# DEVELOPMENTAL CHANGES IN POSTURAL CONTROL DURING STANDING: EVALUATION OF BALANCE REACTION TO PLATFORM TRANSLATIONS AND ROTATIONS IN CHILDREN FROM 2 TO 8 YEARS OF AGE AND IN ADULTS

*by BJORG FALLANG*

**A THESIS**
Presented to the Faculty of Graduate Studies
In Partial Fulfilment of the Requirements
for the Degree of
Master of Physical Therapy

**MASTER OF PHYSICAL THERAPY**

Faculty of Medicine
School of Medical Rehabilitation
Division of Physical Therapy
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# DEVELOPMENTAL CHANGES IN POSTURAL CONTROL DURING STANDING: EVALUATION OF BALANCE REACTION TO PLATFORM TRANSLATIONS AND ROTATIONS IN CHILDREN FROM 2 TO 8 YEARS OF AGE AND IN ADULTS


BY

BJORG FALLANG


A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF PHYSICAL THERAPY

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## ACKNOWLEDGEMENTS

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ABD | Musculus Abdominals |
| AD | Adult |
| A/D | Analog/Digital signals |
| ANOVA | Analysis of Variance |
| A-P | Anterior Posterior direction |
| AV | Peak Active CFP Velocity |
| BT | Backward platform Translation |
| CFP | Center of Foot Pressure |
| CNS | Central Nervous System |
| C1 | Age group 3 years to 4 years 10 months |
| C2 | Age group 5 years to 6 years 8 months |
| C3 | Age group 7 years 6 months 8 years 7 months |
| D/A | Digital/Analog signals |
| Deg | Degree |
| EMG | Electro Myography |
| FT | Forward platform Translation |
| GA | Musculus Gastrocnemius |
| GT | Greater Trochanter |
| HAM | Musculus Hamstrings |
| H-T | Hip-Trunk |
| M-L | Medio Lateral direction |
| PV | Peak Passive CFP Velocity |
| P1 | Age group 19-31 months |
| QUAD | Musculus Quadriceps |
| R | Platform Rotation |
| SD | Standard Deviation (statistics) |
| SEM | Standard Error of Mean (statistics) |
| SPIN | Musculus Erector Spine |
| TA | Musculus Tibialis Anterior |
| TCM | Body's Total Center of Mass |
| TP | Time to Peak CFP displacement |
| TRE | Time to Reach Equilibrium |
| V1, V2, V3 | Velocity 1, 2, 3 |

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# *CHAPTER 1 - INTRODUCTION*

The term motor control encompasses many different aspects of nervous system function, such as, movements, postures, the organization of sensory information, segmental reflex mechanisms and the functions of mind and body that govern posture and movement (Brooks 86). During infancy, childhood and thereafter, individuals learn by practice to sit, stand, and walk. This motor learning is not directed at the control of single muscles but instead concerns the choice and timing of many muscles. The complex timing and control of functional combinations of muscles that act to stabilize and move multiple body segments in a coordinated and goal directed fashion form the basis for our understanding of motor control. How motor function can be improved, is relevant to all studies of work, sports and activities of daily living. To the different health professions working within neurological rehabilitation, how to improve impaired performance is of fundamental concern. This applies also to the rehabilitation of children with neurological disorders. But in order to evaluate and understand pathological motor behaviour in children, knowledge about normal development of motor control and how it is organized must be expanded.

One important component of motor control is postural stability. The control of human posture or balance is a complex motor behaviour in which the involvement of at least 3 neural subsystems has been identified, each of which is responsible for a specific process. These are:

1) Sensory receptor systems which provide information regarding body orientation and motion to the central nervous system (CNS).

2) Those components of the CNS responsible for sensory organization, the calibration and integration of sensory information related to spatial orientation and

motion with respect to the environment.

3) The motor centers responsible for the selection and coordination of task specific balance reactions.

The ability to maintain and regain postural equilibrium is prerequisite to further development of motor capabilities and skills, and in this regard is an important component of child development (Levitt 77, Vojta 81, rev. Reed 89). The early stages of postural development have been widely investigated, but most research studies have been of the time correlations between the emergence of different levels of stability in prone, supine, kneeling, sitting and quiet standing, considering these as "milestones", as a part of the assessment of development. Here, the lack of stability or balance may be both an indicator of motor developmental stage or maturation and may lead to functional impairment. Little work has been done in the study of the developmental aspects of postural control in the standing position. It is important to examine the nature of balance reactions in standing as a function of maturation and age to acquire further insight into the underlying muscular coordination and sensory organization in posture and movement.

This study is intended to analyze movement strategies employed during balance reactions following controlled disturbances of standing balance in children of different age groups and compare the strategies to those of adults. The purpose of the study was to evaluate developmental changes and expand knowledge about motor strategies involved in regulation of standing balance, by studying muscle activation patterns in lower extremities, linear and angular motion of the body segments and the displacement of the center of foot pressure.

# *CHAPTER 2 - LITERATURE REVIEW*

## 1. MOTOR DEVELOPMENT - GENERAL CONSIDERATIONS

Studies of motor development in children have largely focused on descriptions of temporal aspects of the development of primitive reflexes, motor skills, and some qualitative characterizations of movements. One of the early pioneers in the identification and formulation of motor development scales was Arnold Gesell, an American psychologist and pediatrician. He used slow motion film to characterize the movements of normal children (Gesell and Amatruda 54). The British psychologist Ruth Griffiths (1976), developed a new scale including modified test items from Gesell & Amatruda (1954). Based on observations (some of them longitudinal) of English infants and extensive testing of items, she developed a more differentiated scale, still established on "milestones". This is still widely used in diagnosing mental and motor deviations by psychologists in Europe.

Milani-Comparetti from Italy, Bobath from England, and Vojta from Czechoslovakia, are among those who have contributed to a more detailed description of motor development based on their own observations of infants and children. The evaluation of spontaneous motor patterns, implicit reflexes and postural reactions, is used as the foundation for diagnosing neurological dysfunctions in infants and children (Bobath 66, Griffiths 76, Milani-Comparetti and Gidoni 67,77, Hellbrügge 78,80, Vojta 81).

In the developing child, maintaining and regaining of balance in an unsupported weight-bearing position is considered to be critical for further development of motor skills (Levitt 77, Vojta 81, rev. Reed 89). The relationship between body position and stability with respect to gravity is already within the experience of infants before standing. Holding the head up and sitting, both have preferred positions and require postural control. As the child matures, it learns to stabilize itself in more upright postures requiring the simultaneous control of more body segments with a reduction in the size of the base of support, i.e. laying on back to sitting and then to standing. This requires more advanced levels of sensory organization and motor control.

In a child with a neurological disorder, this basic skill of postural control is usually disturbed, which may restrain and disturb further development and acquisition of new skills (Levitt 77, Vojta 81, rev. Reed 89). An unstable sitting position, often seen in children with central disorders, will have a negative influence on the quality of grasping or precision of reaching. The Bobath concept of postural deficits in children with cerebral palsy states that spasticity increases when balance is disturbed and makes the movement pattern even more pathological (Bobath and Bobath 76,86). It is therefore of fundamental importance when examining motor development in healthy children or children with neurological dysfunction, also to evaluate the evolution and current status of postural control. Studies of how movement and balance is controlled in cerebral palsy are slowly emerging (Nashner et al. 83, Berger et al. 85), and give prospects about gaining more specific information about the nature of postural control, its developmental profile, and the impact of neural damage on dysfunction.

The study of the nature of postural control in normal development will form the basis for the interpretation of pathological conditions.

# 2. CONCEPT OF POSTURAL CONTROL

## 2.1. EQUILIBRIUM

Postural control is a multi-dimensional task where the nervous system must insure a specific relationship between the center of body mass and the base of support. The human body consists of a number of segments (head, trunk, thigh, leg, foot, arm, forearm and hand) held together at respective articulated joints. In standing, the stability of this multi-link system is dependent upon generating moments about the joints by contraction of muscles to counter the weight and reaction forces about each body segment. To achieve or insure balance, the postural control system will try to keep or return the body's center of mass over the base of support. To achieve the aim of restoring balance, the postural control system will minimize body sway and maintain the center of body mass within the base of support. When the body's spatial orientation is changed, such as, during voluntary movement of any body segment or due to external disturbances, balance adjustments or reactions are required to restore postural equilibrium. Furthermore, the postural control system must accommodate for changes in configuration of the support surface. Taking the properties of the support system into account further increases the complexity of the postural mechanism. A compliant, uneven or slippery surface will alter the relationship among muscular, gravitational, and ground reaction forces.

## 2.2. SENSORY SYSTEMS

During the regulation of balance, information about body orientation is provided by visual, vestibular and somatosensory (proprioceptive and exteroceptive) input. They identify the amount and direction of motion of body segments, the relative location and characteristics of the support surface and direction of gravitational acceleration. Based on this sensory information, integrative centers within the nervous system determine an appropriate postural response which rapidly and efficiently adjusts the subject's center of body mass with respect to the base of support so that the vertical projection of the center of mass lies within the base of support. Although it should be noted that a person may be relatively safe from falling or losing their balance even though these conditions do not exist, such as during walking.

Each of these sensory channels has a unique frame of reference and thus provides different types of orientation and motion information. The vestibular receptors have the only fixed frame of reference (gravity-inertial), detecting head position relative to the gravity vector. Under normal conditions, vestibular input is always available. All other sources of information have significant restrictions or limitations in that they do not have fixed frames of reference, but certainly they have many properties which the vestibular system does not have. As an example of limitation; the vision is of no help in the dark. Also, vision provides relatively little information about motion between the individual and the environment. Thus the CNS may interpret motion of the visual surround as if it resulted from movement of self and vice versa. (Example: when sitting in a train which is moving parallel to another train, it is difficult to tell by relying on vision which train is moving; the one in which the individual is sitting or the other).

The proprioceptive components of the somatosensory system (muscle spindles, golgi tendon organs and joint afferents) provide information about the relative position of body segments to one another but not the environment (gravity vector or the support surface). Although the exteroceptive component of the somatosensory system can indicate the location of the support surface and the distribution of foot pressure, tactile information can vary depending on the support surface characteristics (level ground, irregular ground, slippery or compliant ground).

# 3. ORGANIZATION OF SENSORY INFORMATION IN POSTURAL CONTROL

## 3.1. ADULT STUDIES

A number of investigators has examined the relative contribution and sensory organization of the three sources of orientational information in the regulation of standing balance (Nashner 76, Lestienne et al. 77, Soechting 77, Nashner et al 78,82, Black et al. 83, 88, Diener et al.84b, Diener et al. 86, Allum et al. 89). Methods have been devised (Nashner 76, Black et al. 83) to manipulate individual sensory inputs while examining balance performance of healthy subjects and patients with absent or reduced vestibular function. Subjects were instructed to maintain a quiet, erect standing position while being exposed to a variety of altered somatosensory and visual conditions. These sensory conditions included: eyes open and closed conditions, normal support surface conditions, and sway "stabilized" support surface and visual conditions.

The sway stabilized support surface condition was achieved by rotating a support platform in direct proportion to the amount of anterior-posterior (A-P) body sway of the subject. Thus, as the subject swayed and the center of mass was displaced, this procedure minimized the rotation that would occur about the ankle joints. The consequence is misleading or inappropriate sensory information from the proprioceptive component of the somatosensory system. This has been termed a sensory conflict situation.

In a similar fashion, the sway stabilized visual condition was achieved by rotating the visual surround in direct proportion to body sway of the subject. Unlike the eyes closed condition, where no visual information is available, the sway stabilized visual condition results in no movement between the body and visual surround. Thus, the visual information is informing the CNS that the body is not swaying. This also leads to misleading or conflicting orientation inputs regarding actual body motion. To estimate body sway, hip horizontal displacement with respect to the ankles was recorded. This was achieved by means of a platform-mounted potentiometer at ankle angle level attached to a light rod about the hips.

These studies have demonstrated:

1) That under normal support surface conditions, patients with absent or reduced vestibular function were able to maintain standing balance with eyes open and eyes closed condition. It was concluded that under these conditions the CNS can function with sensory information derived from the peripheral somatosensory system (muscle spindles, tendon organs, tactile, pressure and/or joint receptors).

2) That healthy subjects could maintain a stable position during the stabilized visual and/or support surface conditions, whereas for patients with absent or reduced vestibular function, A-P body sway significantly increased and they

frequently fell. The degree of postural instability was roughly proportional to the degree of vestibular deficit. In regards to the sensory organization of orientation inputs, it was concluded that loss of an absolute spatial reference normally provided by vestibular inputs, interferes with the resolution of conflicting sensory inputs.

## 3.2. CHILDREN STUDIES

### 3.2.1. SOMATOSENSORY REFLEXES

Bawa (1981) examined stretch evoked EMG responses in wrist flexor muscles of 54 normal children between the ages of 2 and 13 years. The subjects were seated with the forearm resting on a platform holding a handle attached to a precision torque motor. A step load range of 0.2-1.0 kg with a duration between 100 and 400 msec was imposed to rotate the wrist. The angular displacement of the wrist was measured by a potentiometer, but amplitude and velocity of the displacement was not reported. EMG onset latency and duration were determined. Background EMG activity was estimated and duration was defined visually as distance between start and end of the long latency response. The documentation of some of the results, like the comparisons of onset latency between ages, was unclear, but the results demonstrated the presence of proprioceptive mediated muscle responses (reflexes) in all age groups (onset 40-60 ms). The results indicated that all children below 6 years showed longer duration of this long latency component than older children. The relevance of this information according to the regulation of postural control is to demonstrate the presence and form of automatic EMG responses to somatosensory input in the young child.

To investigate these latency responses in an experiment with more functional significance to postural control, Haas et al. (1986) studied the occurrence and latency changes in the lower extremity to a sudden stretch of the ankle plantarflexors produced by toes-up platform rotations in 56 children between 14 months and 15 years of age. Amplitude of rotation was 4° at a peak angular velocity of 50°/s. EMG recordings were obtained from tibialis anterior (TA) and medial gastrocnemius (GA) and the latencies were visually identified on computer stored traces. The criteria for separation into short and medium latencies was not provided. The term," short" and "medium" latencies, were applied to the EMG responses in GA while the term, long latency response, was applied to the TA muscle response. Based on onset latency, the short latency response represents the segmental stretch reflex and the longer latency response in both studies (Bawa 81, Haas 86) refers to the functional response according to direction of movement. Center of foot pressure (CFP) was recorded and showed that all the children were able to compensate for the imposed perturbation in the sense that they did not lose balance or take a step.

Short, medium and long latency responses were identified in all children in the muscles as described above. The short latency values in GA were in the range between 37 ms in the youngest and 41 ms in the oldest. In adults, the onset latency in GA in response to toes-up rotation has been found to be 42-65 ms (Diener et al.84a, Nardone et al.90). When the latency values were normalized for height, the results of a linear regression analysis showed a slight decrease in onset latency of the earliest EMG component in GA from 14 months to 5 years of age, with no change thereafter. The medium latency response in GA did not show significant change in the range between 1 and 15 years, e.g: 1-3 year olds had 85 ms SD ± 14 and 10-15 year olds had 86 ms SD ± 16 (adult values were 108-123 ms, Diener et al.84). When latencies were normalized for height, there was a decrease from 100 ms/m in the 1 year old to 60 ms/m in the 15 year old. Thus, this time difference indicated a different time course of maturational changes than the short latency response. In regard to the long latency TA muscle responses, the differences in mean onset values between ages were large (204 ms SD ± 27 in the 1-3 year old group and 136 ms SD ± 18 in the 10-15 years, adult values 130-148 ms, ref. Diener 84, Nardone 90). When normalized for height the differences were even more substantial; in the youngest age group the latency values were 250 ms/m and ranged to 80 ms/m in the 10 - 15 year olds. Also, a continuous decrease in mean onset of the long latency component was seen until the age of 15 years.

### 3.2.2. VESTIBULAR REFLEXES

The vestibular system has impact on eye-head coordination, perception of body position and postural control. In order to prove the emergence or presence of vestibular function in infants, one must measure reflexive horizontal eye-movements (nystagmus) which occur when the horizontal semi-circular canals are stimulated. The vestibular-ocular reflex. This is achieved by either horizontal head-rotation or by infusion of hot or cold water into the external auditory canal (caloric tests), (Mitchell and Cambon 69, rev. by Ornitz 83). It has been observed that vestibular responsiveness is present already at birth and changes through a maturational sequence during childhood and adolescence. (Ornitz 83, Kaga et al. 81). It should be noted that the emergence of vestibular reflexes related to eye-head coordination may be quite separate from the role of vestibular system in postural control.

Kaga et al. (1981) assessed vestibular responses in relation to eye-head coordination by means of the damped-rotation test. The children were seated on their mother's lap in a rotation chair and horizontal eye-movements were recorded. Responses were recorded according to duration and number of beats of per rotatory nystagmus. Both increased with age, at the most during the first year of life with less change from 6 years on. No clinical tests are available to confirm the function of the vertical semi-circular canals and otolith end organs. But concerning the presence of this sensory system it must be presumed that it is operating in the young child, although not at a mature level (see 3.2.4 Sensory conflict). However, as described above in section 3.1, vestibular inputs play an important role in the control of standing balance. (See also section 3.2.4 on Sensory conflict). The fact that the vestibular reflexes undergo the greatest change in the first year of life parallels the intensive ongoing development of posture during this period of life.

### 3.2.3. VISUALLY MEDIATED RESPONSE

It has been demonstrated that visual inputs have influence on postural control in children even before they are able to stand (Butterworth and Hicks 77). Lee and Aronson (1974) showed that vision has an effect on postural stability in infants who have recently learned to stand, by studying seven subjects aged 13-16 months. The child was standing inside a "movable room" with a fixed floor. Evaluation of the response was performed visually by two experimenters as well as recorded by video camera for later visual analysis. Responses were quantified as fall, stagger or sway in the direction of the moving wall (categorized with graded signs). All children swayed in the direction of the moving walls and had difficulty in maintaining upright stance.

It was concluded that in young children, regulation of standing balance is significantly influenced by visual motion cues, and that the central organization of different sensory inputs related to spatial orientation and body motion is not fully developed in infants.

These results were supported by Butterworth and Hicks (1977) who replicated the study on 12 infants (12.5 to 17 months). Almost all children (92.8%) swayed significantly in the direction of the moving walls. In the same study they addressed the question of, whether postures occurring earlier in development than standing/walking are under visual control. In this part of the study, 12 infants not able to stand (mean age 10.9 months) and 12 infants able to stand, (mean age 15.8 months) were examined in the sitting position. They applied the same methods and estimation procedure as the former studies. In response to the moving walls, 72.1% of the trials in the "standing ability" group, and 90.8% of the trials in the "unable to stand" group showed increased sway, staggering or fall in the direction of the moving walls. Both the above studies analyzed the influence of vision when this was in conflict with the proprioceptive and vestibular inputs, but nevertheless they support the opinion that vision is of importance in postural control in the young infant.

### 3.2.4. SENSORY CONFLICT

Experiments employing somatosensory and visual stabilization procedures, described above in adults (see section 3.1), have been performed on small groups of children ranging in age from 18 months to 10 years. In an investigation by Forssberg and Nashner (1982), four children 18 months to 3½ years old, four 3½ to 5 years old, six 5 to 7½ years old, and three 7½ to 10 years old were studied. None of the children below 5 years of age were tested with the eyes closed. In a study by

Shumway-Cook and Wollacott (1985), six children aged 4-6 years old were examined and additional results from 10 children between 7 and 10 years old were included from a previous study (Nashner et al. 83). Balance performance was compared between different age groups by analysis of antero- posterior (A-P) sway of the hips with respect to the ankles measured by a potentiometer, and the center of foot pressure measured by a force plate. In these studies, the performance was quantified by a "performance-ratio" as the ratio of a rectified integral of the AP-sway and a defined maximum AP-sway amplitude.

The results of these studies demonstrated no significant difference in performance ratio when only vision was stabilized but there was a trend to greater stability with increasing visual information. A significant decrease in the performance ratio with increasing age was observed. All children maintained balance when the support surface was stabilized, but with a performance ratio closer to falling than in the visually stabilized condition. Again, A-P sway decreased with increasing age. However in the condition where both somatosensory and visual information were stabilized, all children below five years lost their balance. The 5 to 7 ½ year old children had performance ratios close to falling and those above this age remained well below their stability limits. It was concluded that the resolution of intersensory conflicts, the processes which establish the appropriate context-dependent weighting among support surface, visual and vestibular inputs, is a high level process undeveloped in children under the age of seven (Forssberg and Nashner 82).

# 4. MOTOR CONTROL OF STANDING BALANCE - ADULT STUDIES

## 4.1. THE MOVING PLATFORM AND ESTIMATED PARAMETERS

In order to evaluate the different sensory inputs and to determine motor control strategies during balance reactions, a number of investigators have employed the "moving platform paradigm". By suddenly translating the platform upon which the subject stands, in a forward or backward direction (Nashner 77, Nashner et al. 79, Horak and Nashner 86, Wollacott et al. 88, Dietz et al. 89) or suddenly rotating the platform toe-up and toe-down (Keshner et al. 87,88, Nardone et al. 90), the position of the center of body mass relative to the base of support, can be altered. For example, backward translation of the support surface results in a backward displacement of the base of support relative to the center of body mass. In this position, the center of body mass is no longer centered over the base of support but in front of it, and the subject is standing in an unstable position. A balance reaction is required to prevent the subject from falling forward and to reestablish an erect equilibrium position by moving the center of body mass backwards over the base of support.

Sudden displacements of the support while standing upright are partially compensated for by the body's inertia and the viscoelastic properties of its muscles, tendons, and ligaments. However, active corrections of larger imposed displacements require appropriate response by a number of muscles acting on several body segments - compensatory reactions. In order to determine movement strategies and underlying neural mechanisms governing the control of balance reactions, different parameters have been used as outcome measures:

* The analysis of EMG recordings of selected lower limb and trunk muscles. Temporal and spatial patterns of muscle activation were determined. Temporal refers to the onset latency and sequence of activation between proximal and distal muscles. Spatial pattern refers to the identification of which muscles were activated.
* Displacement of the center of foot pressure.
* Postural sway, a horizontal movement of the hips with respect to the ankle joints measured by a potentiometer.
* Video analysis of the movements in lower leg and body segments.

