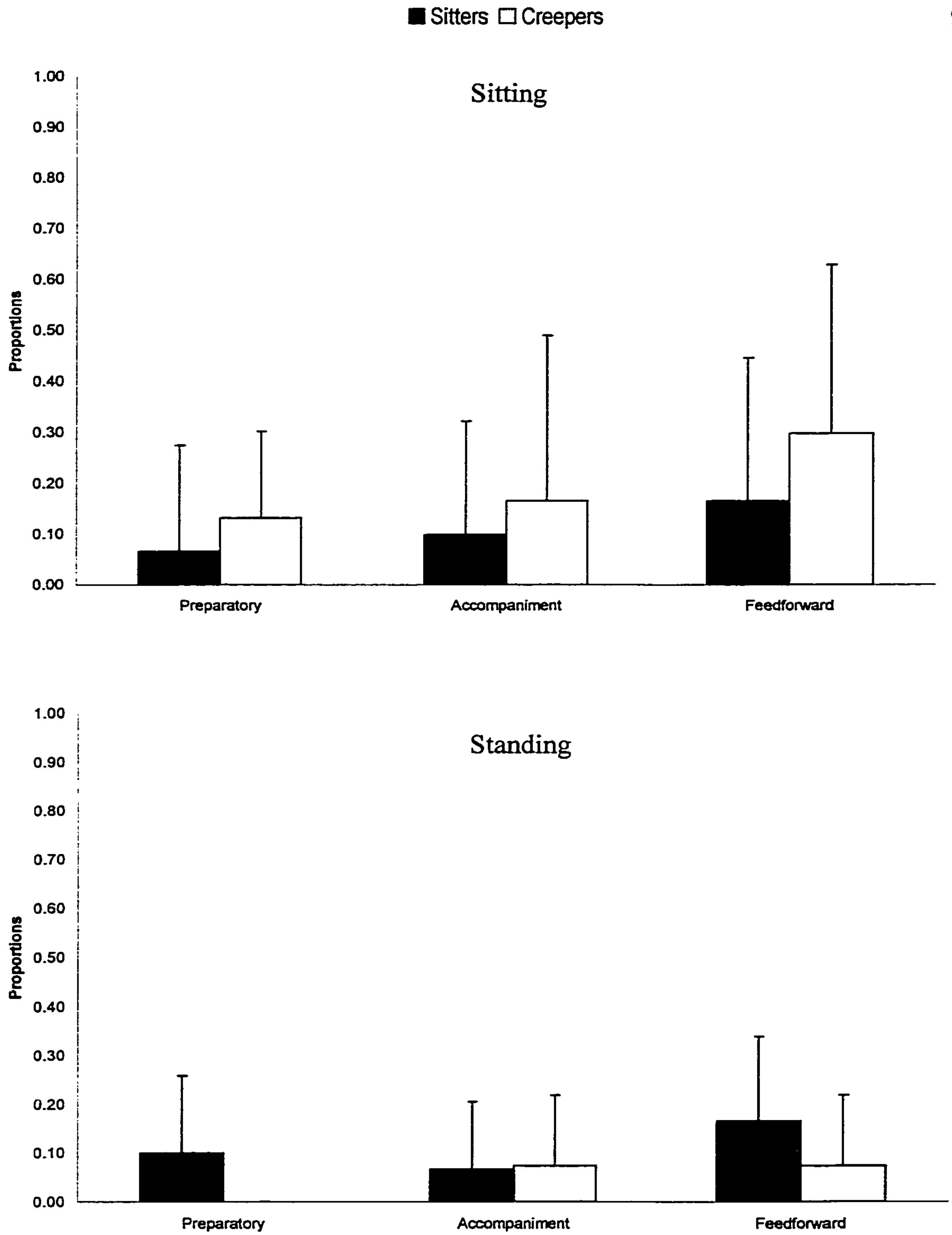

Figure III: Proportions of trials with a center of pressure displacement in the feedforward window were recorded for both behavioral groups in the sitting and standing positions. Values represent group means $\pm$ SD and have been separated into the preparatory period, the accompaniment period and the feedforward period.

(a) The differences in proportions of trials with center of pressure displacement between both behavioral groups were not statistically significant.