## 4.2. MOTOR RESPONSE PATTERNS TRANSLATIONS

Early studies employing platform translations by Nashner and colleagues (Nashner 76,77), indicated that in most healthy adults equilibrium was restored through fixed patterns of short latency muscle activation. EMG activity began in ankle muscles with a latency of 70-120 ms from onset of platform translation. Then, in sequence, the thigh and then trunk muscles became active at further latencies of 10-20 ms. In response to backward translations, soleus/gastrocnemius muscles were activated along with the hamstrings with no or minimal activation of tibialis anterior and quadriceps. The reverse was reported for forward translations; tibialis anterior was activated along with the quadriceps with none or minimal activation of the muscles on the posterior part of the limb. It was suggested that early activation of the ankle muscles was primarily responsible for restoring equilibrium. This sway correcting response was termed the "ankle strategy" which reflects that the body sways mainly like a pendulum about the ankles with little motion about the knees and hips (Nashner

77, Horak and Nashner 86).

Other balance strategies have been observed when the support surface configuration was varied. Different widths of the support surface in relation to foot length gave other muscle activation patterns but still combined in certain temporal relations (Horak and Nashner 86). When standing on a narrow beam during perturbation, most of the subjects displayed a tendency to activate the muscles in the opposite proximal to distal order with early muscle activation of the trunk followed by activation of the thigh. Little or no activation of the ankle muscles was reported. In response to backward translation, the earliest activation occurred in abdominals and was followed by quadriceps activation. In response to forward translation, the paraspinal muscles were activated first, followed by activation of the hamstrings muscles. The term "hip movement strategy" was used to describe this balance reaction, as the primary movement to restore equilibrium occurred about the hip joint; hip flexion in response to backward translation, and hip extension in response to forward translation. No knee movement was reported. During this condition of reduced support surface procedure, a mixed muscle activation pattern was occasionally observed. This pattern was described as a combination of the ankle synergy (normal support surface) and the hip synergy (narrow support surface). It was concluded that the results support the hypothesis that a continuum of balance responses can be generated by one or a combination of a limited set of muscle activation patterns, thus simplifying the control process.

More recent experiments (Keshner et al. 88, Allum et al. 89) have shown discrepancies as to the temporal and spatial organization of activation of lower limb and trunk muscles in response to sudden platform perturbations. It has been demonstrated that trunk and thigh muscles sometimes have been activated as early as the ankle muscles. It should be noted that the experiments were performed with different platform parameters - different velocities and accelerations, which may be one possible reason for variation in the results. The variation in muscle activation patterns in response to platform translations requires further investigation. (see Barin 88 for discussion).

ROTATIONS

The consequence of platform rotations are different from platform translations and will result in a different pattern of sensory inputs (Keshner et al. 87, Allum et al. 88,89, Diener et al. 84,88, Hansen et al. 88, Nashner et al. 89). Unlike platform translations, rotational perturbations have been considered a form of somatosensory conflict (Nashner 76, Nashner et al. 82, Diener et al. 84a). During toes-up platform rotations, the ankle joint is quickly dorsiflexed and a backward displacement of the center of body mass relative to base of support is produced. Here, the initial response is a contraction of the stretched plantarflexors at a latency of 50-90 ms.

However, in this situation this response would be functionally inappropriate; the muscle forces generated by this activity result in ankle plantarflexion which rotates the leg backwards. If the body acted as a single-link inverted pendulum as has been suggested, (Nashner 77, Horak and Nashner 86) this action would lead to further backward displacement of the body away from the erect equilibrium position. A subject does not lose balance in this situation because within 20-50 ms after the response in the plantarflexors, tibialis anterior, quadriceps and hamstrings contract. This pattern of muscle activation resists further backward displacement of the body and contributes to the restoration of equilibrium (Allum et al. 89).

## 4.3. NEURAL PROCESSING INVOLVED IN BALANCE CONTROL

It has been proposed that the postural control system utilizes triggered central programs, often referred to as motor synergies, to restore equilibrium in response to disturbances of balance. The function of this central control process would be to regulate some global parameter, for example, the position and velocity of the center of mass rather than stabilizing each joint. Horak and Nashner (1986) pointed to a central organization of a limited set of muscle activation patterns, as an economic way of simplifying the process of adapting movements to different environmental contexts or balance requirements.

Diener et al. (1988a) attempted to test this hypothesis and distinguish between centrally determined, pre-programmed properties of balance and those resulting from segmental reflex mechanisms mediated by proprioceptive inputs from the lower limbs. They examined how, under normal support surface characteristics, varying platform translation parameters such as velocity and amplitude, influenced the spatial-temporal structure of the postural response following backward platform translation. It was reported that varying the velocity and amplitude of the platform translations, did not influence which muscles were activated or the timing of activation, and the subjects continued to use a relatively consistent movement strategy (ankle strategy). But the intensity of activity in the EMG burst was increased.

However, from an analysis of the area of the EMG signal, it was reported that the magnitude of muscle activity in the earliest EMG burst was positively correlated with stimulus velocity (also see Dietz et al. 89) and the amount of activity of the later more tonic EMG signal was best correlated to the stimulus magnitude of platform displacement. It was suggested that these findings are consistent with the hypothesis that the postural control system utilizes triggered central programs in balance reactions, where the pattern of muscle activity was not affected by the velocity or amplitude of the disturbance (sensory inputs).

Similar findings and interpretations have been reported from perturbation studies in normal humans while walking on a treadmill (Nashner 80, Berger et al. 84 Dietz et al. 89). These experiments showed that the compensatory responses to sudden balance disturbances while walking were highly movement specific; the effect of perturbation induced adjustments of the muscle activity was to modify the parameters of the perturbed steps (rate, amplitude, phasing), rather than to introduce new unrelated patterns of movement.

## 4.4. SUMMARY

In addition to the single-link "ankle movement strategy" and the "hip movement strategy" as described above (Nashner 77, Horak and Nashner 86), recent investigations have reported different multi-link movement strategies used to restore postural equilibrium in response to platform rotations and translations (Allum et al. 89, Horak and Nashner 86, Wollacott et al. 87, Nardone et al. 90). Most studies which have examined the response of humans to imposed balance disturbances have relied upon EMG analysis. Few of these studies (Nardone et al. 90) however, have actually evaluated angular displacements about the ankle, knee and hip joints following platform translations and rotations. In this regard it is important to note that one cannot predict or determine movement strategies, that is; segmental rotations of multiple body segments, solely from EMG analysis (Oliney and Winter 85, Smith and Zernicke 87). The question arises: which movement strategies are utilized and which ones are best suited to restore equilibrium under different types of balance requirements?

In order to advance the understanding of neural processes governing the control of standing balance, further investigations are required to identify the movement strategies that are employed and the contribution of lower limb muscle activity to restore postural equilibrium. It should be noted that muscle activity, under the control of the nervous system, serves a number of functions which include:

1) producing concentric contractions (muscle is shortening under tension)
2) eccentric contractions (muscle is lengthening under tension)
3) isometric contractions (muscle has an average fixed length under tension, noovement)
4) to counteract or produce forces which influence the motion of a segment during multi-segmental motion.

# 5. MOTOR CONTROL OF STANDING BALANCE - CHILDREN BALANCE STUDIES

## 5.1. STUDIES OF STATIC BALANCE

In the literature, static balance refers to the ability of subjects to maintain postural equilibrium during quiet or unperturbed standing. Under these conditions balance performance has been examined in children between 2 and 14 years of age (Shambes 76, Williams et al. 83, Riach and Hayes 83,87). In studies by Shambes (1976) and Williams et al. (1983) the children were asked to remain still for 30 s in seven different postures: pivot prone, prone on elbows, all fours, full kneel, half kneel, erect standing, and one foot standing, and EMG was recorded from upper limb muscles. The main findings showed that the magnitude of muscle activity (raw EMG spike height) decreased with increasing age (Shambes 76, Williams et al. 83), and this was taken as a sign that balance performance improved with age.

However, there are a number of methodological problems with these studies. Firstly, all the muscles recorded were in the upper extremity which do not act as principal postural muscles in the standing positions. Secondly, there were no reports on direction or form of movement that associated with the EMG burst. Lastly, the magnitude of EMG recordings of the motor units producing the spike height of EMG is influenced by skin resistance, electrode placement on the muscle belly, and thickness of fat, e.g: the action potentials are dependent on the diameter of the muscle fiber recorded and the distance between the active muscle fiber and the recording site (De Luca 79). To enable quantification and comparison of the results, both the onset and the amount of activity during a given time of contraction has to be measured and in addition normalized (Winter 80). None of these elements was taken into consideration when the magnitude of EMG responses were compared between groups, which makes the results questionable.

Riach and Hayes (1983 and 1987) examined static balance performance in children in the standing position. The children aged 2 to 14 years (only 4 below 4.5 years), were instructed to stand still on a forceplate for 20 sec. The number of subjects in the two studies was 40 and 76, respectively. The center of foot pressure (CFP) in the anterior/posterior and medial/lateral direction was recorded. The amount of body sway was quantified by computing the root mean square (RMS) values of CFP movement about the mean position. The CFP frequency composition was analyzed using a Fast Fourier Transform algorithm. The main findings demonstrated a decrease in the rate of CFP sway and magnitude of CFP fluctuations with increased age ($r=.5$ $p<.01$), even when the variables: gender, height and weight were taken into consideration. Adult values as found in a previous study (Hayes et al.1984), emerged at approximately 7-8 years of age (Riach and Hayes 83).

The effect of closed eyes on body sway was also examined for children above 4.2 years. The amount of sway in the eyes-closed condition was expressed by the RMS value as a percentage of the eyes-open RMS value (Romberg quotient). The children between 4-15 years of age, tended to show less sway with eyes closed than that reported in adults (statistical "sign" test) (Hayes et al.84). The youngest children (age 4-5 years, $n=3$) even tended to sway more with eyes open than closed (Riach and Hayes 87). This would indicate that the visual system information is not being appropriately integrated within the postural control system.

Studies in static balance with eyes open and closed, also failed to show differences between healthy children and children with vestibular dysfunction age 7-10 (Horak et al. 88). This suggests that children, like adults, develop compensation for sensory loss and are able to maintain a quiet erect standing position with information derived from the somatosensory system (Nashner et al. 82, Horak et al. 88). As stated above in section 3.1, it should be noted that studies involving maintenance of quiet standing with eyes open or closed, only challenges a limited part of the postural control system.

These studies provided no information about the ability of children to restore equilibrium following a disturbance of balance, and provided limited information regarding the motor strategies employed during balance reactions. To maintain a static position does not elicit the great challenges the nervous system is exposed to, and has to deal with during normal functional activities. In order to extend the knowledge about the nature of balance reactions and the development of standing balance control during maturation, the experimental conditions must be related to the actual conditions in daily life activities where not only maintenance of, but regaining balance in response to external disturbances is crucial in adequate function and where complex sensory integrations and sensory conflicts will occur.

## 5.2. THE MOVING PLATFORM PARADIGM AND MOTOR RESPONSE PATTERNS

Only a few studies have examined balance reactions to sudden platform translations and rotations in healthy children (Forssberg and Nashner 82, Shumway-Cook and Wollacott 85, Wollacott et al. 87).

### TRANSLATIONS

Forssberg and Nashner (1982) studied 17 healthy children aged 1½-10 years old, grouped into four age groups: four aged 1½-3½ years old, four aged 3½-5 years old, six aged 5-7½ years old and three aged 7½-10 years old. The children were subjected to forward and backward translations at velocities between 15 to 25 cm/s for 250 ms, for a distance of 3.75 cm to 6.25 cm depending on the height of the child. Platform acceleration was not reported. Center of foot pressure was recorded with a forceplate. A potentiometer attached to the hips via a lightweight rod and belt, recorded the anterior/posterior sway of the hips with respect to the ankle joints. EMG signals were recorded from surface electrodes placed at GA, TA, hamstrings (HAM) and quadriceps (QUAD). The EMG signals were full wave rectified, and band pass filtered (0 to 40Hz). The onset latency was determined by visual inspection and amplitudes of proximal and distal muscle responses were quantified by numerical integration of EMG signals during a 75 ms interval following onset of activity. The ratios of both the EMG onsets and of the integrated amplitudes of proximal to distal synergists (GA to HAM and TA to QUAD) were computed to compare the EMG patterns between age groups. The ratio of the onset latency of GA to TA activation (referred to as antagonist muscle pair) was used to indicate the level of co-activation. No statistical analysis to prove significance of findings was reported in this study, only means and standard error of the means were presented.

The reported results showed a tendency to higher rates of acceleration of hip displacement with respect to ankles, and more fluctuation in the recordings of hip sway were reported in children below 7 years of age. It should be mentioned that only one figure was shown and no group table was presented. The temporal order of muscle activation in all the children groups showed a similar pattern of distal to proximal activation as was observed in the adults (Nashner 77). Although the young age groups, those below 7½ years, had an average longer time to EMG onset latency of GA (135-150 ms) in response to backward translation and of TA (120-130 ms) in response to forward translation compared to adults. The younger age group also showed a tendency to longer delay between distal and proximal responses. This was most evident in forward translation with an average delay of 41 ms between onset of TA and QUAD in the youngest group as compared to 13 ms in the 7-10 year olds. Adult values for delay between TA and QUAD responses were 8 ms (Nashner 77).

Greater variability of the onset times was observed in response to both forward and backward platform perturbations. The standard deviations of the difference between distal and proximal muscle activation ranged from ±25 to ±12 in backwards translation and from 36 to 20 in forward translation, the deviations decreasing with increasing age. The standard deviations of amplitude ratios of ankle to thigh muscle pairs (synergists) decreased with increasing age in both perturbations. The co-activation ratio of antagonists decreased with increasing age in the GA/TA ratio, most notably in forward translation; 0.88 SD±0.40 in the 1½-3½ year olds and 0.22 SD±0.10 in the 7½-10 year olds (values approaching unity indicated greater co-activation).

When these results in children were compared to those obtained from adult subjects exposed to similar platform translations (Nashner 77), the onset latency and sequence of muscle activation and the amplitude relationship between GA-HAM and TA- QUAD of children above 7 years of age is primarily the same as those observed in adult subjects. A distal to proximal EMG pattern in response to translational perturbations was also seen in the younger children in terms of onset latency, but the quality of the EMG response was different. The immaturity in children below the age of 7 was seen as delayed EMG onset latency, a greater delay between onset of distal and proximal muscle activation, and a tendency to co-activation of GA-TA muscles, especially in forward translation.

In a similar study, Shumway-Cook and Wollacott (1985) tested the response to platform perturbations in 21 children ranging in age from 15 months to 10 years; five aged 15-31 months and six aged 4-6 years, the remaining ten children aged 7-10 had previously been studied (Nashner et al. 83). The amplitude of forward and backward platform translations was 2 cm at a rate of 8 cm/s. The EMG recording procedure and analysis were the same as in the study by Forssberg and Nashner (1982). Sway was measured by a potentiometer of hip movement relative to the base of support. To quantify sway, the potentiometer data were numerically integrated and scaled to the theoretical limits of sway of each child (height and foot measurements were taken, and center of mass determined; how this was done was not specified). A stability index was computed to represent the body sway (the integrated sway) as a percentage of maximal sway (maximum excursion of sway during a trial), with 100% representing loss of balance and 0% representing no hip sway. Motion of the subjects was recorded using high speed film. The images were digitized at 20 frames per second, and angular displacements about the hip, knee and ankle were quantified. These results were only presented graphically utilizing stick figures constructed from digitized data points.

Subjects in the youngest age group (15 months to 31 months) swayed closer to their limits of stability compared to the 4-6 year olds: 50% compared to 25% in response to backwards translation and 75% compared to 40% in response to forward translation, respectively. The movement strategies employed by the children in response to perturbation were only presented with one stick figure of a 5 year old in forward translation. This indicated compensating angular movement in both knee and ankle joints. There was no information on backward translation or rotation, and no data were presented on amplitudes or velocities of angular displacements. Results from EMG analysis showed little difference in onset latencies of GA and TA in the 15-31 month old children as compared to the 7-10 year olds, while the mean onset latency of the 4-6 year olds was significantly longer than ($p < .001$). Also, in general, the 4-6 year old group had greater variability in onset of muscle activation. The temporal delay between distal and proximal muscle activation was also greater in the 4-6 year olds ($p < .01$). In fact, the youngest group showed temporal delays between the TA and QUAD response (forward translation) close to the values obtained in 7-10 year olds. This is not consistent with the findings of Forssberg and Nashner (1982) where a tendency to less difference in temporal delay between those below 3½ years and adults was found in backward translation (GA to HAM), but not in forward translation, here a gradual decrease in temporal delay with increasing age was seen. These differences are perhaps due to the small samples in the two studies and the large variability in the EMG responses.

The variability in the amplitude ratio of distal and proximal muscles was nearly constant in children above 7 years (SD $\pm$ 3) and adults (SD $\pm$ 2). A greater variability was seen in the younger children; 15-31 months SD $\pm$ 4, and 4-6 year old SD $\pm$ 5. EMG traces of three sequential trials of forward translation were presented for a 27 month old child, a 5 years old child and 7 years old child. Inspection of these EMG signals revealed the activation of all four leg muscles in the youngest children compared to the increasing level of directional specificity of the EMG response in the older children.

The authors hypothesize that the 4-6 years age group represents a transition period in postural development when children learn to integrate and alternate between visual, proprioceptive and vestibular inputs in controlling posture. At this stage this theory is difficult to evaluate due to the following reasons: 1) the variable results from the studies of Forssberg and Nashner (1982) and Shumway-Cook and Wollacott (1985); 2) the lack of information identifying the movement strategies employed by children of different ages; and 3) small sample size.

Wollacott et al. (1987) also examined age related changes in postural response patterns during childhood development. In this study, seven children aged 2-3 years, seven aged 4-6 years and eleven aged 7-11 years, were exposed to forward and backward translations of 2 cm displacement at 8 cm/s. In addition, four of the eleven 7-8 years old were subjected to two different velocities and amplitudes (2 cm at 8 cm/s and 3 cm at 24 cm/s). Each translation was repeated five times. Center of foot pressure and hip displacement relative to the ankles were recorded as described above. EMG recordings (rectified and filtered 0-40Hz) of GA, TA, HAM, QUAD, paraspinal muscles, abdominal muscles, neck extensor and flexor muscles were obtained and onset latencies determined by visual inspection. Comparisons between ages were tested with t-tests. The distal to proximal organization of EMG responses were reported in all age groups. Here the onset of GA in backward translation and TA in forward translation was similar in all age groups. Starting with the youngest age group, GA onset latencies were 109 ms, 99 ms, and 96 ms and for TA they were 102 ms, 110 ms, and 106 ms. Age difference was observed as temporal delay of the proximal onset latency in backward (HAM) and forward translation (QUAD). The onset latency between thigh and trunk muscles decreased with increasing age (no statistical significance was presented). Activation of trunk muscles only appeared in 20% of the trials in the 2-3 years old. The incidence of trunk muscle activation was not reported in the other groups. Amplitude of EMG responses was reported to be increased in the youngest age group. However, the authors did not present any methods of quantification or normalization procedures. No results of center of foot pressure or body sway recordings were presented. In this study they did not observe less variability or less temporal delay in EMG responses in the 2-3 years old group compared to the 4-6 years old as in the above described study by Shumway-Cook and Wollacott (1985).

In response to the slow (8 cm/s) versus fast (24 cm/s) platform velocity tested in backward translation in four 7-10 year old children, a tendency towards an increase in onset latency of trunk and neck muscle activation at the higher platform velocity was noted. No such trend was seen for the thigh and ankle muscles.

ROTATIONS

In the study by Shumway-Cook and Wollacott (1985) it was reported that in response to platform rotations (24°/sec, amplitude 6°) no "long latency response" in GA-HAM was seen in the 15-31 months old infants (n=3). Five of six (83%) of the 4-5 year old children exhibited a GA-HAM response to rotation. No results from TA response were shown or discussed. This statement is difficult to relate to because "long latency response" in GA in response to rotation of the platform is not reported in the adult studies (see adult studies 4.1.2). The stretch evoked response in GA is reported to be succeeded by a "long latency" response in the TA after rotation perturbation as a part of the functional strategy to regain balance. In the study by Haas et al.(1986) medium (in GA) and long latency (in TA) responses were reported to be present in children down to 14 months of age in response to rotation (see section 3.2.1). Shumway-Cook and Wollacott (1985) did not present any information on body movements or results from CFP displacements. Thus, this study provided little information as to how children in the different age groups responded to balance disturbance caused by sudden platform rotations.

In the study by Forssberg and Nashner (1982) the children were subjected to platform rotations of 20°/s. No amplitude was specified. This part of the study only looked at the adaptation of the early stretch evoked GA response during repeated exposures to platform rotations. To characterize the ability to attenuate the GA response, an adaptation ratio was employed of the fourth and fifth EMG response to the first and second EMG response. Although not statistically analyzed because of large variability, a tendency of little attenuation was seen in children below the age of seven and a consistent attenuation was seen above this age. They did not analyze the actual movement strategy employed by the children, and no information was presented as to the temporal sequencing of muscle activation. The difference between platform translation and rotation is discussed in the article, and also the problem of solving sensory conflict situations. As referred to in section 3.2.4, SENSORY CONFLICT, children under seven years of age supposedly have difficulties in suppressing the influence of sensory inputs that provide inappropriate orientation information. It is based on this interpretation and the concept that rotational perturbation is a sensory conflict situation and probably processed at a higher level of maturation than translation (see 3.2.4), that it is of interest to see how the regaining of balance after sudden rotation of the platform, is organized by muscle activation and biomechanical movement patterns, in children below and above seven years.

## 5.3. SUMMARY

In regards to studies of platform translation (Forssberg and Nashner 82, Shumway-Cook and Wollacott 85, Wollacott et al. 87) it was generally agreed that the basic distal to proximal organization of muscle activation reported for adults (Nashner 77, Horak and Nashner 86) is present in young children even as early as 15 months of age. The information gained from CFP and hip displacement although scarcely presented and without statistical analysis, shows a tendency of increased sway amplitude and frequency of sway with decreasing age (Forssberg and Nashner 82, Shumway-Cook and Wollacott 85).

Typical of all studies was the large variation in the parameters derived from EMG recordings, such as: onset latency, time delay between distal and proximal muscles, and amplitude relationships between distal and proximal muscle synergies. This is especially true when results between studies are compared. The study by Shumway-Cook and Wollacott (1985) noted an apparent "regression" in postural EMG responses in the 4-6 year olds compared to the younger and the older children. This was not in correspondence with the measure of balance stability which indicated that the 4-6 year olds are well below their limits of stability, eg; better performance than the 15-31 month old children. In this respect these results do not correspond with the results in the two other studies (Forssberg and Nashner 82, Wollacott et al. 87) which did not report on a divergence between EMG recordings and balance stability in 4-5 year olds. Information gained from recordings of hip sway and CFP is insufficient to illustrate the biomechanics of body movements during balance reactions. That information is sufficient only if the child is considered to react as single mass rotating about the ankle joint and not as a multi-link segmental system.

In a theoretical paper by McCollum and Leen (1989), the possible limits of stability for erect standing were analyzed. They suggested that, based on the experimental information of increased sway frequency in young children during standing, the increased latency of lower leg muscle activation, and on the height of the child and location of body mass, it would be more economical for children under 3 years to use ankle movement strategy and not hip movement strategy for rapid postural adjustments. In this way a simplified control strategy would be adopted, by reducing the degrees of freedom through movement of fewer joints. The indication of additional movements in the knees observed in the 4-6 year old children in the study by Shumway Cook and Wollacott (1985) does not support this theory. The need for a closer investigation of the movement strategies and the relationship to the pattern of muscle activation in the young children is apparent.

The neuromuscular response seen as delayed EMG onset and temporal delay between distal and proximal muscles, increased amplitude and co-activation of antagonists, (in the children below 7 years) is difficult to interpret without knowing the kinematics of body movement.

# *CHAPTER 3 - PROPOSED STUDY AND STATEMENT OF OBJECTIVES*

## 1. IDENTIFICATION OF THE PROBLEM

Studies of static postural control in young children have demonstrated that below the age of six, the amount of sway and the frequency of sway increased with decreasing age (Riach and Hayes 83, 87). Thus even when the function of postural control is to just maintain standing balance, certain age related differences are seen. In regards to acquisition of motor skills in the standing position, the postural control system must not only learn to maintain equilibrium, but also learn to restore equilibrium in response to external disturbances.

Recovery of postural equilibrium following balance disturbances, a complex task, is a basic requirement of many activities of daily living. Few investigations of motor development in children have addressed this aspect of postural control. Studies which have examined balance reactions in children following sudden platform translations or rotations, have concentrated mainly on EMG analysis of the temporal pattern of activation of lower leg and trunk muscles and estimates of postural stability or body sway derived from analysis of displacement of the CFP and hip displacement relative to the feet.

Age-related differences have been reported: a larger amplitude and higher frequency of body sway in the younger children, differences in onset latencies in EMG such as, delayed onset latencies and delayed sequencing of activation in lower leg and trunk muscles and a trend towards co-activation of ankle muscle agonist and antagonist (Forssberg and Nashner 82, Shumway-Cook and Wollacott 85, Wollacott et al. 87). There are discrepancies however, in the results of EMG analysis obtained in the different studies as described above in section 4.3.3.

Where a kinematic analysis was performed (Shumway-Cook and Wollacott 85), only limited data were presented. This information is not sufficient to predict which movement strategies are employed by different age groups following different types of balance disturbances or in platform perturbations of increasing degree of difficulty. This is also the case in adult studies, where segmental motion of the shank, thigh and trunk has not been systematically evaluated. In regards to movement strategies, it has been suggested that the interplay of joint movements in children is possibly different from adults in balance reactions. At least in forward platform translation, one case has been presented which shows children move not only about the ankle joints (ankle movement strategy reported in adults), but also about the knees. Based on the above described studies and their main findings, the coordination of muscle patterns and body movements under dynamic balance conditions is still not sufficiently identified and analyzed at different levels of maturation and age.

Measures of body sway, either displacement of CFP or hip displacement, cannot reveal the movement strategy a child employs to regain balance. Since the body is a multi-link structure, analysis of the linear and angular motion of all body segments is required to learn the kinematics of postural reactions. EMG analysis will provide information about the temporal and spatial pattern of muscle activation, but not the pattern of motion of a multi-link system. With the movement strategy identified, the functional results of muscle activation in the regulation of postural control can be determined, e.g. body segment stabilization or angular displacement controlled by eccentric, concentric or isometric contraction.

It has been suggested that a higher level of neural processing, and consequently of maturation, is required to restore balance in situations of sensory conflict (Forssberg and Nashner 82). However, this is not substantiated by any experimental evidence. There is little information as to how children of different ages and levels of maturation respond to balance disturbance where sensory conflicts do exist such as following platform rotations as compared to backward platform translation.

The influence of varying stimuli parameters, such as velocity of platform motion on the postural response, has not been systematically examined as a function of age. This is suggested as a method to distinguish between centrally predetermined properties of balance reactions and segmental reflex mechanisms involved in postural control. If the pattern of active angular displacement about the ankle, knee and hip joints, and the pattern of muscle activation during balance reactions are independent of platform velocity, this would be consistent with the hypothesis of a pre-programmed postural response. Through the application of different platform velocities, this hypothesis will be tested in children at different stages of maturation.

## 2. CLINICAL RELEVANCE OF THE STUDY

Information about controlling aspects and the coordination of posture and movement in healthy children at different stages of development will provide a foundation for understanding the consequences that neural deficits have on postural control and the acquisition of motor skills. The current concept of postural control is that all voluntary movements are accompanied by postural adjustments. In this regard, postural context will affect the nature and success of movement (Reed 89).

The characteristics of postural control and the ability to balance are important components in the assessment of dysfunction, and are also major components in physiotherapy treatment programs (Bobath 66, Levitt 77). When more is known about how balance is regulated and the developmental aspects of postural control, physiotherapists will be better able to characterize the nature of disabilities associated with balance dysfunction in children and establish appropriate treatment programs. Consequently it is of great importance to understand the nature of balance reactions and the stages of maturation of postural control.

## 3. OBJECTIVES OF STUDY

1) To quantify the movement strategies employed by children at different stages of maturation compared to adults, during balance reactions to backward and forward support surface translations and toes-up platform rotations.

2) To examine the relationship between body kinematics and the organization and timing of muscle activation in the lower extremities during balance reactions to platform translations and rotations.

3) To evaluate the effect of varying platform velocity, holding acceleration constant, on the organization and timing of muscle activation in the lower extremities, and active angular displacements at the ankle, knee and hip joints.

4) To examine the difference in balance reactions between platform translation and rotation toes-up, as a function of age. The platform rotation and translation backward do impose similar segmental rotations about the ankle joint, but require a different response from the subject to regain balance. The platform rotation condition is considered a form of sensory conflict, and it is suggested that the ability to effectively restore balance in response to platform rotations would appear later in childhood development as compared to platform translation.

# *CHAPTER 4 - METHODS*

## 1. SUBJECTS

Experiments were performed on 14 healthy adults and 32 healthy children. The adults were 8 males and 6 females, 15-42 years of age, mean age 25.8 years with standard deviation (SD) 6.6 years. The subjects reported no history of neurological deficit or orthopaedic maladies. They were volunteers among students and staff at the University of Manitoba and a local High-School. The children were divided into 4 groups of 8, based on age:

P1 GROUP: age 19 months to 31 months, mean age 27 months (SD 0.4). Range of height 79-98 cm.

C1 GROUP: age 3 years to 4 years and 10 months, mean age 4 years 2 months (SD 0.7 years). Range of height 87-110 cm.

C2 GROUP: age 5 years to 6 years 8 months, mean age 5 years 6 months (SD 0.6 years). Range of height 107-119 cm.

C3 GROUP: age 7 years 6 months to 8 years 7 months, mean age 7 years 9 months (SD 0.4 years). Range of height 124-142 cm.

The children had no history of neurological deficit or orthopaedic maladies and were recruited among the children of the staff at the university, employees at the hospital, friends, and from a local kindergarten. The parents gave their written consent. The experiments for each individual were fulfilled during one session lasting one hour and were approved by the University of Manitoba Human Ethics Committee.

## 2. EQUIPMENT

### 2.1. MOVING PLATFORM

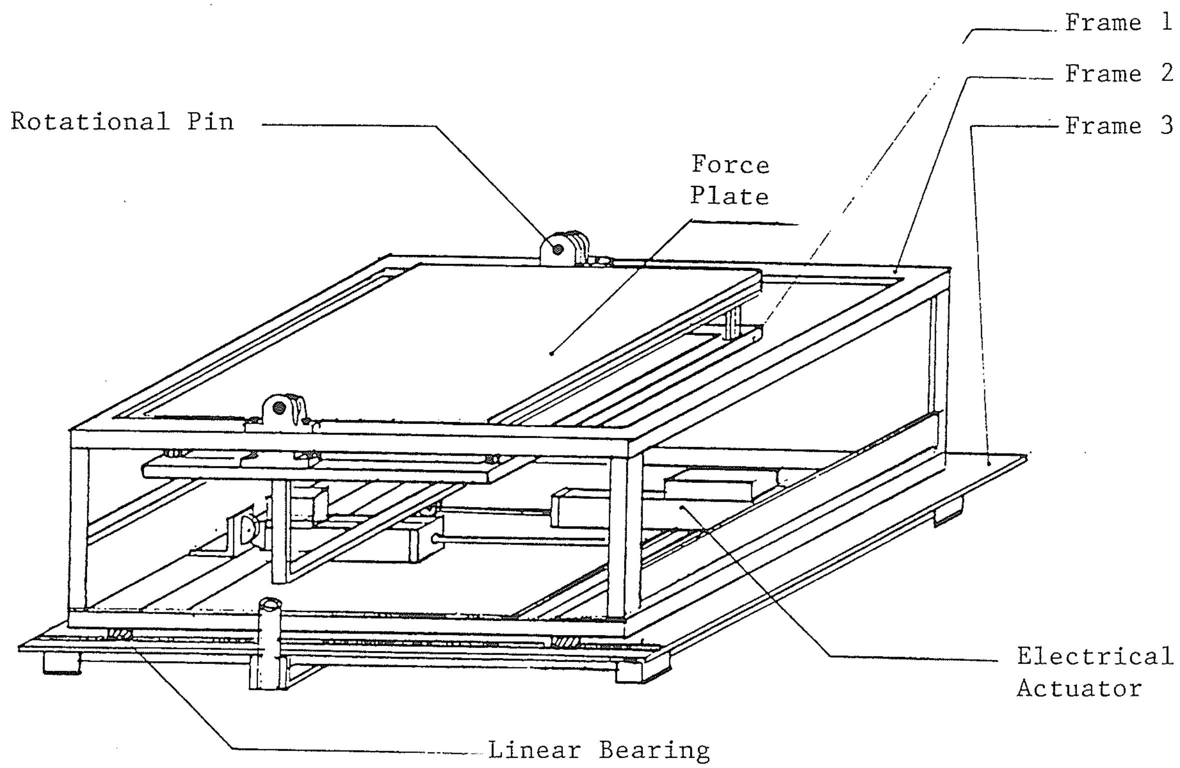
A two-degrees of freedom movable platform with appropriate safety features was constructed to produce:

1. Sudden forward or backward support surface translations in the horizontal plane.

2. Sudden toes-up support surface rotations about an axis approximately co-linear to the ankle joint.

The sudden support surface movements placed the subjects in an unstable position, and a balance reaction was required to prevent the subject from falling. Figure 1 is a drawing of the moving platform device which illustrates the main features. Frame 3 is the main frame which is mounted on Neoprene rubber to minimize vibration and is bolted to the floor. Frame 2 moves horizontally in translation, forwards and backwards on two linear bearing tracts. Frame 1 moves in rotation about the rotational pin blocks. The axis of rotation, of Frame 1 is positioned 3 cm above the surface of the platform. A force plate, upon which the subjects stood, is incorporated into Frame 1.

*Fig.* 1 Shop drawing of the moving platform apparatus. Frame 3 is the main frame which is bolted to the floor. Frame 2 is mounted with linear bearing blocks to metal rods which runs the full length of Frame 3. Frame 2 is capable of moving horizontally in translation, forwards and backwards. Frame 1 is attached to Frame 2 at the rotational pin block and is free to rotate about this axis. The force plate is firmly mounted into frame 2. Two drive motors, electrical linear actuators model H105B, are mounted to Frame 3, and one attached to Frame 2, and the other to Frame 1. These motors operate to move the respective frames in translation or rotation. Each motor is computer controlled as described in the methods.



The motion of both the translation and rotation frames is produced by two identical electrical DC motors/linear actuators, model H105B, (Industrial Devices Corporation, 35 Pamaron Way, Novato, CA 94949). Each motor drives a cylinder which has an excursion of 30 cm. Each motor base is firmly mounted to Frame 3 using a pivot base mount. The cylinder end is mounted to the respective moving frame. The pivot base mount allows the rotational motor to move freely up and down during platform rotations. The motors are rated at a maximum speed of 30 cm/s with a maximum rated thrust of 350 pounds. The motors are controlled by a H3401 Motor Control Unit (Industrial Devices Corporation). The control units have an analog speed input of 0-10 volts and produce an output current pulse which drives the DC motors.

In order to precisely determine the platform displacement, velocity and acceleration, a factory installed linear potentiometer is mounted inside the cylinder of the translation and rotation motors. After calibration, the linear potentiometer signals were used to determine linear displacement during platform translations and angular displacement during platform rotations. The linear potentiometer signals were recorded on computer (see below), low- pass filtered, 15 Hz, using a fourth order Butterworth zero page lag digital filter, and differentiated, with respect to time, to obtain the platform velocity.

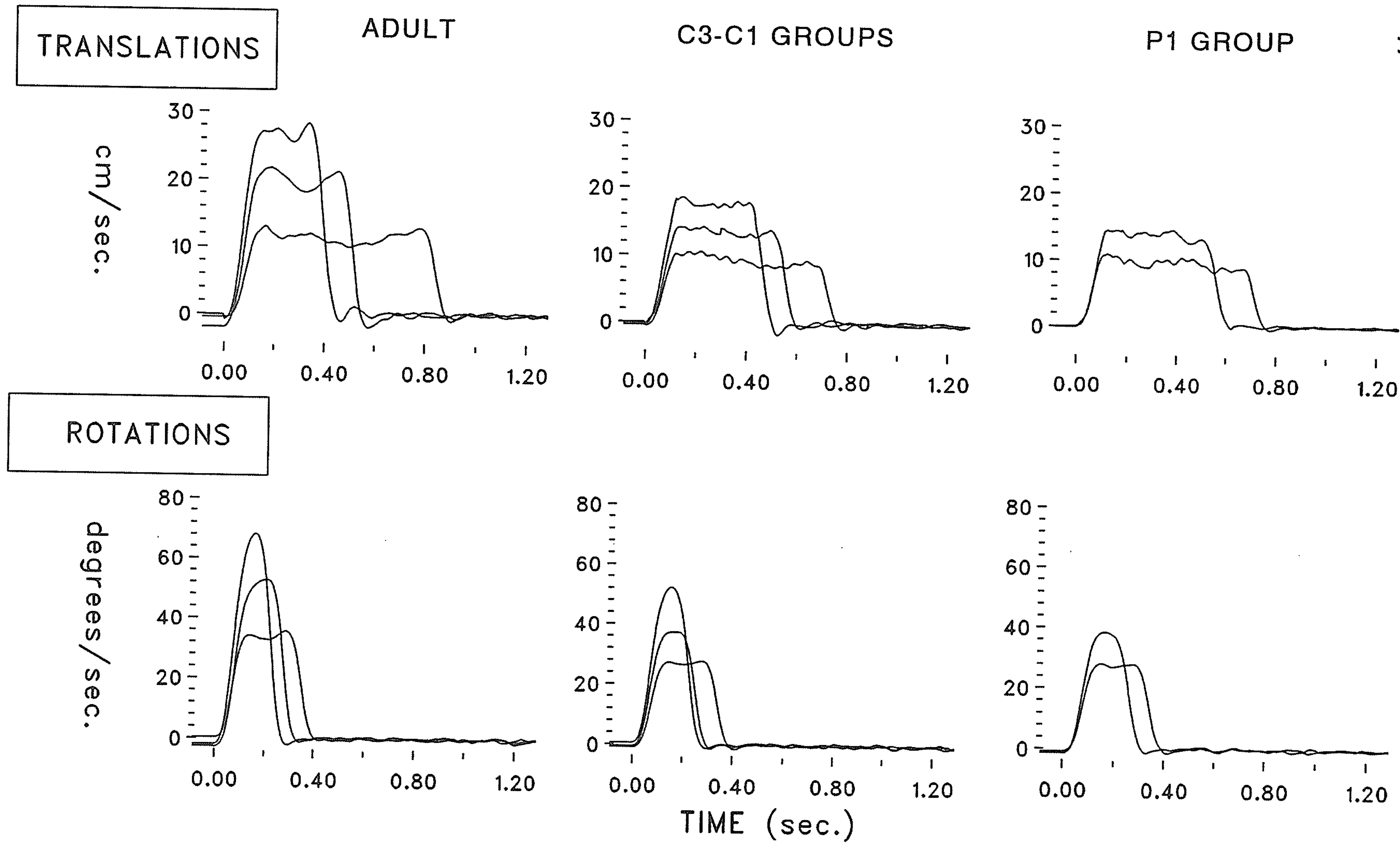
The contacts of the linear potentiometer are connected to a constant voltage source (+/- 5 volts). For platform motion in translation, the voltage difference across the variable resistor is recorded at 2 cm intervals of platform displacement from zero to 30 cm. The relationship between voltage and displacement was linear (regression coefficient r = .989), and a calibration of 1 volt = 4.71 cm has been determined. For platform motion in rotation, the voltage difference across the variable resistor was recorded at 2 degree intervals of platform rotation from 16 degrees toes-up rotation to 16 degrees toes-down rotation. In the range of 10 degrees toes-up rotation to 10 degrees toes-down rotation, the relationship between voltage and angle of platform rotation is linear (regression coefficient r = .96), and a calibration of 1 volt = 6.8 degrees has been determined.

## 2.2. COMPUTER CONTROLS

A model 2000 Amiga computer equipped with a custom 4 channel, 8 bit digital to analog (D/A) convertor (Biosys Inc., Winnipeg, Manitoba, Canada) was employed to control platform motion. The analog output signal from the D/A convertor was conditioned to match the analog speed input of the motor control unit, 0-10 volts. Custom computer software was developed which allowed variations of the output voltage of the D/A convertor, full scale (0-10 volts) in intervals of 1 ms. This permitted a wide range of platform motion profiles, where platform displacement velocity and acceleration could be precisely defined.

A number of platform velocity profiles were constructed for these experiments. Figure 2 presents platform velocity in translations and toes-up rotations for all age groups. With the exception of the P1 age group, each subject was tested using three different platform velocity profiles, achieved with constant acceleration and displacement magnitude. In general, selection of a range velocity profiles was chosen that: a) would maximally challenge the balance control system of the subjects of each age group; b) would overlap between age groups. The same velocity profiles were used for forward and backward platform translation. The average target velocity (cm/s) and the displacement amplitude (cm) of platform translations were as follows:

*Fig. 2* Platform velocity derived from linear poentiometer recordings of drive motor cylinder. Top three plots are velocity profiles during the different platform transactions (forwards and backwards) for adults, C1-C3 age group and P1 age groups. Bottom three plots are velocity profiles during platform rotations for adults, C1-C3 age group and P1 age groups.



P1 AGE GROUP

V1 = 10 cm/s, 6.1 cm

V2 = 15 cm/s, 6.1 cm

C1, C2 and C3 AGE GROUP

V1 = 10 cm/s, 6.1 cm

V2 = 15 cm/s, 6.1 cm

V3 = 20 cm/s, 6.1 cm

ADULTS

V1 = 15 cm/s, 8.3 cm

V2 = 20 cm/s, 8.3 cm

V3 = 30 cm/s, 8.3 cm

The average target velocity (degrees/s) and the angular displacement amplitude (degrees) of platform rotations were as follows:

P1 AGE GROUP

V1 = 20°/s, 7 degrees

V2 = 36°/s, 7 degrees

C1, C2 and C3 AGE GROUP

V1 = 20°/s, 7 degrees

V2 = 36°/s, 7 degrees

V3 = 50°/s, 7 degrees

ADULTS

V1 = 36°/s, 9 degrees

V2 = 50°/s, 9 degrees

V3 = 70°/s, 9 degrees

When groups were statistically compared, it must be noted that velocity 2 in C1, C2, C3, corresponded to velocity 1 in adults. Velocity 3 in C1, C2, C3, corresponded to velocity 2 in adults. The numbering in children velocities has been used. Only children groups were compared in velocity 1, adults were not tested in this velocity. In P1 only velocities 1 and 2 were employed, and this group was compared to the other children groups, not to adults.

## 3. EXPERIMENTAL SET-UP AND PROCEDURES

Before positioning subjects on the movable platform, the following preparations were made:

1. Pre-package disposable surface EMG electrodes (Mediicotest model # M-00-S, 2.5 cm in diameter) were secured to the skin over the right side at six different muscles (see section 3.4.1).
2. 3-M light reflective markers 1.5 x 2 cm, were firmly secured to the skin at a number of body landmarks to reference body segment endpoints and axis of rotation (see section 3.5.1).

### 3.1. VIDEO RECORDING AND MOTION ANALYSIS

The subjects were then asked to stand on the movable platform, with bare feet, and with eyes open, looking forward at a black dot on a blank white wall, 3.5

meters away. They were instructed to fold their arms on their abdomen. The feet were aligned on the platform in a comfortable distance apart and parallel, with toes facing forward. A line was placed on the force plate surface to mark the axis of rotation, and care was taken to align the lateral malleoli with this line.

With the exception of the P1 age group (see below), all participants were subjected to nine different platform movements:

* Forward platform translations at three different velocity profiles.
* Backward platform translations at three different velocity profiles
* Toes-up platform rotations at three different velocity profiles

The P1 age group was subjected to only 2 different velocity profiles for the forward and backward platform translations and toes-up platform rotations.