(b) Center of pressure displacement occurred only in small proportion of trials. Minimal differences between both behavioral groups can be observed with the exception of the preparatory period. It is important to note that infants were provided with external support by their parent during data acquisition.

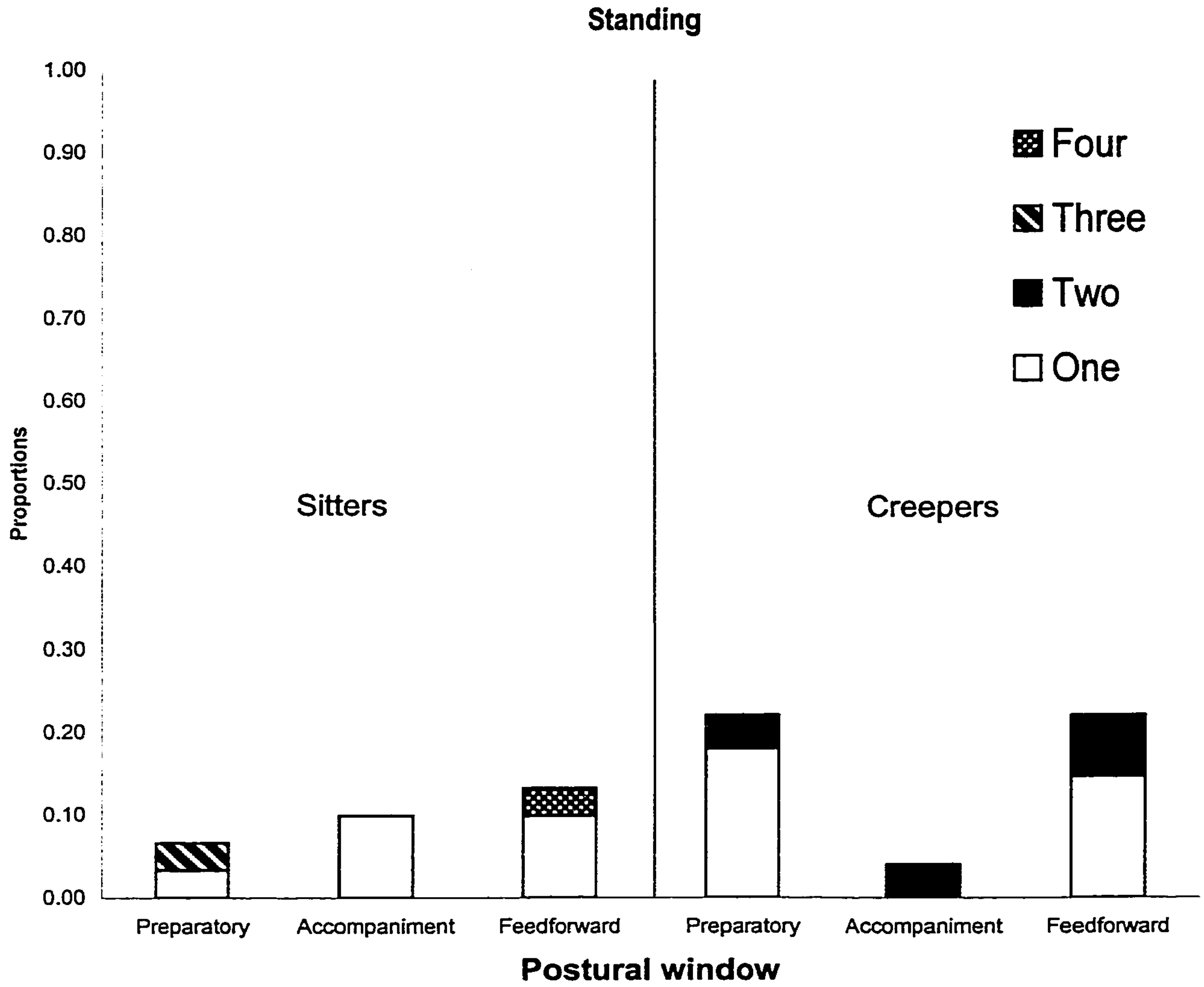

Figure IV : Proportions of trials with feedforward postural muscle activity recorded in one, two, three or four, postural muscles for both behavioral groups in the standing position. Values represent group means + SD and have been separated into the preparatory period, the accompaniment period, and the feedforward period. A very small proportion of trials showed postural muscle activity for both behavioral groups. There were no statistically significant differences between groups.