To control for anticipation or the presetting of body orientation and balance responses, the different platform movements, forward and backward translation and rotation, the different platform velocities were presented in a predetermined random order. The time period between platform movements ranged from 20 to 60 seconds, and thus, the subjects could not predict when the platform would move. This procedure was repeated three times for all age groups. The order of platform movements, which was randomized, was different in each trial, to control for anticipation.

Before the platform was set into motion, care was taken to see that the subject was in the correct standing position, standing still, not making voluntary movements, and not leaning in any direction. For the younger children, a second operator was positioned directly behind the child to re-position him/her if necessary.

## 3.2. DATA ACQUISITION AND COMPUTER SYSTEM

EMG and center of foot pressure signals (described below), linear potentiometer recordings from both motors, and the video synchronization pulse were recorded on an IBM compatible 386 computer equipped with a 16 channel, 12 bit, 1 MHz analog to digital (A/D) convertor (RC Electronics Inc., 6464 Hollister Ave, Goleta CA, USA). The data acquisition software was set to trigger input mode. Upon receiving a trigger pulse, which was generated from the Amiga 2000 computer, a 3.5 second sweep of data was collected at a sampling rate of 333 Hz. The Amiga computer was programmed to generate a trigger pulse 700 ms before activating the motors and producing platform motion. Thus each 3.5 second sweep of data consisted of a 700 ms pre-movement period and a 2.8 second period following onset of platform movement. The experimental data was stored on computer for off-line display and analysis.

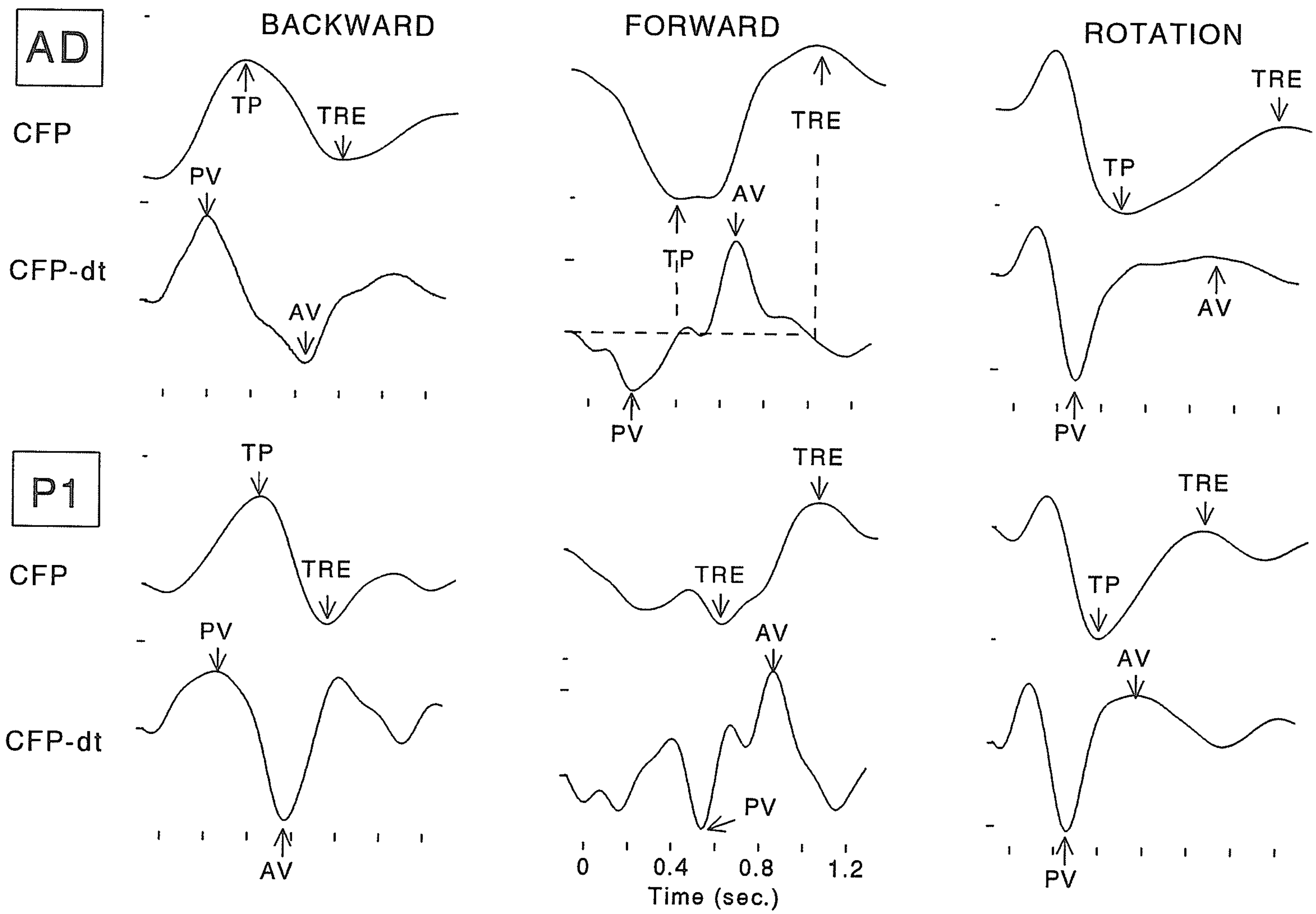
## 3.3. FORCE PLATE DATA

### 3.3.1. EQUIPMENT AND APPLICATION

The force plate, upon which the subjects stood, was firmly mounted into frame 2 of the platform. It is a multi-purpose stabilometric platform (Model T-1100, Terctronics Co,. Biomedical Instrumentation Research, Development & Manufacturing, P.O Box 29731 San Antonio, Texas 78229 USA). The force plate has 4 strain gauge transducers in each corner which transform ground reaction forces in two planes. One set of transducers is orientated to record the position of the force vector in the sagittal plane (X) about the y axis, and one set is orientated to record the position of the force vector in the frontal plane (Y) about the x axis. The force plate is designed to operate in the range up to 200 kg. The summed outputs of the two strain gauge transducer pairs were fed into a full bridge amplifier (GOULD). In this manner, the path of the center of foot pressure (CFP) in the anterior-posterior direction (A-P), or sagittal plane, and in medio-lateral direction (M-L), or frontal plane was recorded. The force plate was calibrated and the amplifier gain set and locked in position at the beginning of the experiment. This was checked throughout the four months testing period.

The raw CFP data were stored on computer for off-line analysis, as described above. The raw CFP data were low-pass filtered at 10 Hz, using a fourth order Butterworth type zero phase lag digital filter. The low-pass filtered CFP signal was also differentiated, with respect to time, to obtain the velocity profile of the CFP. Figure 3 presents plots of CFP displacement and velocity of CFP displacement of a representative adult subject and a representative child (C2 age group) during forward translations, backward translations and toes-up rotations. The terms passive and active are used to differentiate the main components of the displacement of CFP and velocity of CFP records. The passive component is here defined as the component of the CFP or its velocity profile that is not yet influenced by compensatory activity from the nervous system in response to the mechanical effect of platform movement. Thus, a passive component must begin earlier than the onset of any change in EMG activity. Given a particular type of platform motion, the onset of the passive component of the CFP and its peak velocity would depend on the inertia of the body segments and the viscoelastic properties of its muscles, tendons, and ligaments. The active component,

*Fig. 3* Plots of CFP displacement and immediately below its derivative, velocity of CFP displacement (CFP-dt), for one representative adult subject (AD) and 2 year old subject (P1) during backward and forward transactions (AD = 20 cm/s, and P1 = 15 cm/s) and during platform rotations (AD = 50 °/s and P1 = 36 °/s. Dashed lines and arrows shown in CFP and CFP-dt plots for AD during forward transactions illustrate quantification of; time to peak CFP displacement (TP), time to return to equilibrium position of CFP (TRE), peak passive CFP velocity (PV), and peak active CFP velocity (AV).



would be that component of the CFP which represents the body's active response or balance reaction to the mechanical perturbation.

3.3.2. CFP ANALYSIS

From recording of CFP displacement, the following parameters were quantified for the first set of platform movements (trial 1):

1. Relative to start of platform motion, the time to initial peak CFP displacement before the change in direction and return to equilibrium position. This time value was determined from the velocity plot, and was determined as the time at which the CFP displacement reached zero velocity or time to zero velocity (TZ). Following fixed platform displacements, the time to reach peak CFP displacement will depend upon a number of passive properties, such as, the inertia of the body, the passive viscoelastic properties of muscle, tendon and ligaments, and on the level of background muscle activity. The neural response or active component will also contribute to the deceleration of the CFP displacement (moving away form the base of support) before causing the change in direction and return to equilibrium position, and for this reason, the time to zero velocity (TZ) does not truly represent the onset time of the active component.

2. Relative to start of platform motion, the time interval to return to equilibrium position of CFP, which was defined as the time it took the displacement of CFP to return to the pre-movement position of quiet standing. This was determined from the CFP velocity plot as the time when the active phase of CFP displacement reached zero

velocity (TAZ). For toes-up platform rotation, the CFP did not return to its pre-movement position because the orientation of the base of support had been tilted toes-up. Thus, the base of support was in essence narrowed and a new equilibrium position of CFP was required. Thus in rotations it was necessary to quantify the time to return to a new zero position.

3. Ratio of peak passive CFP velocity (PV) to peak active CFP velocity (AV). These values were determined from the plot of the derivative, with respect to time of CFP displacement. (See arrows at respective peaks in the velocity plots of the CFP shown in Figure 3). The PV was the time when the velocity of the initial passive displacement of the CFP was at its peak before being decelerated by the body's passive visco-elastic properties and active muscle responses to counteract the balance disturbance (see above). The AV was the peak velocity of the active component of CFP displacement on return to equilibrium position. The ratio value provided a general performance measure of the ability of the individual to restore balance in response to the mechanical platform perturbation.

Figure 3 presents a graphical illustration of the procedure used to quantify the time to reach initial CFP peak displacement, time to return to equilibrium position of CFP and ratio of PV to AV for one representative adult and a 2 year old subject.

The CFP displacement and the rate of change or velocity of CFP displacement provided timing information related to the separation of passive versus active components of the body's response to mechanical platform perturbations that could be used in the interpretation of the kinematic parameters (see below).

## 3.4 EMG DATA

### 3.4.1. EQUIPMENT AND APPLICATION

As stated above, pre-packaged disposable surface electrodes were used. The placement of the EMG electrodes was secured to the skin over the right of:

1. M. Tibialis anterior (TA) mid-point of muscle belly.
2. M. Gastrocnemius (GA) proximal part of lateral head.
3. M. Hamstrings (HAM) mid-point of lateral muscle belly.
4. M. Quadriceps lateralis (QUAD) mid-point of muscle belly.

In some of the children, EMG activity from the abdominal muscle and back extensor muscles was collected in order to examine the activity in the truncus muscles during development. The electrodes were applied at m.Rectus Abdominis (ABD) in the umbilicus region, and at m.Erector Spina (SPIN) in the L3, L4 region.

The EMG electrodes were connected with a cable 20 cm long to miniaturized preamplifiers (Biosys Inc., Winnipeg, Manitoba) which were 3 cm by 2 cm by 1 cm in dimension and 30 grams in weight. The preamplifier was secured to the respective body segment with surgical tape. At this stage the raw EMG signals were amplified 100 times. A cable connected the preamplifier to a battery operated amplifier and signal conditioning unit (Biosys Inc.). The cables were all collected and attached to the back of the subject. This arrangement did not impede the movement of the subjects in any way. At the main amplifier stage, the EMG signals were band-pass filtered at 10 Hz to 3 KHz, rectified and low-pass filtered at 50 Hz. All filters were analog RC type filters (-3 Db). The signals were converted analog to digital at a sampling rate of

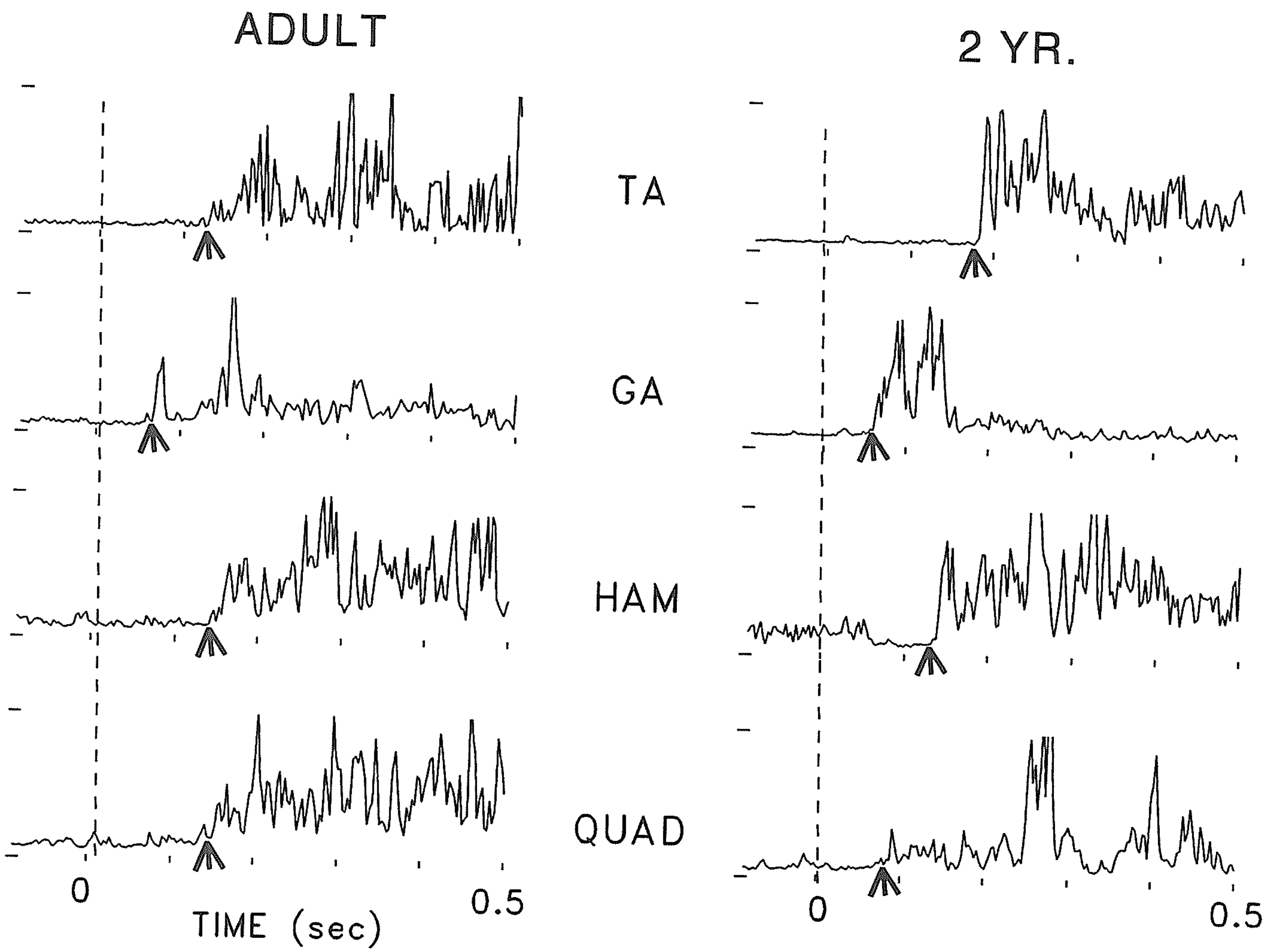
333 Hz., using the RC Electronics A/D convertor. These data was recorded and stored on computer for off-line analysis.

### 3.4.2. EMG ANALYSIS

Onset latency of muscle activation following a sudden platform translation or rotation was assessed as the time interval between the start of the platform motion, as determined from inspection of motor linear potentiometer recordings, and the beginning of the first burst of muscle activity relative to the pre-movement muscle activity level. For each muscle, the onset latencies were determined on the computer by visual inspection of the stored EMG recordings. Figure 4 presents typical EMG recordings from one adult and one 2 year old subject. The dashed vertical line at time zero represents onset of platform motion and the arrows represent onset of muscle activity.

In order to estimate the magnitude of the muscle response, the area of the rectified EMG signal was computed within fixed time intervals which were; (a) the area of the first 50 ms of the rectified EMG signal, (b) the area of the next 200 ms. The interval time of 50 ms is consistent with studies which have shown that the EMG burst durations of the short latency component of the stretch induced muscle response is approximately 50 ms (Gottlieb and Agarwal 80, Lee and Tatton 83), and studies which have shown EMG burst durations of the earliest muscle responses to platform displacements to be approximately 50 ms (Nashner 77, Horak and Nashner 86, Dietz et al. 89, Allum et al. 88). The second interval was chosen to avoid the inclusion of any short latency reflex contractions, and reflect the long duration muscle responses demonstrated in some perturbation studies (Diener et al. 84a, Nardone et

*Fig. 4* **Typical EMG recordings from all four muscles of one adult and one 2 year old subject during toes-up platform rotation of 36 °/s. Dashed vertical lines at time zero indicate onset of platform rotation and arrows are placed at the point where muscle responses first occur.**



al. 90).

In order to examine the effect of platform velocity on EMG area of muscle response, it was necessary to normalize the EMG values between the different platform velocities. Thus, for each individual, the EMG area at platform velocity 1, platform velocity 2, and platform velocity 3, was calculated as a percentage of the total EMG area at all three platform velocities. For example the normalized EMG area value for platform velocity 1 would be the EMG area at platform velocity 1 divided by the sum of the EMG area at platform velocity 1 and 2 and 3. Similarly, in order to compare the relative magnitude of muscle activity between the different types of platform perturbations, the EMG area was normalized for platform perturbation type. This was done by dividing the EMG area in one perturbation type by the sum of the EMG area in all the perturbation types. For example the normalized EMG area for backward translation would be the EMG area in response to backward translation divided by the sum of the EMG area in response to backward translation and forward translation and platform rotation. This information was used in the interpretation of the muscle activity and movement strategy that is involved in the body's compensating response, since onset of muscle activity only identifies the sequence of muscle activity and does not inform about the amount of muscle activity involved.

## 3.5. VIDEO ANALYSIS OF MOTION

### 3.5.1. EQUIPMENT AND APPLICATION

A Sony Hi 8 CCD-V101 camera was used to record body motion. The camera was set to a variable shutter speed mode, between 1/60 and 1/500 of a second, with automatic aperture adjustment to maintain the appropriate exposure according to the speed of the subject. The SVHS output of the video camera was fed into a Sony SVHS VCR MODEL for video recording of the subjects.

To detect body segment movement, 3-M light reflective markers, 1.5 x 2 cm, were firmly secured to the skin at the following locations:

FOOT: at the distal end of the fifth metatarsal.

ANKLE: on the lateral malleolus of the fibula.

KNEE: on the lateral aspect of the knee joint line.

HIP: on the prominence of the greater trochanter.

PELVIS: at the anterior superior iliac spine (ASIS).

SHOULDER: lateral aspect of the shoulder at the level of tuberculum majus humeri, just distal to the lateral aspect of the acromion process.

HEAD: at arcus zygomaticus in front of the ear. To enhance detection of the reflective markers and provide adequate illumination, a standard video flood light was used. At the beginning of each recording session a calibration rod with markers attached at fixed distances was recorded.

### 3.5.2. VIDEO DIGITIZATION

The reflective markers were computer digitized from the stored VCR recordings using the Peak Performance 2D motion analysis system (Peak Performance Technologies Inc. 7385 S Revere Parkway, Suite 601, Englewood Colorado). The markers on the calibration rod were digitized first, and this information was used to calibrate the displacement and velocity of the digitized body segment markers. Also, a stationary, earth-fixed reference marker was digitized.

For each digitized image of 0.01667 s (16.67 ms) interval or 60 Hz video sampling rate, the Peak Performance system provided the calibrated (in cm) X and Y coordinates for each marker, aligned to the reference marker. In the adult subjects, 60 images or one second of video was digitized; 10 images before the onset of platform movement and 50 images following onset of platform movement. In the children, 50 images or 0.83 seconds of video was digitized, 10 images before the onset of platform movement and 40 images following onset of platform movement. The raw coordinate data were low-pass filtered at 4 Hz using a fourth order Butterworth type zero phase lag digital filter. The filtered linear displacement data were then differentiated, with respect to time, to obtain linear velocity data.

Based on the marker locations, the following angular displacements were calculated:

1. Ankle angular displacement was measured as the angle formed by the intersection of the line segment from the knee to ankle marker and line segment from the ankle to foot marker.

2. Knee angular displacement was measured as the angle formed by the intersection of the line segment from the greater trochanter to knee marker and line segment from the knee to ankle marker.

3. Hip angular displacement was measured as the angle formed by the intersection of the line segment from the ASIS to the greater trochanter marker and the line

segment from greater trochanter to knee marker.

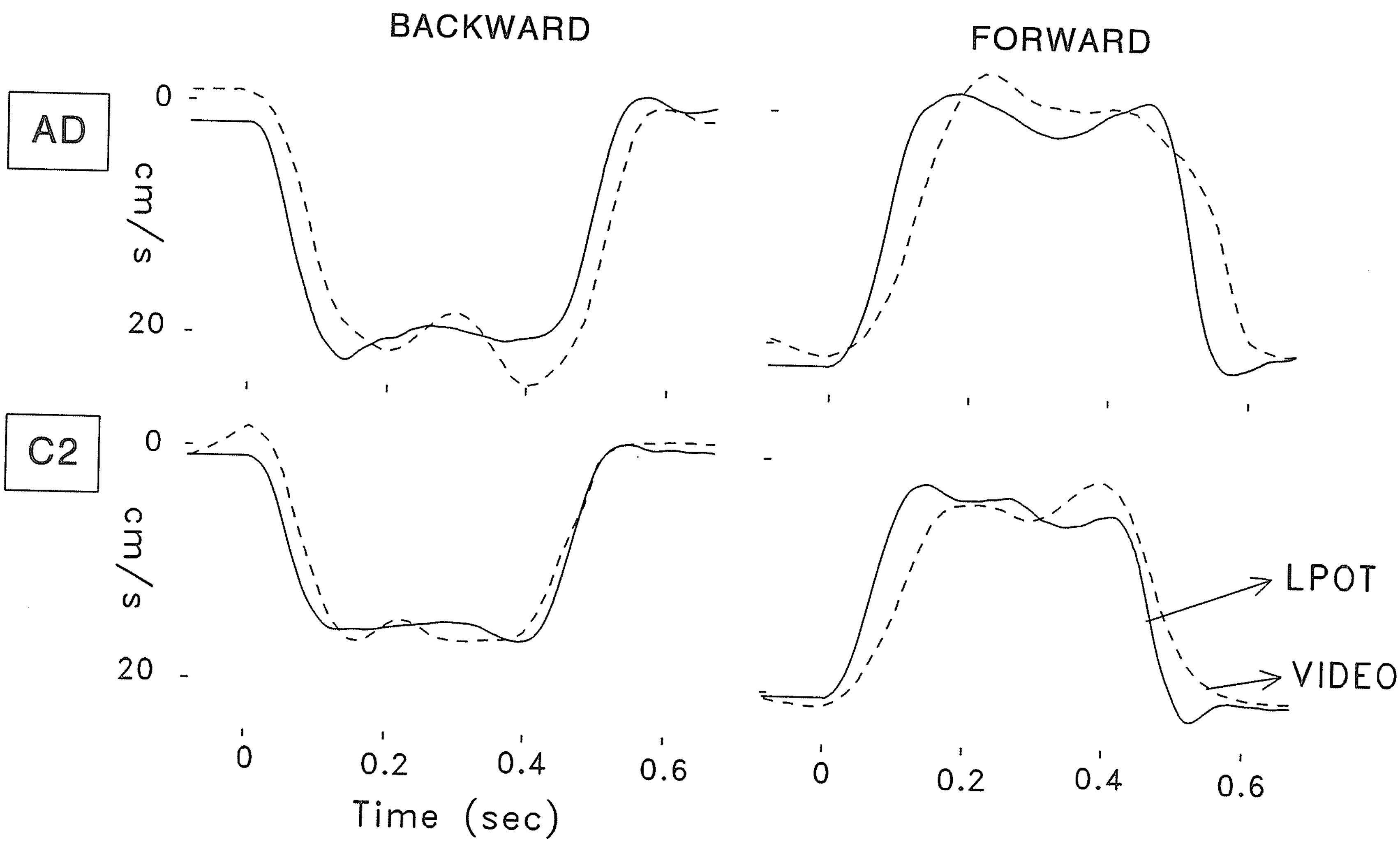
4. Hip and trunk (H-T) angular displacement was measured as the angle formed by the intersection of the line segment from the shoulder to greater trochanter marker and line segment from greater trochanter to knee marker.

### 3.5.3. SYNCHRONIZATION OF VIDEO AND A/D DATA ACQUISITION

Each motor control unit has eight output status terminals. From one terminal, a short pulse is generated at the moment the motor begins to move. This motor onset synchronizing (sync) pulse was electronically conditioned (square wave pulse 3 volts peak, 100 ms in duration), recorded through one channel of the A/D convertor and was used to activate a light bulb for 100 ms. Thus, the onset of the motor sync pulse collected on computer occurred at precisely the same time as the activation of the light bulb. This procedure provided the synchronization of the video recordings and the analog signals collected on computer with the A/D convertor.

To check the synchronization procedure and evaluate the sensitivity of the Peak Performance video analysis system, platform velocity in translation as derived from the drive motor linear potentiometer recordings (also see Fig. 2) and from the digitization of horizontal linear displacement (x coordinate) of the lateral malleolus marker were compared. The plot of platform velocity for forward and backward translation by both methods are presented in Figure 5. The identical onset times and the high degree of overlap of the platform velocity profiles demonstrates the reliability of the synchronization procedure and sensitivity of the Peak Performance motion analysis system.

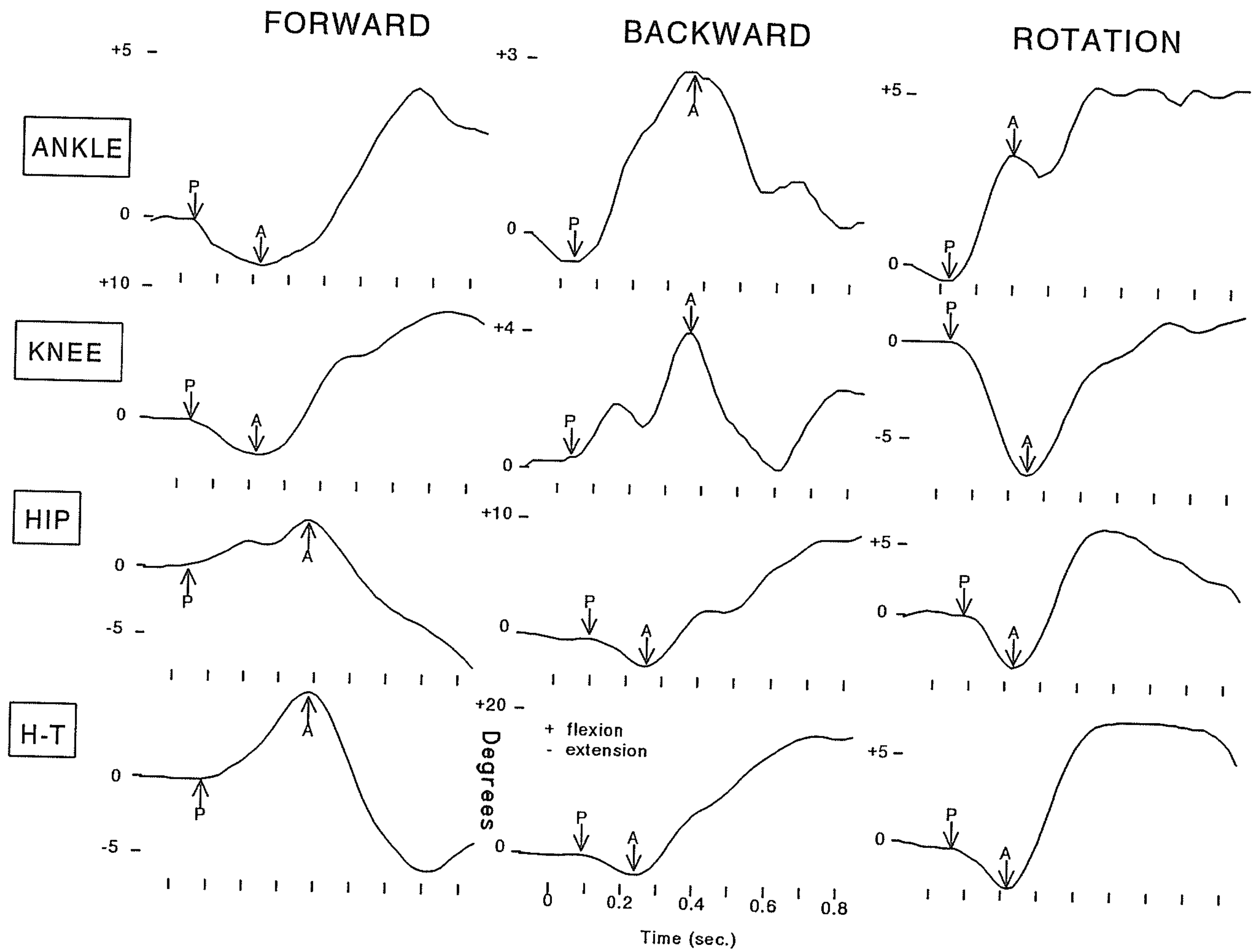
*Fig. 5* **Plot of platform velocity during forward and backward transactions for one adult subject and one child in the C3 age group. The trace labelled LPOT (solid lines) is platform velocity derived from the drive motor linear potentiometer recordings (low-pass filtered at 15 Hz and differentiated), and the traces labelled VIDEO are derived from x coordinate data obtained from video digitization of the lateral malleolus marker (low-pass filtered 10 Hz and differentiated).**



### 3.5.4. ANALYSIS OF KINEMATIC DATA

In analyzing the linear displacements of the individual markers and the angular displacements about the respective joints, passive and active components were identified, as for the CFP data. The onset time of the passive and active components was determined from the examination of both the linear/angular displacement plots and velocity plots. A movement was defined as a passive component if: it occurred within the first few video frames relative to onset of platform motion, or it occurred before or near onset of the muscle activity, or if a movement occurred before a decrease was seen in the velocity of the passive component of the CFP displacement. Active components, which must occur later than the onset of muscle activity, were identified when a change in direction of the passive displacement occurred, that is, where velocity of displacement became zero before abruptly increasing or decreasing depending upon direction of active displacement. Figure 6 presents ankle, knee, hip and H-T angular displacement records of one representative adult subject to forward and backward platform translations at 30 cm/s and to toes-up platform rotations at 70 o/s. Arrows labelled "P" represent onset of passive component of angular displacement, and arrows labelled "A" represent onset of active component of angular displacement. It should be noted that in some cases, in particular knee angular displacement following backward translation, there is sometimes more than one active component. The onset time of the passive and active movement components, displacement magnitude and peak velocity, were determined from the following kinematic data:

*Fig. 6* Plots of ANKLE, KNEE, HIP and H-T angular displacement of one representative adult subject to forward and backward platform transactions at 30 cm/s and to toes-up platform rotations at 70 °/s. Arrows labelled "P" represent onset of passive component of angular displacement, and arrows labelled "A" represent onset of active component of angular displacement. Time zero indicates onset of platform motion. Positive displacement values (+) are flexion/dorsiflexion, and negative values (-) are extension/planterflexion.



1. Horizontal linear displacement and linear velocity of the x coordinate of the greater trochanter and ASIS markers. This provided timing information and measures of linear hip sway relative to space. Also, since these markers are located near the center of body mass in a subject standing erect, these measures can be used to determine the onset and direction of movement of the centre of body mass relative to space, at least in the early phase of the response before significant angular displacements and velocities are observed. In regards to onset of movement and movement direction, no significant differences were observed between the greater trochanter marker and the ASIS marker. Thus, only data from the greater trochanter marker will be presented.

2. Ankle, knee, hip and H-T angular displacement and angular velocity. This analysis provided a description of the movement strategy used to restore equilibrium in response to the mechanical perturbation.

## 4. STATISTICAL ANALYSIS

The information gained from the CFP recordings, EMG results and the kinematic analysis of motion provide measures of balance performance and led to the identification of movement strategies employed during balance reactions in response to different types of balance disturbances, induced by platform translators and rotations, and different degrees of disturbances or velocities of platform motion.

Conventional statistical methods were used to calculate group means and standard error of means. To examine the influence of platform velocity and age on

CFP, EMG and kinematics parameters, the ANOVA statistical procedure was used. When testing for the main effect of age on the respective parameters, data from common platform velocities were used. Thus, the values of adults, C3, C2 and C1 age groups at the two common platform velocities of 15 cm/s and 20 cm/s for translations and 36°/s and 50°/s for rotation were used in one ANOVA, and in a second ANOVA the values of C3, C2, C1 and P1 groups at the two common platform velocities of 10 cm/s and 15 cm/s in translation and 20°/s and 36°/s in rotation were used. Consequently, P1 was never statistically compared with the adult group, only to the children groups.

The following is a list of the parameters and statistical tests that were performed:

I. CFP

a) time to peak displacement, ANOVA - effects due to platform velocity and effects due to age. Only the results from Trial 1 were analyzed.

b) time to return to equilibrium position, ANOVA - effects due to platform velocity and effects due to age. Only the results from Trial 1 were analyzed.

c) ratio between peak passive velocity and peak active velocity, ANOVA - effects due to platform velocity and effect due to age. Only the results from Trial 1 were analyzed.

II. EMG

a) onset to muscle activation, ANOVA - effects due to platform velocity and effect due to age. The results from Trial 1, 2 and 3 were analyzed.

b) magnitude of normalized EMG area, ANOVA - effect of platform velocity. Only the results from Trial 1 were analyzed.

c) magnitude of normalized EMG area, ANOVA - test for differences between types of platform perturbation. Only the results from Trial 1 were analyzed.

III. KINEMATICS

a) linear displacement of greater trochanter marker in the horizontal. Included: )i( onset time to active linear displacement; (ii) peak magnitude of linear displacement; and (iii) peak velocity linear displacement. ANOVA - effects due to platform velocity and effect due to age. Only the results from Trial 1 were analyzed.

b) ankle, knee, hip and H-T angular displacement. Included: (i) onset time to active linear displacement; (ii) peak magnitude of linear displacement; and (iii) peak velocity linear displacement. ANOVA - effects due to platform velocity and effects due to age. The results from Trial 1 and Trial 3 were analyzed.

# *CHAPTER 5 - RESULTS*

The main objective of this study was to investigate the developmental changes in the regulation of standing balance. It was therefore necessary to acquire knowledge about the mature adult pattern of reactions to controlled disturbances of standing balance, in order to achieve a reference for the results in children. The results are divided into three sections presenting results from:

SECTION 1. CFP - a) time to peak displacement, b) time to return to equilibrium position and, c) ratio between peak velocity and peak active velocity.

SECTION 2. EMG - a) the onset latency and magnitude of muscle activation.

SECTION 3. Kinematics - a) linear displacement of greater trochanter marker; its onset, peak amplitude and peak velocity, b) angular displacement of ankle, knee and hip joints and the trunk; its onset, peak amplitude and peak velocity.

These sections are broken into subsections presenting results from comparisons between age groups and between different platform velocities. Differences between age groups were examined using the ANOVA statistical method in an adult-C3-C2-C1 comparison and in the C3-C2-C1-P1 comparisons. Two common velocities were used in the adult-C3-C2-C1 grouping; 15 cm/s and 20 cm/s for translation and 36 °/s and 50 °/s in rotation, and two common velocities for the C3-C2-C1-P1 grouping; 10 cm/s and 15 cm/s in translation and 20 °/s and 36 °/s in rotation. ANOVA was also used to determine the main effect of platform velocities on the various parameters described in the methods section.

# 1. CENTER OF FOOT PRESSURE (CFP)

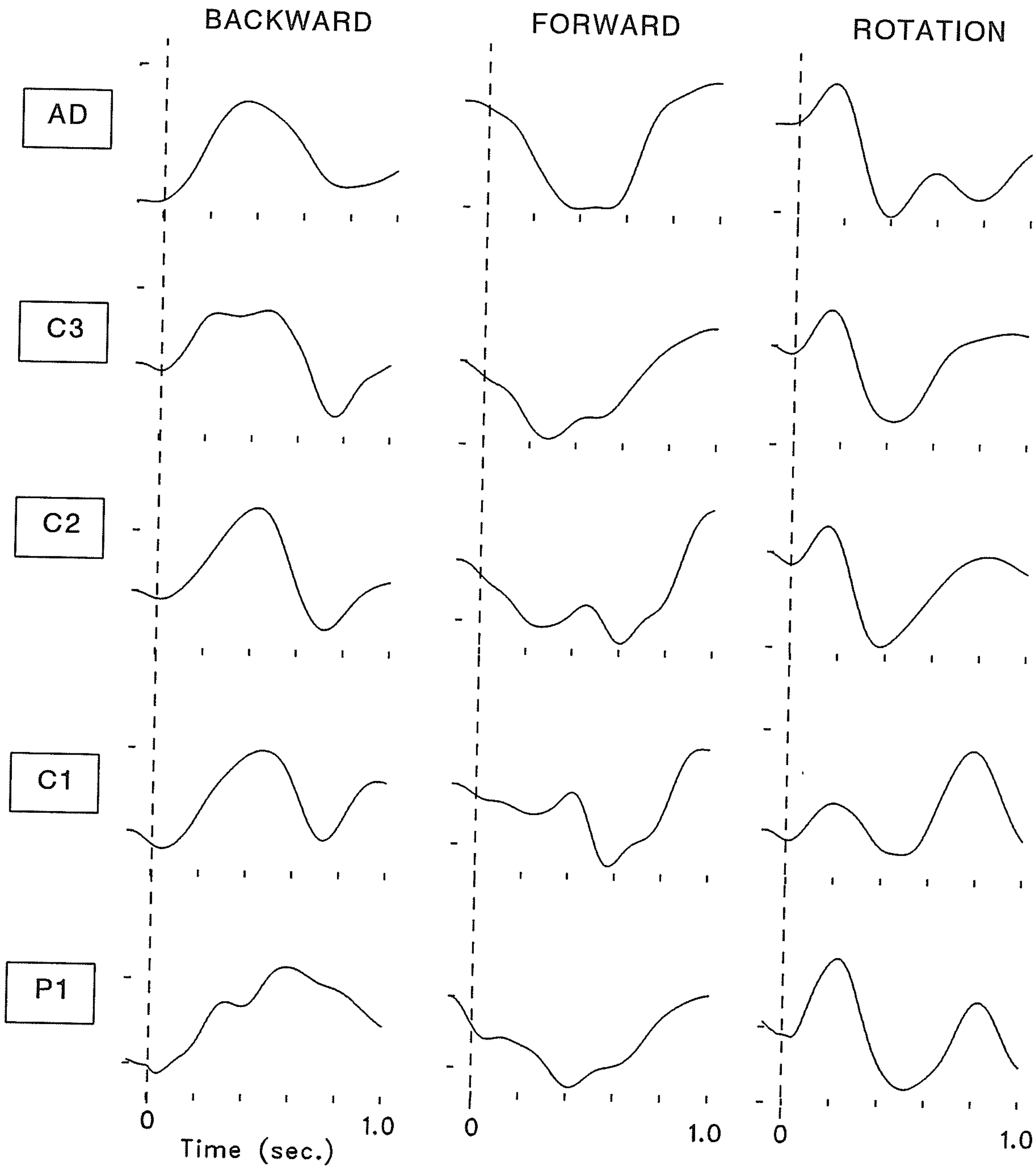
All CFP results presented are in the anterior/posterior direction, since no substantial changes were seen in the medio/lateral direction.

## 1.1. GENERAL FEATURES

CFP recordings in response to backward and forward platform translation and platform rotation of one representative subject from each age group are presented in Fig. 7. Upward shifts in CFP represent anterior displacements towards the forefoot, and downward shifts represent posterior displacements towards the heel. The direction of displacement was the same in all age groups.

In backward translation, the initial response was anterior displacement, the passive displacement of the foot pressure in response to the displacement of the platform. After reaching the peak anterior shift, the CFP changed into a posterior direction and turned back to the original pre-translation equilibrium position. The decline in the anterior shift of the CFP and the posterior path of CFP represents the active response, that is to bring the body back over the base of support. As illustrated in Fig. 7, this basic pattern of CFP displacement was observed in all age groups, although one difference observed in the younger age groups was the presence of small amplitude fluctuations in the CFP recordings. This was seen most distinctly and frequently in the P1 age group although the number of fluctuations differed between

*Fig. 7* **Plots of CFP displacement to backward platform translation, forward platform translation and platform rotation for one representative subject from each age group. Platform velocity in translations and rotations for adults (AD) and C3-C1 age groups was 20 cm/s, 50 °/s, and for P1 age group 15 cm/s, 36 °/s. Dashed vertical lines at time zero indicate onset of platform motion.**



children. The time to reach peak anterior displacement and thus to change direction was longer in children as compared to adults, which suggests a longer time to onset of an active response to counteract the disturbance of equilibrium (see below).

In response to forward translation, the CFP pattern was similar to backward translation but in opposite direction. The initial displacement was in the posterior direction followed by displacement in anterior direction. When the base of support (platform) moved forward, the CFP displacement went in posterior direction. This was followed by a displacement of the CFP in the anterior direction to move the body back over the base of support. As illustrated in Fig. 7 the basic pattern of CFP displacement in response to forward platform translations was the same in all age groups. Here too, fluctuations in the CFP recordings were observed in the younger children, particularly in the C1 and P1 age groups. A more complex pattern of CFP displacement was observed following platform rotations. The initial response was an anterior displacement similar to that observed in backward translation, but of short duration lasting only 100 ms versus 350-450 ms in backward translation. The rapid tilting of the platform, which actually signified a reduction or narrowing of the base of support, resulted in an apparent anterior displacement of the CFP. This was immediately followed by a rapid and large posterior displacement of the CFP which was similar to that following forward translation. This posterior displacement was probably the main disturbance caused by the platform rotations and actually reflected a backward motion of the body relative to a stationary but tilted base of support. The CFP then changed into anterior direction similar to the displacement curve seen in forward translation. The anterior displacement indicated the active movement of CFP into a new equilibrium position. In this respect, it has to be remembered that in rotation, the base of support has acquired a new tilted position after perturbation compared to the starting position (see methods). Fluctuations in the CFP recordings were also observed in some children in the C1 and P1 age groups, but not as frequently as which occurred following backward and forward translations.