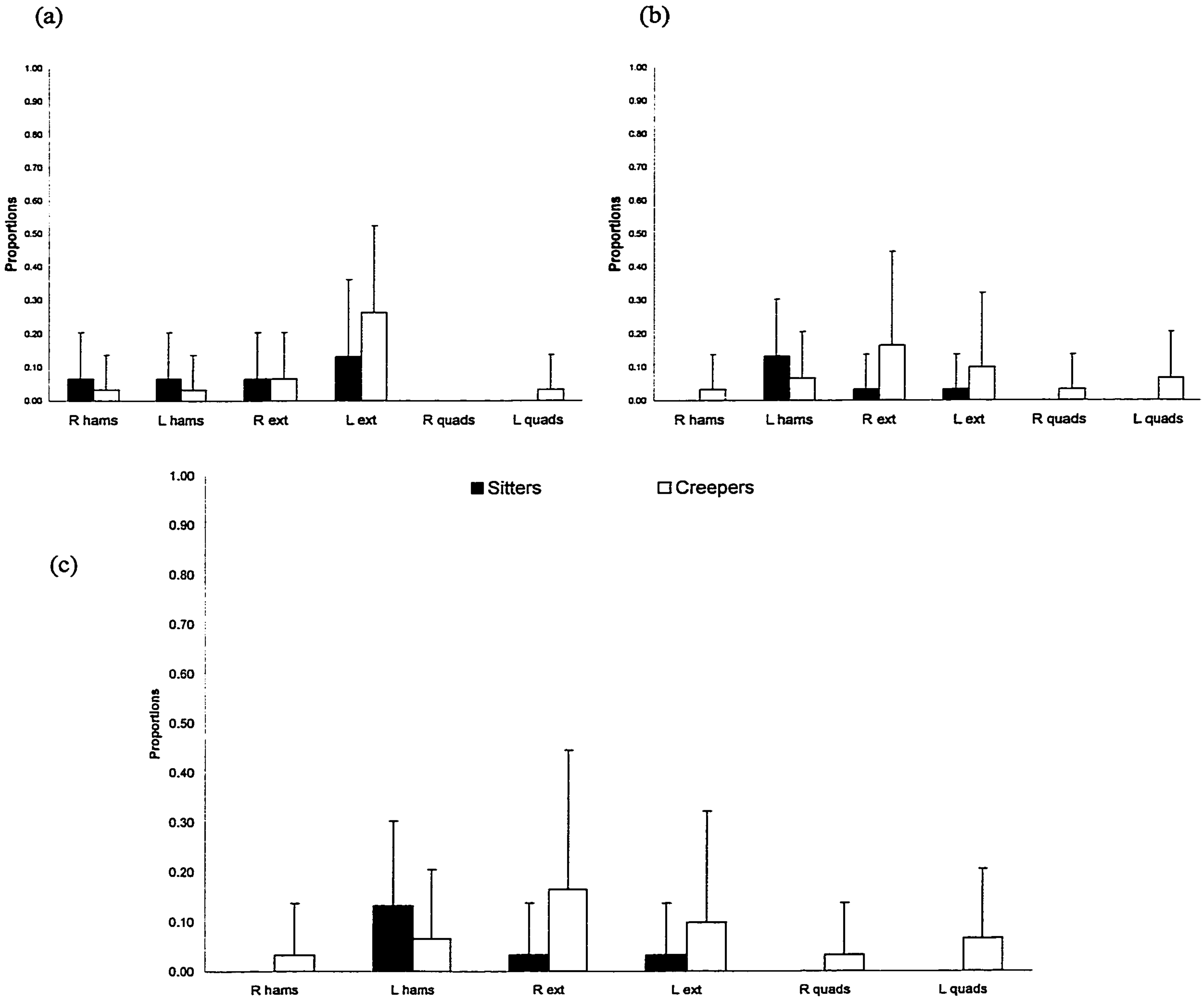

Figure V: Proportions of trials with specific feedforward postural muscle activity in the sitting position. Values represent group means ± SD and have been separated into the (a) preparatory period, (b) the accompaniment period and (c) the feedforward period. There were no statistically significant differences in the proportions of trials with specific feedforward postural muscle activity in the siting position between groups.