## 1.2. TIME TO PEAK CFP DISPLACEMENT

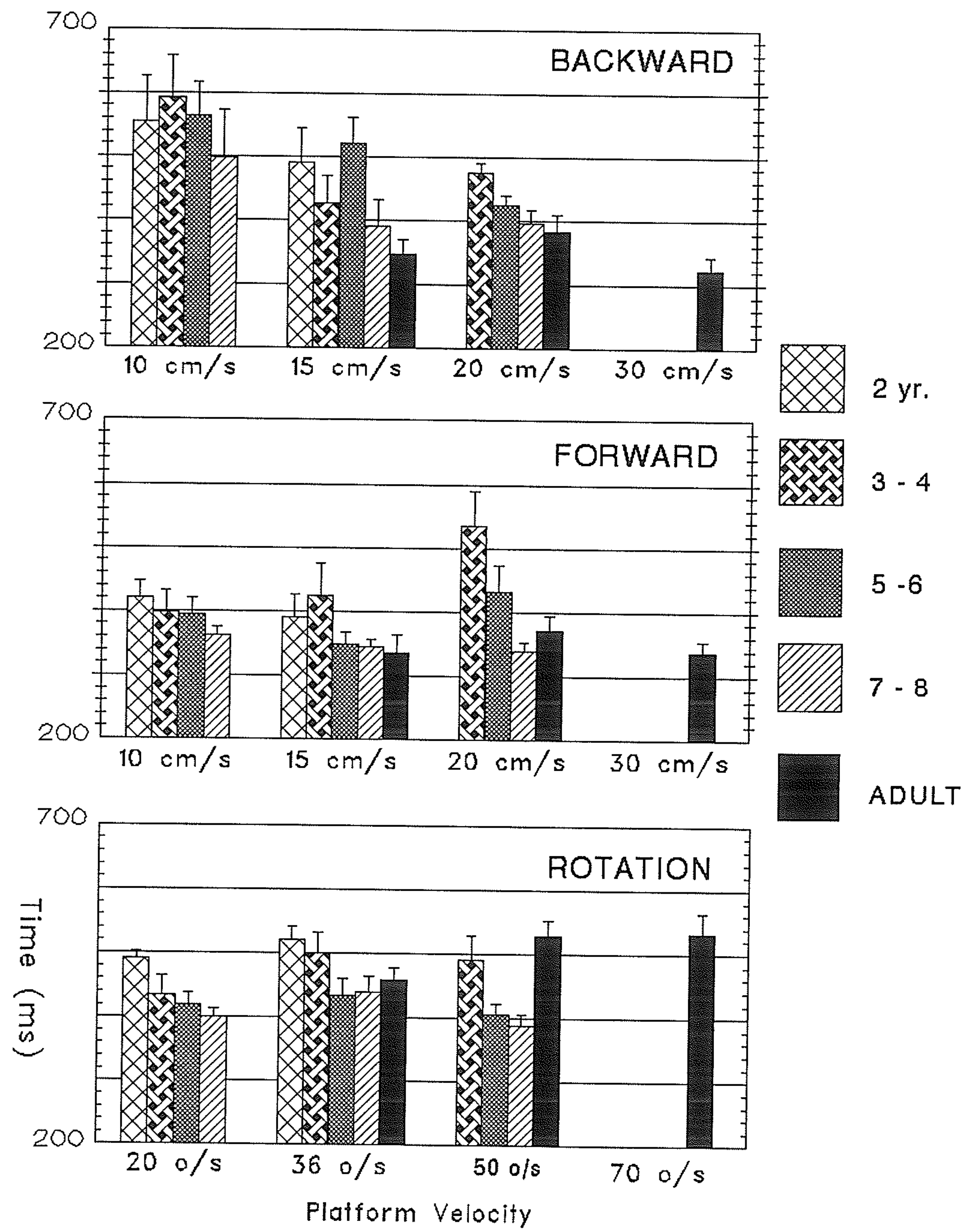
The time to reach initial peak displacement after onset of platform translations and rotations was in the order of 300 to 650 ms. As described below, the onset latency of the earliest muscle activity was in the order of 80 to 100 ms, and the onset of the earliest active angular displacement about ankle, knee or hip, was in the order of 150-250 ms. As described in the methods section, the time to peak CFP displacement does not truly represent the onset time of the active component but rather the functional start of the corrective displacement of the CFP in response to the mechanical platform perturbation. As such, this time is representative of a "performance measure" for the time when the CFP displacement changes direction and returns to an equilibrium position. Figure 8 presents the group means (SEM) of time to peak CFP displacement for adults, C3, C2, C1, P1 at all platform velocities.

Generally, the time to peak CFP displacement was earlier in forward translation than in backward translation and rotation, particularly in children. In adults the time to peak CFP displacement was longer for rotations than in translations.

### EFFECT OF PLATFORM VELOCITY

There was no statistically significant effect of platform velocity on time to peak CFP displacement in any age group for platform translations or rotation, except for C2

*Fig. 8* Group means and standard error of means (SEM) of Time to Peak CFP Displacement in response to backward platform translations, forward platform translations and platform rotations, at all velocities of platform motion..



in backward translation ($p < 0.03$). However, as illustrated in Fig. 8, there was a clear trend towards a decrease in time to peak CFP displacement with increasing platform velocity for all children in backward translation.

EFFECT OF AGE

The main effect of age on time to peak CFP displacement was evaluated using results obtained at common platform velocities (see methods, section statistics).

In backward translations, a statistically significant effect of age on time to peak CFP displacement was observed when adult C3- C2-C1 at platform velocities 15 cm/s and 20 cm/s, were compared ($p < 0.01$). No statistically significant effect of age was found when the C3-C2-C1-P1 (platform velocity 10 cm/s and 15 cm/s) were analyzed. Here, the time to peak CFP increased with decreasing age, ranging from 300 ms in adults to 400/550 ms children.

In forward translation, statistically significant differences were found both in the adult-C3-C2-C1 comparisons ($p < 0.001$), and in the C3-C2-C1-P1 comparisons ($p < 0.05$). Following forward translations, time to peak CFP increased with decreasing age, ranging from 300 ms in adults to 350-450 ms in children (see Fig. 8). Also of note, the 7-8 year olds showed values similar to the adults in the backward and forward translation.

In rotation, for the adult-C3-C2-C1 comparison, the results showed no statistically significant difference. However, as for the C3-C2-C1-P1 comparison a statistically significant difference was found ($p < 0.01$). Like that for platform translation, time to peak CFP displacement increased with decreasing age.

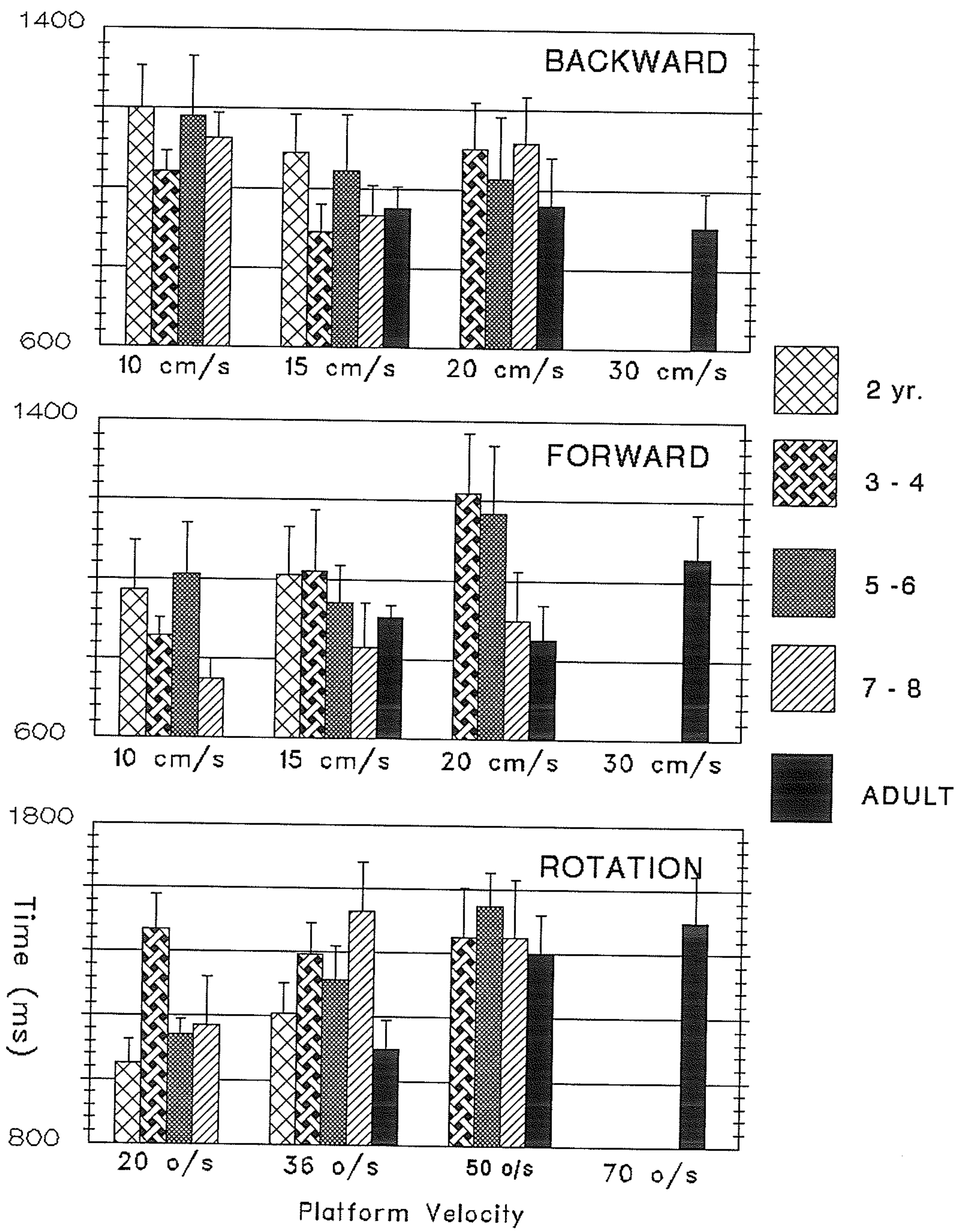
## 1.3. TIME TO RETURN TO EQUILIBRIUM POSITION

This is the time it took for the active component of the CFP displacement to reach an equilibrium position following the platform perturbations. This was determined from the velocity plot when CFP returned to or reached zero velocity after the change in direction of displacement or as in rotation when the new equilibrium position was reached (see Fig. 3, in METHODS SECTION). This position was not necessarily the erect starting position, but never the less an acquired equilibrium position, erect or non-erect. This time value was a quantification of the ability to restore equilibrium after platform perturbation and as such was also used as an indication of balance performance. Generally, the time to equilibrium position was in the range between 800 ms in adults and 800-1100 ms in children in both forward and backward translation. In rotation, the time range to reach equilibrium seemed to be longer, ranging between 1100 ms to 1400 ms (see Fig. 9).

### EFFECT OF PLATFORM VELOCITY

The only statistically significant difference in the effect of platform velocity on time to reach CFP equilibrium position was found in the C2 group ($p < 0.01$) following platform rotation. Here the time value increased with increasing platform rotation velocity.

*Fig. 9* Group means and SEM of Time for CFP displacement to Return to Equilibrium Position in response to backward platform translations, forward platform translations and platform rotations, at all velocities of platform motion.



EFFECT OF AGE

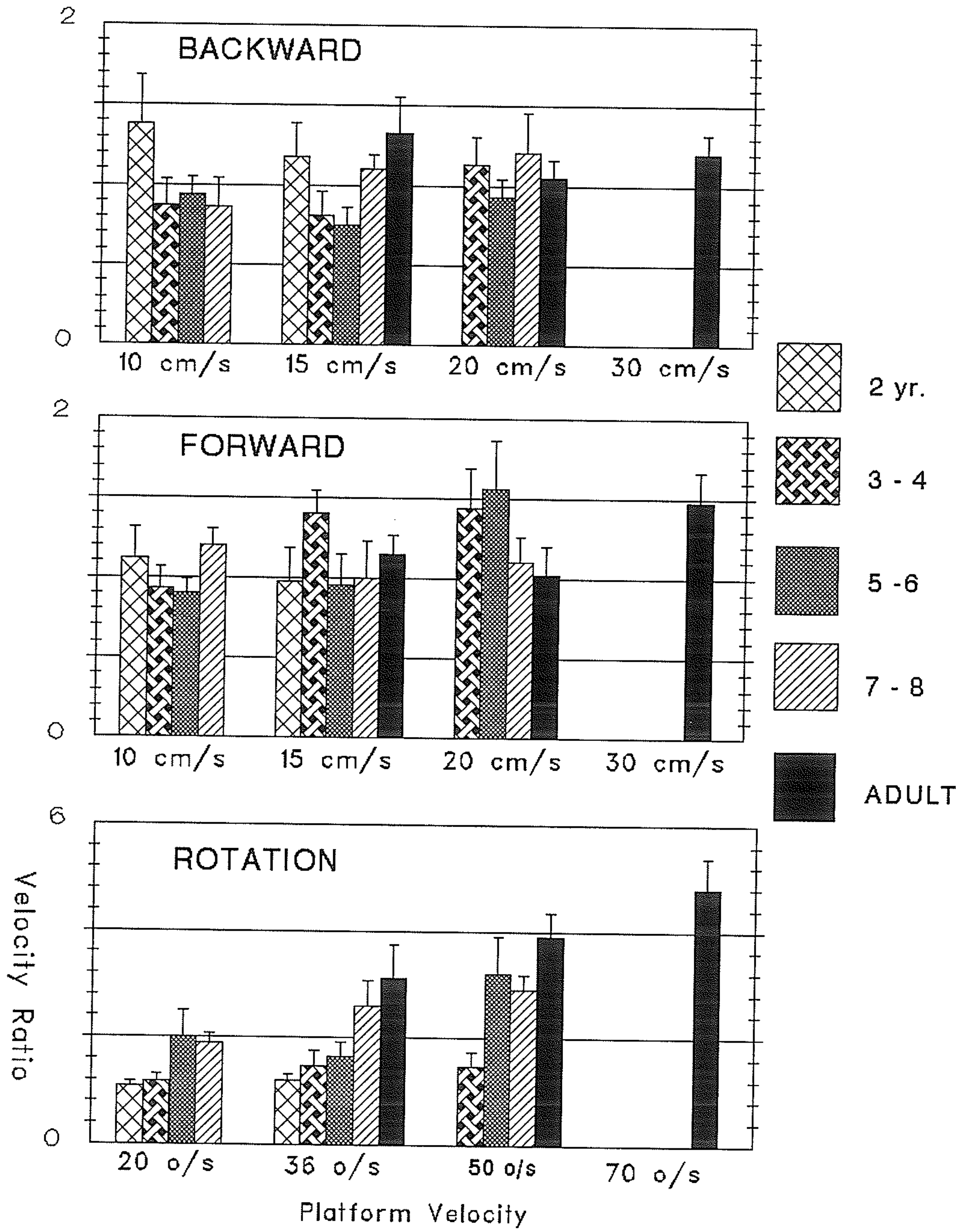
Statistically significant differences between age groups were found in forward translation in both the adult-C3-C2-C1 comparison ($p < 0.002$) and C3-C2-C1-P1 comparison ($p < 0.05$). The time to reach CFP equilibrium position decreased with increasing age. It should be noted that the 7-8 year olds demonstrated time values similar to the adults. No statistical significance of age effect was found in backward translation nor in rotation. However, a clear trend towards decrease in time to reach equilibrium with increasing age was observed in backward translation. In rotation large variations in results made it difficult to support any tendency.

## 1.4. RATIO OF PEAK PASSIVE TO PEAK ACTIVE CFP VELOCITY

This ratio represents an estimate of the relative relationship between the magnitude of the passive and active components of CFP displacement. A value of one means that the peak velocity of the active response was equal to the peak velocity of the passive CFP caused by the platform perturbation. A value larger than one, would indicate lower velocity in the active response than in the passive response. This ratio is considered to be a measure of balance performance in the sense that it provides information about the relative rate of balance compensation.

As illustrated in Fig. 10, the ratios in forward and backward translations were in a similar range, all of them close to 1. Examples of the mean ratio values in forward translation (platform velocity 15 cm/s) were: P1 = 0.96, C1 = 1.4, C2 = 0.95, C3 = 1, AD = 1.16, and backward translation (platform velocity 15 cm/s): P1 = 1.2, C1 = 0.84, C2 = 0.76, C3 = 1.12, AD = 1.36. In rotation, the ratios had higher values for the adult and C3 age group than observed in platform translation, as for

***Fig. 10*** **Group means and SEM of the Ratio of Peak Passive Velocity of CFP displacement to Peak Active Velocity of CFP displacement in response to backward platform translations, forward platform translations and platform rotations, at all velocities of platform motion.**



example, for platform velocity 36°/s: P1 = 1.1, C1 = 1.49, C2 = 1.65, C3 = 2.64, AD = 3.08.

## EFFECT OF PLATFORM VELOCITY

Platform velocity had no significant effect on the peak velocity ratio in any age group or for any type of platform perturbation. However, as presented in Figure 10, C1 and C2 groups showed a clear trend to higher ratios with increasing platform velocity in forward translation, and C2, C3 and adult groups showed a similar trend in platform rotations. This would suggest that for forward translations and rotations, the rate of the compensatory response did decrease relative to the magnitude of the balance disturbance as platform velocity increased. The number of observations is probably the reason for lack of statistical significance.

## EFFECT OF AGE

As described above, the main effect of age on the passive active peak velocity ratio was evaluated using results obtained at common platform velocities. In forward and backward platform translations, the results of ANOVA showed no significant effect of age on peak velocity ratio. On the other hand, in rotation, a significant difference was found in both the AD-C3-C2-C1 comparison ($p < 0.007$), and the C3-C2-C1-P1 comparison ($p < 0.01$). As illustrated in Fig. 10 (Rotation), the passive-active peak velocity ratio decreased with decreasing age, meaning that the rate of the compensating response relative to the magnitude of the disturbance was significantly greater in the younger children.

## 2. EMG

From inspection of the raw EMG records, as presented in Fig. 11 (backward translations), Fig. 12 (forward translation) and Fig. 13 (platform rotations), a complex long duration activation pattern was observed in all muscles and in all three platform perturbations. The four muscles were activated within about 50 ms of each other, and the activity lasted for over 400 ms. This was the case in all subjects.

### 2.1. ONSET LATENCY OF MUSCLE ACTIVATION

Onset latency was assessed as the time interval between the onset of platform displacement and beginning of the first burst of EMG activity that was clearly discernable from any pre stimulus tonic activity. It should be noted that when tonic activity, (observed in some children), made the clear identification of EMG onset difficult, these responses were excluded from quantification (see methods). Generally, a larger variability, as estimated by standard error of the mean in onset of muscle activation, in response to all types of platform perturbations, was observed in the results of the children as compared to in adults. Exceptions to the larger variability in children was found in: TA for rotations, GA for backward translation and rotations, and HAM in forward translation (see below). Fig.14 presents the mean (SEM) onset of muscle activation for all age groups and platform perturbations.

EFFECT OF PLATFORM VELOCITY

The results of statistical analysis (ANOVA) showed no effect of platform velocity on onset of activation of TA, GA, HAM and QUAD for any age group or type of platform

*Fig. 11* EMG recordings of TA, GAST, HAM and QUAD activity during BACKWARD platform translation for one representative subject from each age group. Platform velocity for adults (AD) and C3-C1 age groups was 20 cm/s, and for P1 age group 15 cm/s. Dashed vertical lines at time zero indicate onset of platform motion.

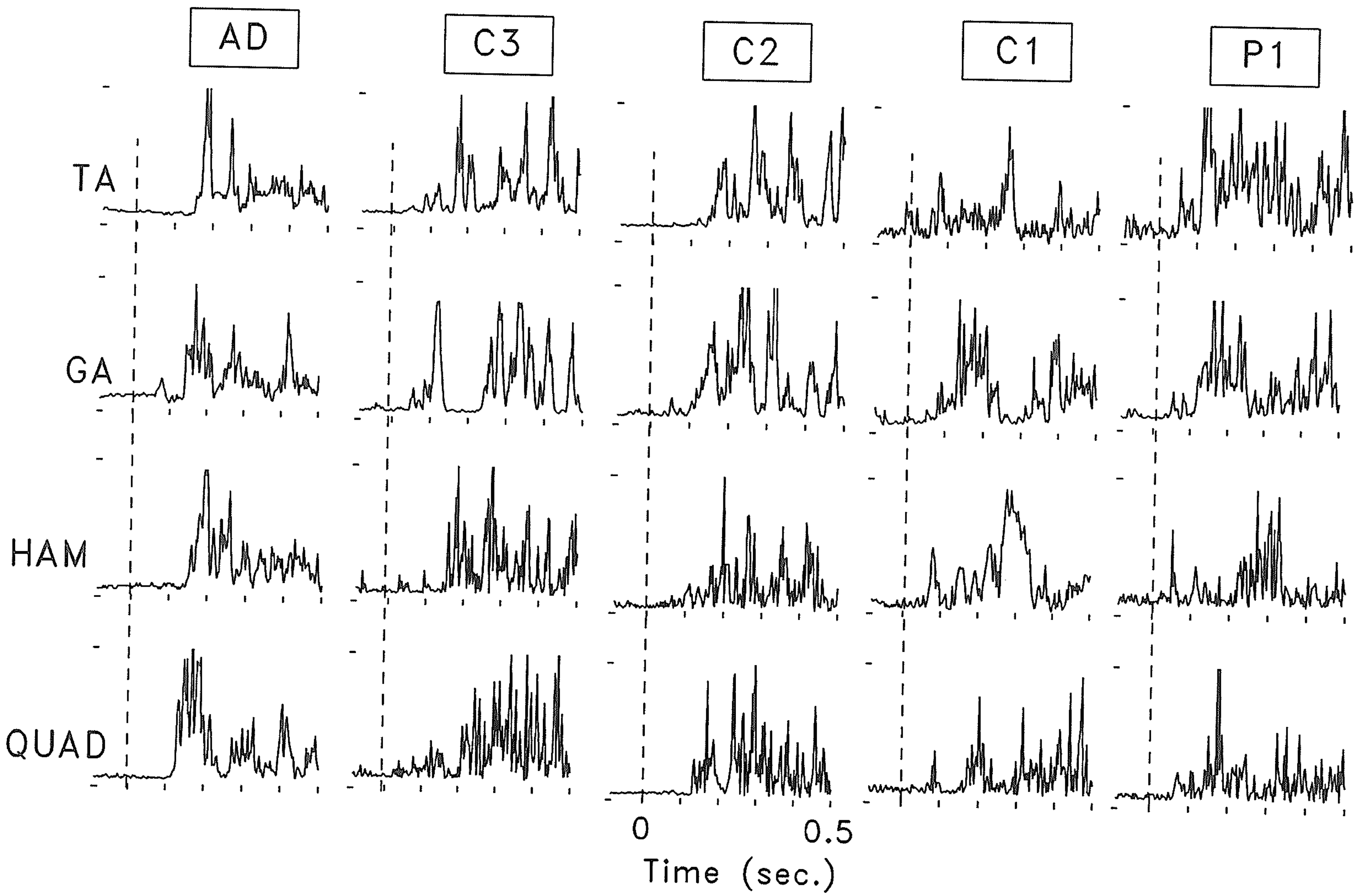


*Fig. 12* **EMG recordings of TA, GAST, HAM and QUAD activity during FORWARD platform translation for one representative subject from each age group. Platform velocity for adults (AD) and C3-C1 age groups was 20 cm/s, and for P1 age group 15 cm/s. Dashed vertical lines at time zero indicate onset of platform motion.**

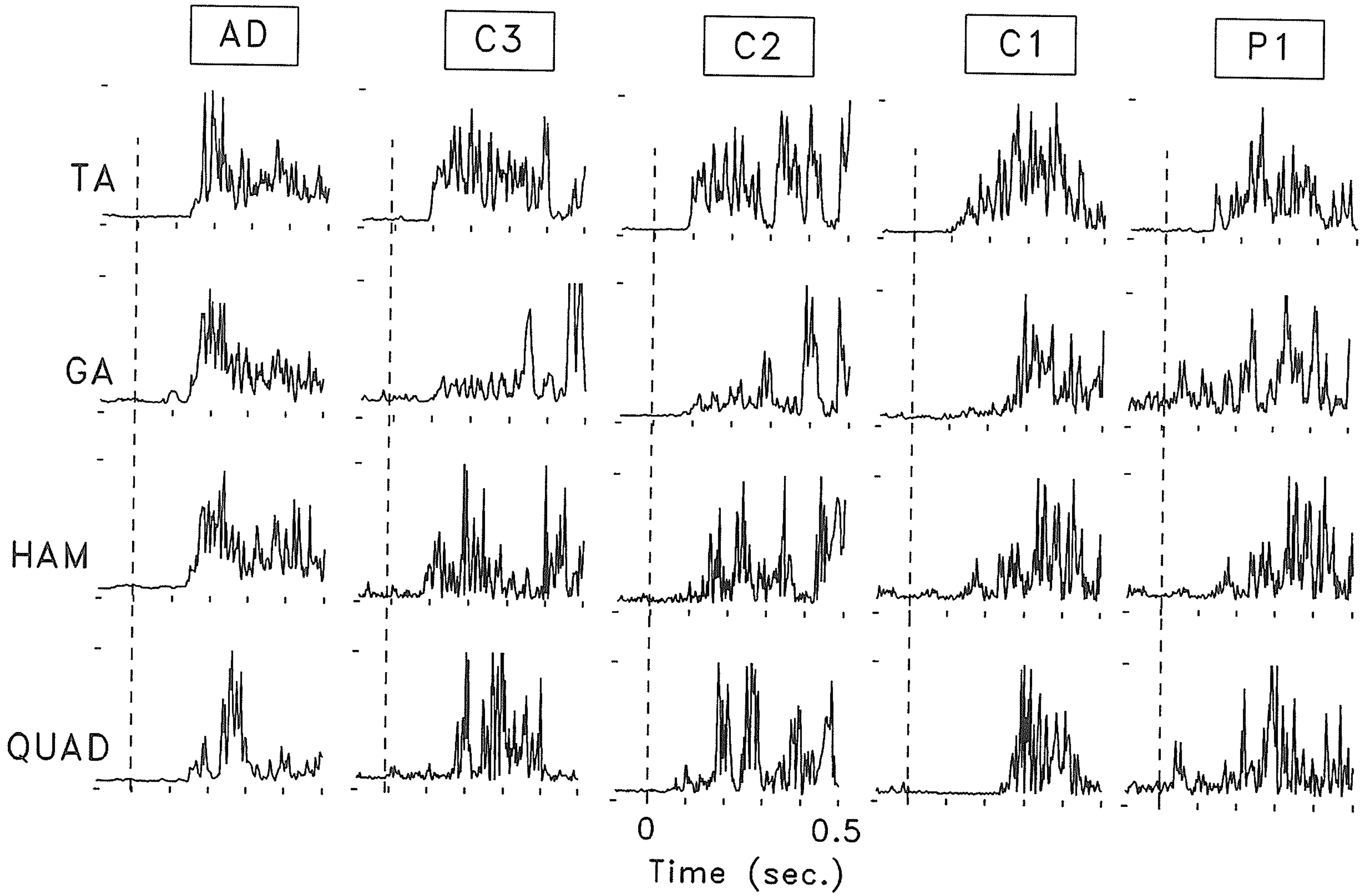


*Fig. 13* EMG recordings of TA, GAST, HAM and QUAD activity during platform ROTATION for one representative subject from each age group. Platform velocity for adults (AD) and C3-C1 age groups was 50 °/s, and for P1 age group 36 °/s. Dashed vertical lines at time zero indicate onset of platform motion.

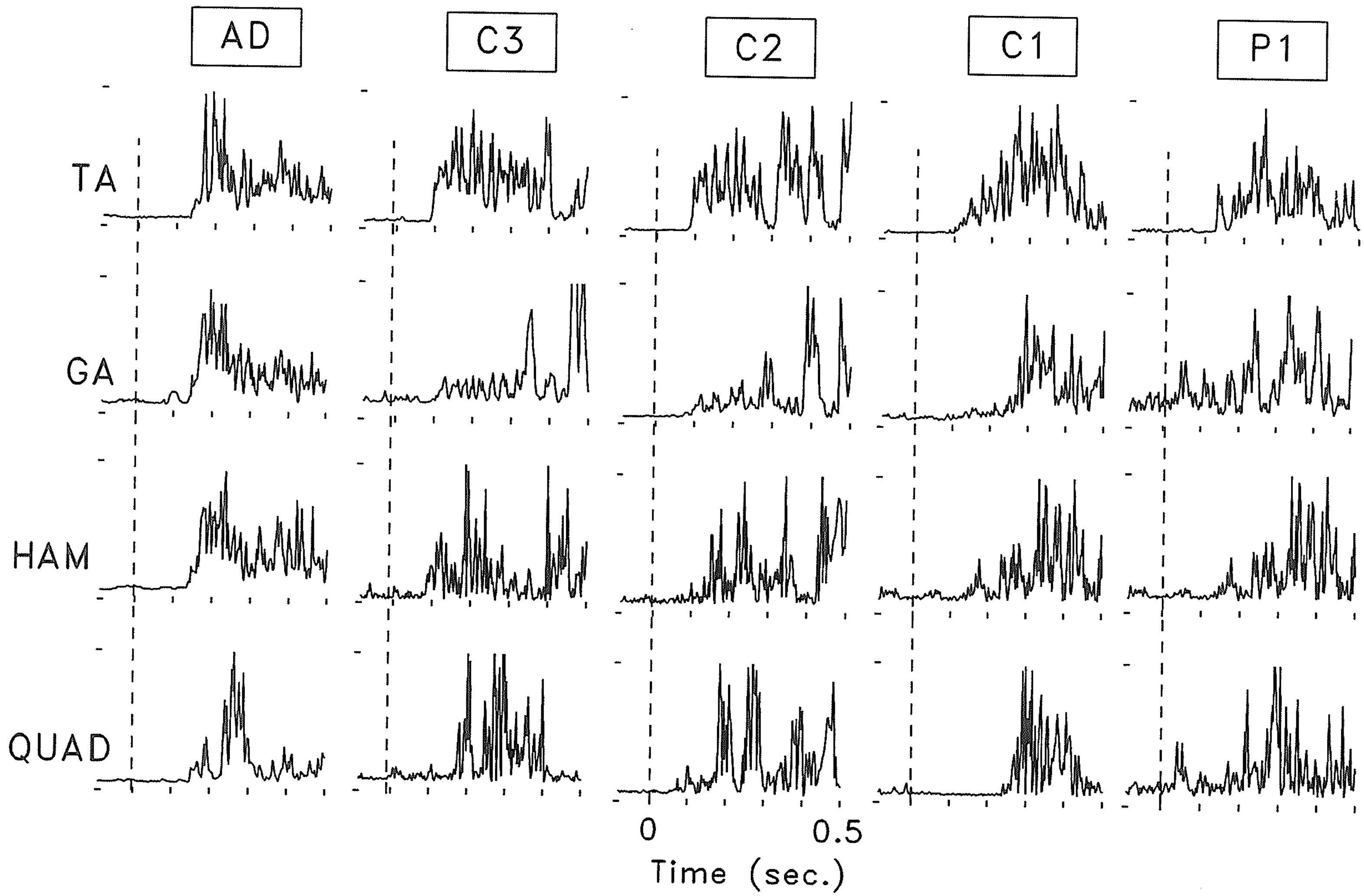
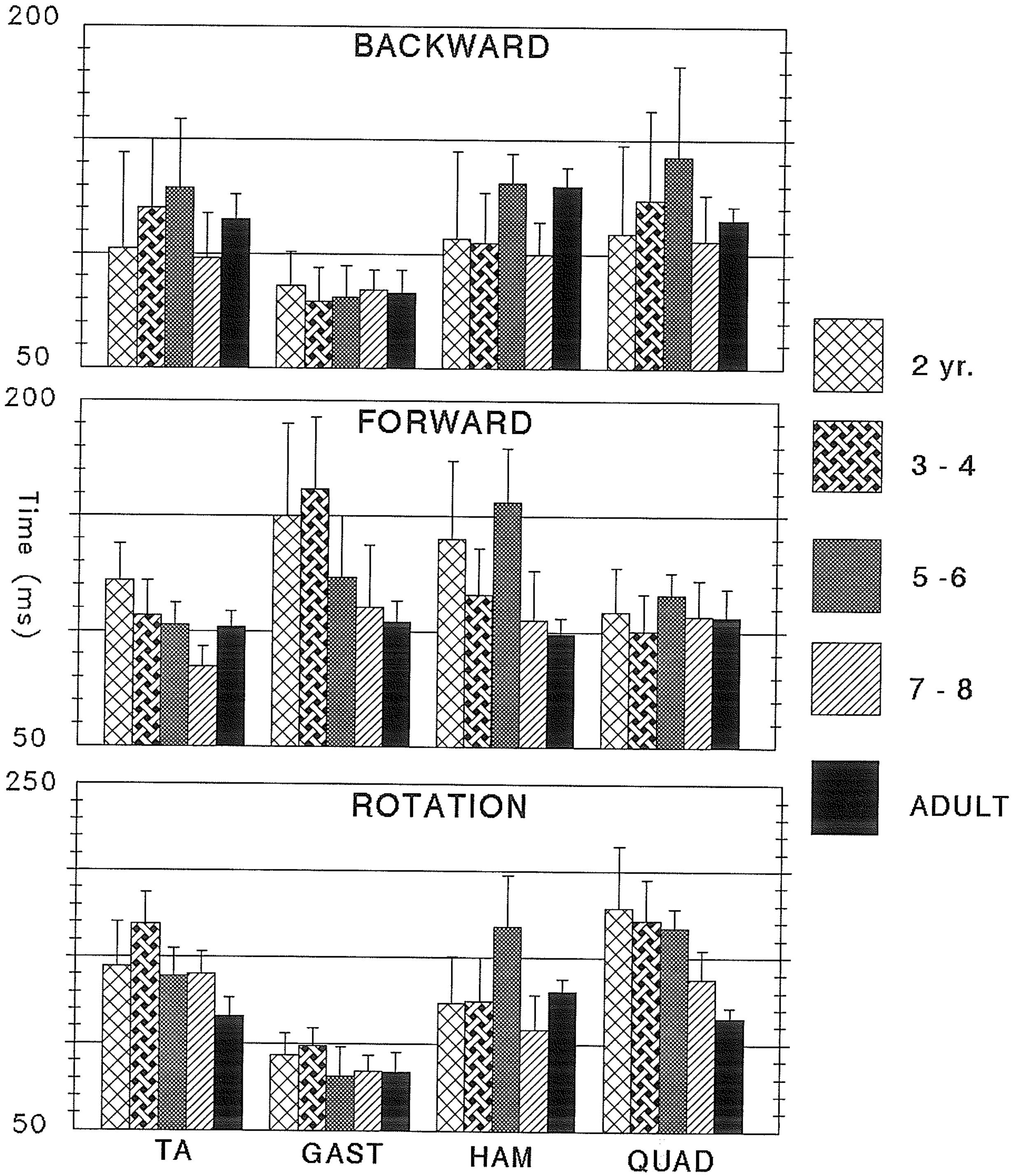


*Fig. 14* Group means and SEM of time to onset of muscle activation in response to backward platform translations, forward platform translations and platform rotations for all muscles. Platform velocity in translations and rotations for adults (AD) and C3-C1 age groups was 20 cm/s, 50 °/s, and for P1 age group 15 cm/s, 36 °/s.



perturbation. Although not statistically significant, a tendency of later onset in the lowest velocity compared to velocity 2 and 3 was seen in all age groups (see Fig. 14).

2.1.1. EFFECT OF AGE - BACKWARD TRANSLATION

No significant age effect on onset latency was found. As illustrated in Fig. 14, in general, the variability in mean onset latency in children was greater than in adults, with exception of the short latency response in GA. Activation of GA was the first response in all groups with mean onset of: adults = 98.3 ± 6.5, C3 = 75.9 ± 5.1, C2 = 87.4 ± 6.1, C1 = 79.6 ± 6.2, and P1 = 79.6 ± 6.4 ms. In all groups, a larger amplitude response was observed in GA, which occurred 30-80 ms after the initial burst of activity. The mean onset of TA was varying without any age pattern: adult 126.6 ± 7.6 ms, C3 = 101.9 ± 12.3, C2 = 145.6 ± 16.1, C1 = 133.5 ± 12.9, P1 = 100.7 ± 13.1 ms. Mean onset of HAM tended to be later in adults than children; adults = 132.6 ± 9.2, C3 = 116.8 ± 12.3, C2 = 118.3 ± 7.9, C1 = 128.1 ± 10.9, and P1 = 100.4 ± 9 ms, whereas mean onset of QUAD was similar in time for onset in adults and C3 (122 ± 6.8 / 125 ± 13.6, respectively), earlier in P1 (91.6 ± 12 ms) and later in C1 and C2 (159 ± 16 and 166.8 ± 22.5, respectively).

As to the temporal order of mean onset latency (see Fig. 14), in C3, GA was followed by TA at a delay of 25 ms and by HAM at a delay of 50 ms. Onset of GA was followed by HAM in the C1 and C2 age groups at a delay of about 32-45 ms. In the C3, C2 and C1 age groups, HAM and TA did vary in the temporal sequence that they followed onset of GA response. The delay between the mean onset of TA and GA in C1 and C2 was 57-58 ms, thus this was 20-30 ms longer than the delay observed in C3 (mean onset delay = 25 ms) and adults (mean onset delay = 28 ms). The temporal order of mean onset latencies in the P1 group at a platform velocity of 15 cm/s was; GA first, followed by QUAD at a delay of 12 ms, and TA and HAM at a delay of about 20 ms after GA, whereas at the platform velocity 10 cm/s, P1 responded with TA, QUAD and HAM all at the same time. TA responses were evident in nearly all records and most often preceded or occurred at the same time as the QUAD response of the other children age groups.

In the adult, the QUAD response occurred earlier than the HAM and TA response, the mean latency relationship between QUAD and HAM was 10.6 ms. The reverse was true for the children, here the HAM response most often was earlier than the QUAD response, except in the lowest velocity in C3, where QUAD was early. Age groups C1 and C2 showed the longest delay of QUAD onset. The mean time delay between activation of antagonists, HAM and QUAD in children was; C3 = 9, C2 = 48, C1 = 31 and P1 = 9 ms. When examining each individual, in most cases the results showed the tendency that this opposite timing between HAM and QUAD did correspond to the employment of flexed knee strategy when HAM was the earliest and extended knee strategy when QUAD was the earliest (see SECTION 3 - KINEMATICS).

### 2.1.2. EFFECT OF AGE - FORWARD TRANSLATION

The only statistically significant age effect was found in the adult-C3-C2-C1 comparison for onset of HAM ($p < 0.01$) which was earlier in adults compared to children. As illustrated in Fig. 14, mean onset of TA and QUAD activation did not show large differences. Mean (SEM) values for TA; adults = 111 ± 3.3, C3 = 106.3 ±

5.9, C2 = 120 ± 7.4, C1 = 117.7 ± 6, and for QUAD; adults = 97 ± 8.5, C3 = 123.3 ± 8.1. C2 = 129.2 ± 9 and C1 = 105.7 ± 7.2. The youngest group (P1) presented the largest variability for TA, 128 ± 10 and for QUAD, 125 ± 12.4. The variability in the responses was generally higher in all muscles in the P1 age group than in the other groups. In regards to GA activation, mean (SEM) onset values of the C1 and P1 age groups were later than the other age groups; adults = 126 ± 6.9, C3 = 112.1 ± 10.3, C2 = 136.9 ± 13, C1 = 165.6 ± 14.7, P1 = 188.3 ± 18. The onset of activity in HAM showed less difference between age groups: adults = 103.3 ± 3.5, C3 = 125 ± 11, C2 = 135.5 ± 12.6, C1 = 111.7 ± 14.7 and P1 = 152.2 ± 18.1. As seen from the standard error of mean, the variability in onset of GA and HAM activation was large in all childrens' groups compared to the adults.

In regards to the temporal pattern, in the adults, HAM responded earliest, which was followed by a near synchronous activation of TA and GA and QUAD at a delay of 6-10 ms. The onset times were very close which made it difficult to describe a precise sequence of onset activity in adults. With the exception of TA which was the first response, a similar pattern of close temporal order was observed in the C3 age group. Here, GA activation occurred 6-7 ms later than TA, followed by a synchronous activation of HAM and QUAD at a delay of 18 ms from TA onset. The younger children did not exhibit the near synchronous activation pattern of the adults and C3 age group. TA and QUAD were activated earlier than GA and HAM. Activation of GA was the latest for the C1 and P1 age groups, GA was 60 ms later than TA in the youngest group, 48 ms in the C1 group and 16 ms in the C2 group. Generally, from inspection of the results, the two youngest age groups frequently presented a proximal to distal response, in that, QUAD was activated before TA. A tendency of more variation in the temporal order was observed in the results from the two youngest age groups. This variation of temporal order was more evident in forward translation compared to both backward translation and rotation.

### 2.1.3. EFFECT OF AGE - PLATFORM ROTATION

The adults had earlier onset in both TA and QUAD than the C3- C2-C1 group. The difference for QUAD was statistically significant at both platform velocities (at 36 °/s = $p < 0.01$ and at 50°/s = $p < 0.004$). The earlier mean onset latency of TA in the adult-C3-C2-C1 comparison, was only statistically significant in the highest platform velocity of 50°/s ($p < 0.02$). The results of the C3-C2-C1-P1 comparison showed no statistically significant differences. The mean onset of TA activation in the adults was 128.7 ± 5 ms. The C3 and C2 age groups showed similar onset latencies in TA of 151 ± 7.1 and 158.6 ± 7.8 ms respectively, whereas the C1 and P1 age groups had slightly longer latencies of 170 ± 12 and 161.5 ± 12 ms, respectively. The mean onset latencies for QUAD were: adults = 121.2 ± 7.4 ms C3 = 176.6 ± 9.6, C2 = 169.4 ± 10.3, C1 = 185.8 ± 10.7 and P1 = 193.4 ± 17.5 ms. Although not statistically significant, the mean (SEM) values of GA onset increased with decreasing age; adults = 73.3 ± 6 ms and C3 = 73.8 ± 5.8 ms showing the shortest mean onset, C2 = 81.6 ± 9.1 ms, C1 = 85.3 ± 7.6 ms, and P1 = 108.4 ± 16 ms. As for HAM, mean (SEM) values were similar in all groups: adults = 145.8 ± 6.4, C3 = 139.6 ± 11.1, C2 = 138.9 ± 14.1, C1 = 142.4 ± 11.9 and P1 = 161 ± 16.

In regards to the temporal pattern, all groups responded with GA first, but for TA, HAM and QUAD, the temporal order of EMG response differed between children and adults (see Fig. 14). In the adults, approximately 50 ms after the GA response, TA and QUAD were activated at nearly the same time. This was followed by activation of HAM about 70 ms after activation of GA. The order of muscle activation in the children groups following GA, was HAM at about 50 ms in all children. Activation of TA followed; in the C3 group by 70 ms, in the C2 group by 65 ms, in the C1 group by 85 ms, and P1 at the shortest delay of 53 ms. QUAD responded last at about 95 ms after GA activation in the C3, C2 and C1 age groups, and at 85 ms in the P1 age group. The activation of antagonist muscles QUAD and HAM was reversed in the children (HAM first) as compared to the adults (QUAD first). Furthermore, the time delay between activation of HAM and QUAD was longer in children than adults; adult = 16 ms C3 = 37 ms, C2 = 36 ms, C1 = 43 ms and P1 = 32 ms.

## 2.2. MAGNITUDE OF MUSCLE ACTIVATION

As described in the Methods, the magnitude of the muscle response to platform translation and rotation was determined from the calculation of the area of the EMG signals during two time intervals; the first 50 ms after onset of muscle activation and a 200 ms interval following this interval. It should be noted that for translation backward and rotation, the area of the first 50 ms of the GA response would most likely represent the effect of the short latency, segmental stretch reflex (Gottlieb and Agarwal 80, Lee and Tatton 83). Similarly, in forward translation, the area of the first 50 ms of the TA response would most likely represent the effect of the stretch reflex.

### 2.2.1. EFFECT OF PLATFORM VELOCITY ON RESPONSE MAGNITUDE

In order to examine the effect of platform velocity on EMG area, it was necessary to normalize the values or EMG area among the individuals within each age group (see Methods). Generally, platform velocity seemed to have less influence on the magnitude of the response in platform rotation as compared to platform translations, particularly in the three youngest childrens' groups for the 200 ms interval. The group means (SEM) of the normalized EMG area for the 50 ms and 200 ms interval at the various platform velocities are present in Fig. 15A (backward translation), Fig. 15B (forward translation and Fig. 15C (platform rotation).

BACKWARD TRANSLATION

Table 1 presents the p values of the results of ANOVA testing the effect of platform velocity on EMG area, for all age groups, and both time intervals. In the adults, an effect of platform velocity on the EMG area of the first 50 ms was statistically significant in all muscles except TA, which only showed a small tendency of increased activity with increased platform velocity (see Fig. 15A). This was very different from the children where statistical significant effect of platform velocity was only shown for HAM in C2 ( $p < 0.01$) and in P1 ($p < 0.05$). Although in the C1 and C3 age groups a trend of increased activity of HAM between the platform velocity of 10 cm/s to 15 cm/s was observed. In regards to EMG area of the 200 ms interval, adult results showed a statistically significant effect of platform velocity in the magnitude of EMG area of all muscles. Whereas for the children, significant statistical effect of platform velocity on EMG area was observed in the C3 and C2 age groups in all muscles but GA; in the C1 age group the only significant increase in EMG area was of GA (although not statistically significant, a clear trend towards increased EMG area with increased velocity was seen in TA, HAM and QUAD), and the P1 age group

*Fig. 15A* Group means and SEM of the normalized EMG area of the 50 ms and 200 ms intervals for TA, GAST, HAM and QUAD activity in response to BACKWARD platform. Values for V1 represent group averages of EMG area at platform velocity 1 divided by the sum of the EMG area at platform velocity 1 and 2 and 3. Values for V2 represent group averages of EMG area at platform velocity 1 divided by the sum of the EMG area at platform velocity 1 and 2 and 3. Values for V3 represent group averages of EMG area at platform velocity 1 divided by the sum of the EMG area at platform velocity 1 and 2 and 3.