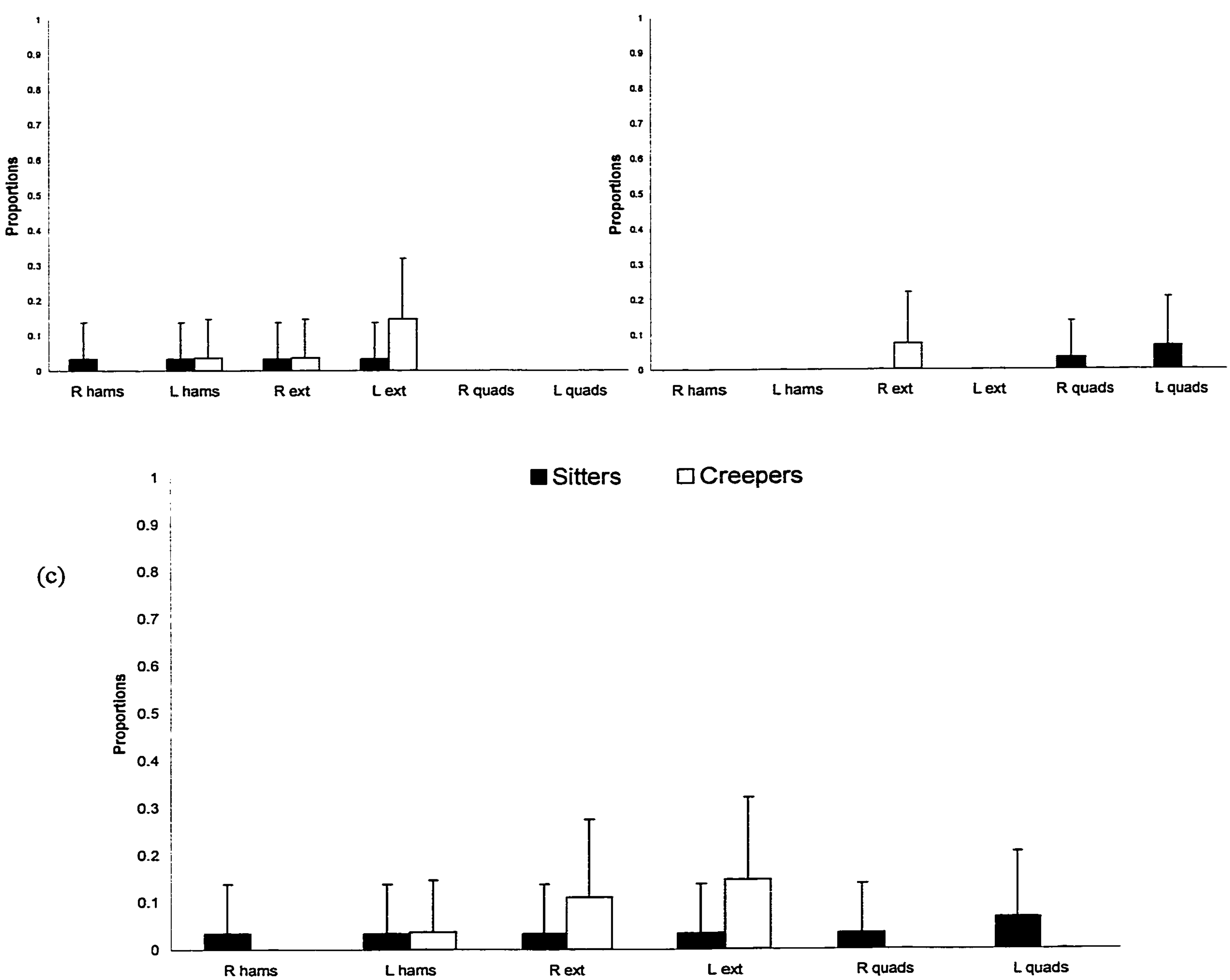

Figure VI: Proportions of trials with specific feedforward postural muscle activity in the standing position. Values represent group means ± SD and have been separated into the (a) preparatory period, (b) the accompaniment period and (c) the feedforward period. Specific postural muscle activity was only recorded in a small proportion of trials. There were no statistically significant differences in the proportions of trials with specific feedforward postural muscle activity in the standing position between groups.

Appendix II

Statement of Contribution of Collaborators

This study is a continuation of a series of ongoing studies at the University of Ottawa motor control research laboratory. Under the supervision of Dr. Heidi Sveistrup of the School of Rehabilitation Sciences, I assumed primary responsibility for recruiting the infant subjects, collecting the data with a laboratory assistant, coding and processing of the data, analyzing the data and producing this manuscript.

Université d'Ottawa • University of Ottawa

Faculté des sciences de la santé
Cabinet de la doyenne

Faculty of Health Sciences
Office of the Dean

Appendix III

le 5 février 1999

Étudiante Lynn Casimiro
Professeure Heidi Sveistrup
Sciences de la réadaptation
Intra

Objet : **Le projet intitulé - - *"Anticipatory Postural Adjustments Produced by Infants and Young Adults in the Sitting and Standing Positions"***

Chères professeure et étudiante,

Je suis heureux de vous annoncer que le *Comité d'éthique en recherche chez l'humain de la Faculté des sciences de la santé (CÉRCH)* a jugé que le projet en titre est conforme aux exigences éthiques de l'Université et est approuvé sous la **CATÉGORIE 1A**.

Vous trouverez ci-joint la copie du certificat du Comité de déontologie vous autorisant à poursuivre ce projet.

L'autorisation du Comité est valide pour une durée d'un an, à compter de la date de la signature du rapport. J'aimerais aussi vous rappeler que, conformément aux règlements internes du CÉRCH, vous devez aviser le Comité de toute modification importante au projet.

Veuillez agréer, chère professeure, chère étudiante, tous nos voeux de succès dans la conduite de votre projet.

Le président du Comité,

J. Roger Proulx, Ph.D.

451, ch. Smyth
Ottawa (Ontario) K1H 8M5 Canada

451 Smyth Rd.
Ottawa, Ontario K1H 8M5 Canada

(613) 562-5432 • Téléc./Fax (613) 562-5437

Université d'Ottawa • University of Ottawa

Faculté des sciences de la santé
Cabinet de la doyenne

Faculty of Health Sciences
Office of the Dean

CERTIFICATION INSTITUTIONNELLE DU COMITÉ D'ÉTHIQUE EN RECHERCHE CHEZ L'HUMAIN
FACULTÉ DES SCIENCES DE LA SANTÉ

Le Comité d'éthique en recherche chez l'humain de la Faculté des sciences de la santé, mandaté à cette fin par l'Université d'Ottawa certifie avoir étudié le projet soumis par **la professeure Heidi Sveistrup et étudiante Lynn Casimiro de l'École des sciences de la réadaptation** pour le projet intitulé ***"Anticipatory Postural Adjustments Produced by Infants and Young Adults in the Sitting and Standing Positions".***

Le comité confirme que ce projet répond entièrement aux normes déontologiques à un niveau de **Catégorie 1A.**

COMPOSITION DU COMITÉ

Nom (Optionnel)	Poste occupé	Département ou discipline
Victor Boucher	Professeur	Programme d'audiologie et d'orthophonie
Claire-Jehanne Dubouloz	Professeure	Programme d'ergothérapie
Roch Paquin	Membre affilié	
J. Roger Proulx	Président	Comité de déontologie
Jocelyne Tourigny	Professeure	École des sciences infirmières
François Tremblay	Professeur	Programme de physiothérapie
Nicole Denis	Étudiante	École des sciences infirmières
Pierre Boudreau	Professeur	Faculté d'éducation

SIGNATURE

Date **Président du comité de déontologie - J. Roger Proulx, Ph.D.**

451, ch. Smyth
Ottawa (Ontario) K1H 8M5 Canada

451 Smyth Rd.
Ottawa, Ontario K1H 8M5 Canada

(613) 562-5432 • Téléc./Fax (613) 562-5437