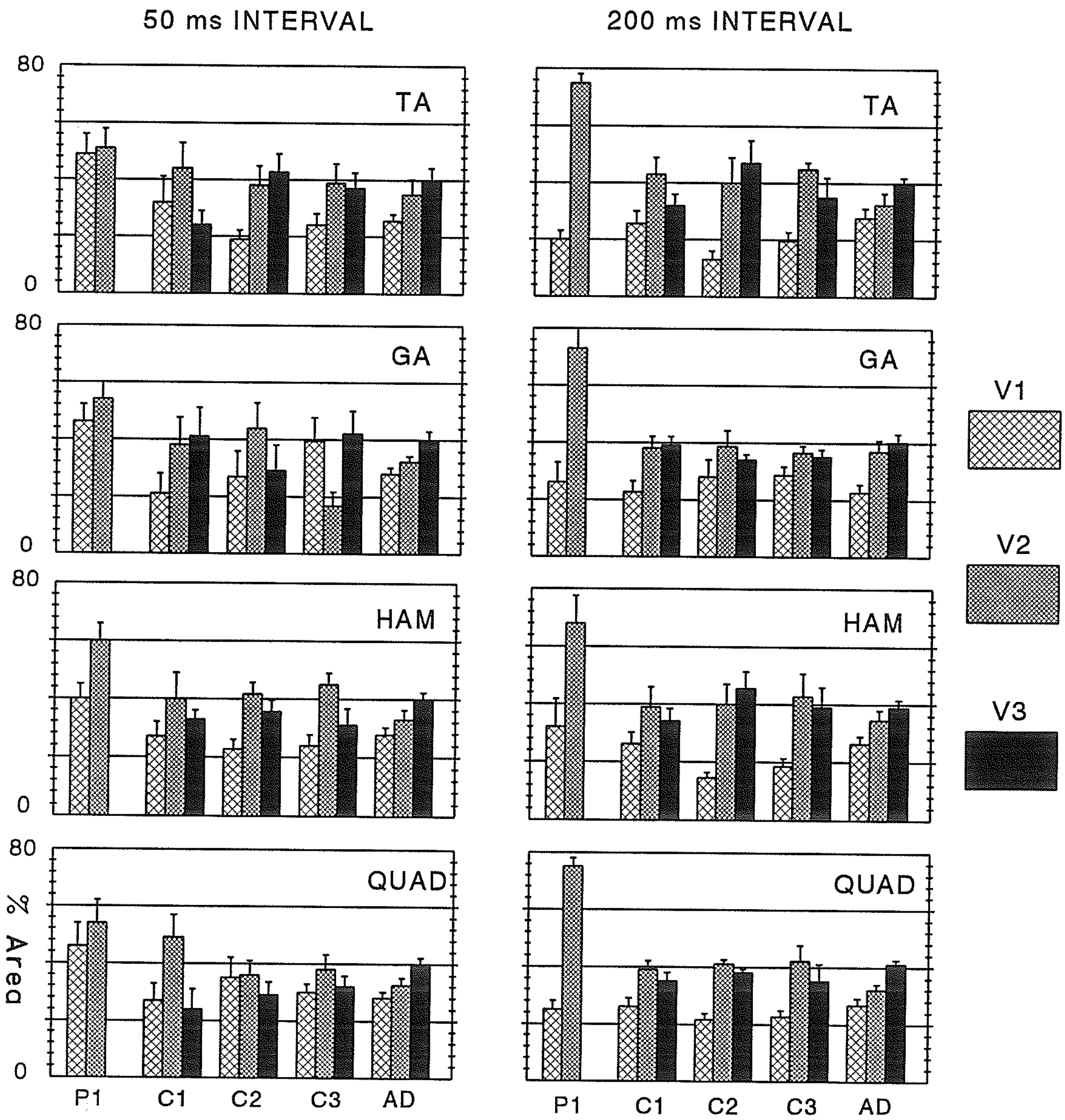


***Fig. 15B*** **Same as Fig. 15A, except mean (SEM) normalized EMG area of muscle activity in response to FORWARD platform translations.**

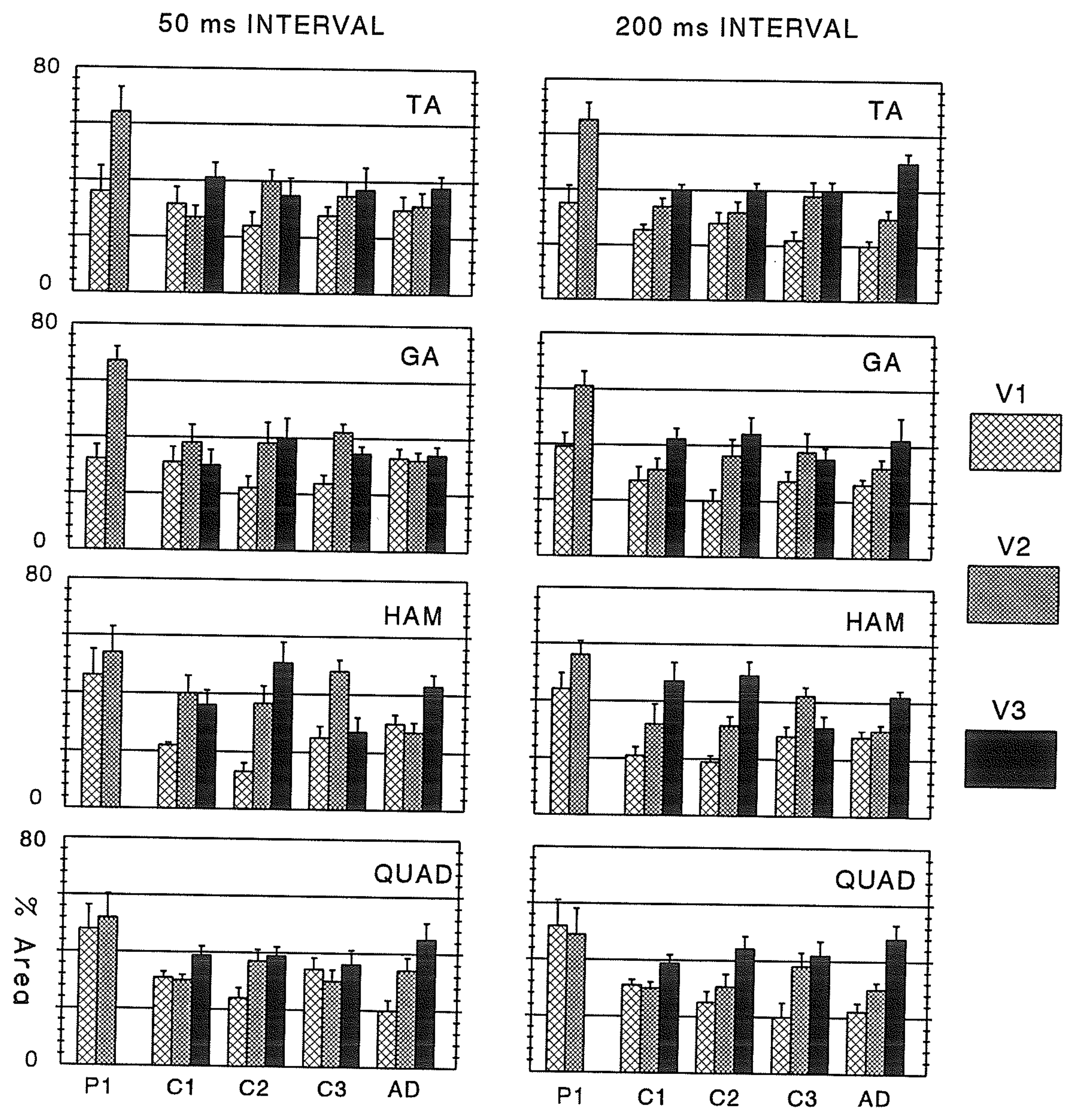
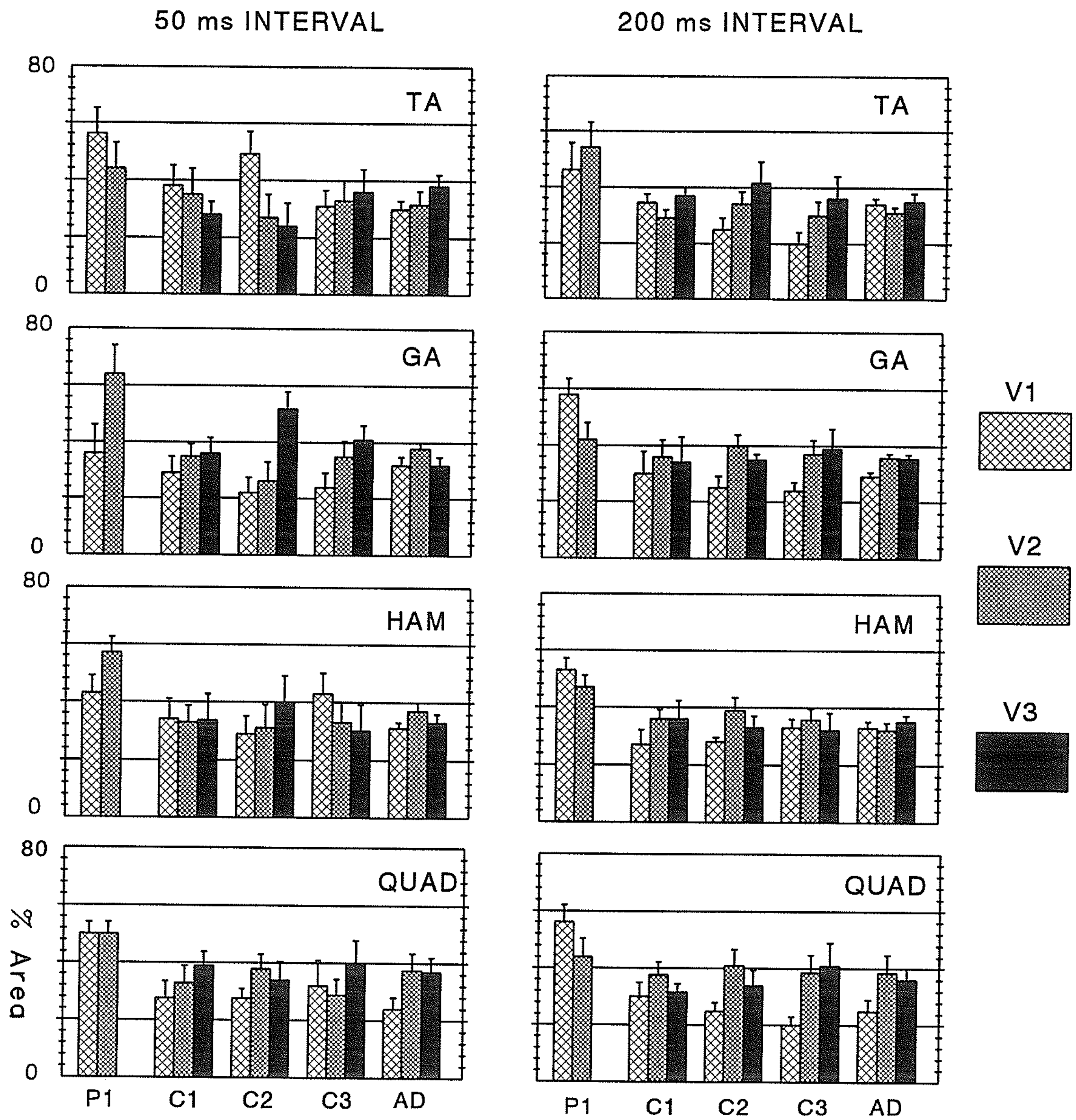


***Fig. 15C*** **Same as Fig. 15A, except mean (SEM) normalized EMG area of muscle activity in response to platform ROTATIONS.**



presented a significant increase, with increasing platform velocity, in all muscles.

*TABLE 1* **P values obtained form ANOVA - Effect of platform velocity on normalized EMG area of the 50 ms and 200 ms intervals for TA, GA, HAM and QUAD activity in response to BACKWARD platform translation.**

| | TA | | GA | | HAM | | QUAD | |
|---|---|---|---|---|---|---|---|---|
| **INTERVAL** | **50** | **200** | **50** | **200** | **50** | **200** | **50** | **200** |
| **AD** | NS | .05 | .005 | .01 | .03 | .03 | .05 | .02 |
| **C3** | NS | .02 | NS | NS | NS | .03 | NS | .05 |
| **C2** | NS | .01 | NS | NS | .01 | .01 | NS | .03 |
| **C1** | NS | NS | NS | .01 | NS | NS | .05 | NS |
| **P1** | NS | .001 | NS | .001 | .05 | .01 | NS | .001 |

FORWARD TRANSLATION

Table 2 presents the p values of the results of ANOVA testing the effect of platform velocity on EMG area, for all age groups and both time intervals. In adults, statistically significant effects of platform velocity on EMG area were seen in HAM and QUAD for the 50 ms interval, and in all muscles for the 200 ms interval. In the children, the effect of platform velocity on EMG area in the 50 ms interval was less consistent. Significant effects were found: in the C3 age group for GA and HAM, in C2 age group for HAM and QUAD, in C1 age group for HAM only, and in P1 for TA and GA. In regards to the 200 ms interval, the largest deviation from adult results was found in the youngest age group who only showed significant effects of platform velocity in the two distal muscles TA and GA. The results of the statistical analysis revealed significant effects of platform velocity; in all muscles but GA in the C3 age group, in all muscles but TA in the C2 age group (although a trend to increased TA activity with increased platform velocity was observed see Fig. 15B), and in all muscles but QUAD in the C1 age group.

***TABLE 2*** **P values obtained form ANOVA - Effect of platform velocity on normalized EMG area of the 50 ms and 200 ms intervals for TA, GA, HAM and QUAD activity in response to FORWARD platform translation.**

| | TA | | GA | | HAM | | QUAD | |
|---|---|---|---|---|---|---|---|---|
| **INTERVAL** | **50** | **200** | **50** | **200** | **50** | **200** | **50** | **200** |
| **AD** | NS | .001 | NS | .005 | .01 | .005 | .005 | .02 |
| **C3** | NS | .01 | .05 | NS | .01 | .05 | NS | .01 |
| **C2** | NS | NS | NS | .01 | .001 | .005 | .01 | .01 |
| **C1** | NS | .05 | NS | .05 | .05 | .005 | NS | NS |
| **P1** | .01 | .005 | NS | .01 | .02 | ..01 | NS | NS |

PLATFORM ROTATION

Table 3 presents the p values of the results of the ANOVA, testing the effect of platform velocity on EMG area, for all age groups and both time intervals. As stated above, the EMG area seemed to be less influenced by increasing platform velocity input in rotation compared to platform translations (see Fig. 15C). No statistically significant effect of platform velocity on EMG area magnitude was seen in adults in the 50 ms interval, and in the children, statistically significant effect of platform velocity was only found in GA for the C3 and C2 age group. In regards to the 200 ms interval; adults and C3 age group presented statistically significant effects of platform velocity on EMG area of GA and QUAD ($p < 0.05$). No other tendencies of velocity influence was seen.

***TABLE 3*** **P values obtained form ANOVA - Effect of platform velocity on normalized EMG area of the 50 ms and 200 ms intervals for TA, GA, HAM and QUAD activity in response to platform ROTATIONS.**

| | TA | | GA | | HAM | | QUAD | |
|---|---|---|---|---|---|---|---|---|
| **INTERVAL** | **50** | **200** | **50** | **200** | **50** | **200** | **50** | **200** |
| **AD** | NS | NS | NS | .05 | NS | MS | NS | .05 |
| **C3** | NS | NS | .05 | .05 | NS | NS | NS | .05 |
| **C2** | NS | NS | .02 | NS | NS | NS | NS | NS |
| **C1** | NS | NS | NS | NS | NS | NS | NS | NS |
| **P1** | NS | NS | NS | NS | NS | NS | NS | NS |

### 2.2.3. COMPARISONS OF MAGNITUDE OF MUSCLE ACTIVATION BETWEEN DIFFERENT TYPES OF PLATFORM PERTURBATIONS

In order to compare the magnitude of muscle activity employed at the different types of platform translation, the EMG area was normalized for platform type (see METHODS). Perturbations are here presented in the short form: backward translation = BT, forward translation = FT, and rotation = R. The group means (SEM) of the normalized EMG area for the 50 ms and 200 ms interval at the various platform velocities are present in Fig. 16A (TA), Fig. 16B (GA), Fig. 16C (HAM) and Fig. 16D (QUAD). Table 4 presents the p values of the results of ANOVA testing effects of type of platform perturbation on EMG area, for all age groups and both time intervals.

#### TIBIALIS ANTERIOR

The magnitude of TA muscle activity during the specified time periods showed a clear pattern in all age groups and at all platform velocities. The statistical analysis revealed that the magnitude of TA activation was significantly larger for FT and R than for BT in all age groups. This was true for both the 50 ms and the 200 ms intervals ($p < 0.001$). With respect to the relative EMG area of TA muscle activity in response to BT, FT and R, it has to be noted that in both forward translation and rotation, the active compensating response to perturbation in the ankle was dorsiflexion (see SECTION 3 - KINEMATICS).

#### GASTROCNEMIUS

In adults the magnitude of GA activation showed no difference between perturbations in the 50 ms interval. In the children groups, a clear trend of stronger GA

*Fig. 16A* Group means and SEM of the normalized EMG area of the 50 ms and 200 ms intervals for TA activity in response to backward translation, forward translation and platform rotations. Values for backward translation at each platform velocity represent group averages of EMG area to backward translations divided by the sum of the EMG area to backward translation (BT) and forward translations (FT) and platform rotations (R). Values for FT represent group averages of EMG area to FT divided by the sum of the EMG area to BT and FT and R. Values for R represent group averages of EMG area to R divided by the sum of the EMG area to BT and FT and R.

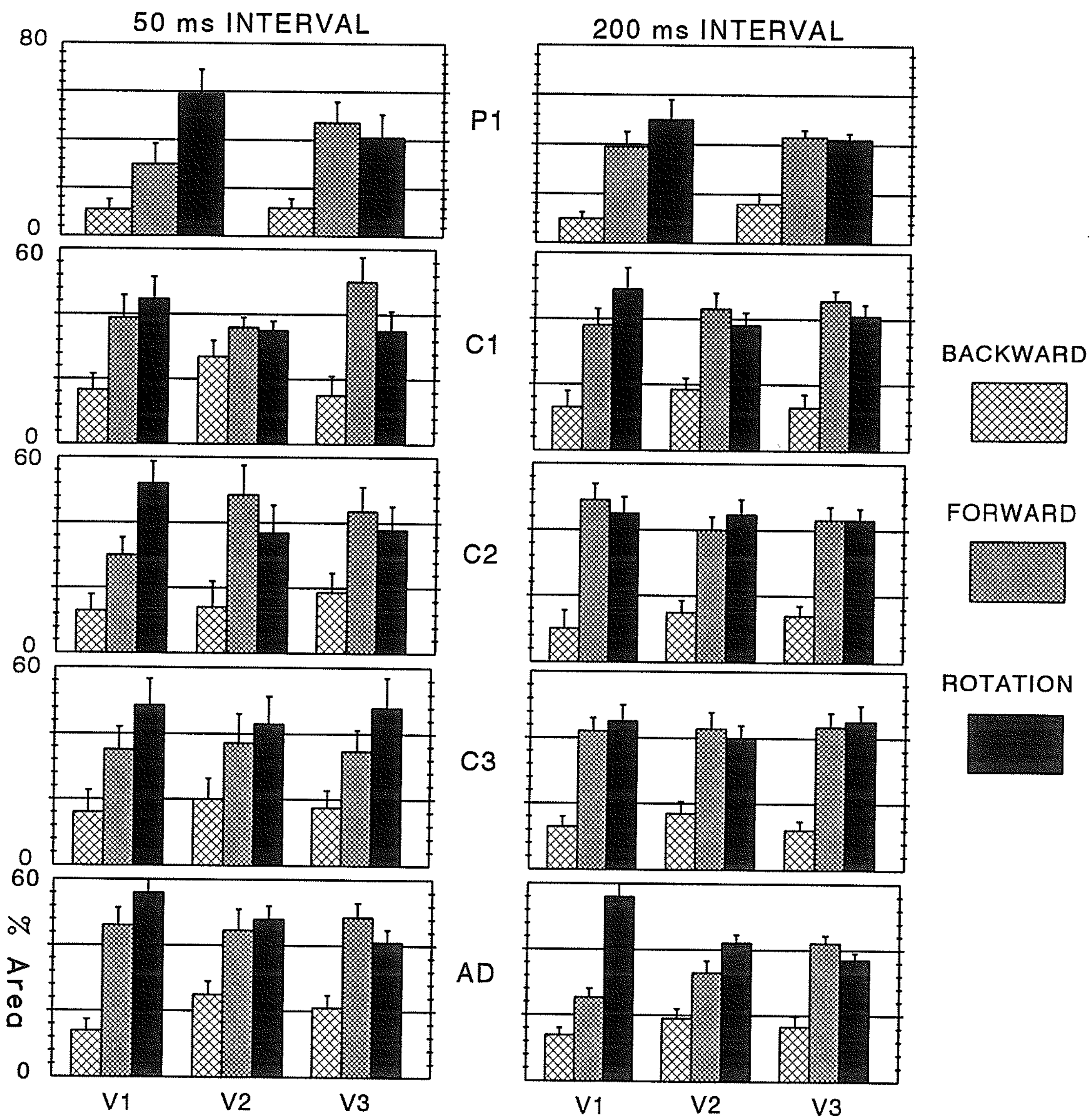


*Fig. 16B* **Same as Fig. 16A, except mean (SEM) normalized EMG area of GAST muscle activity.**

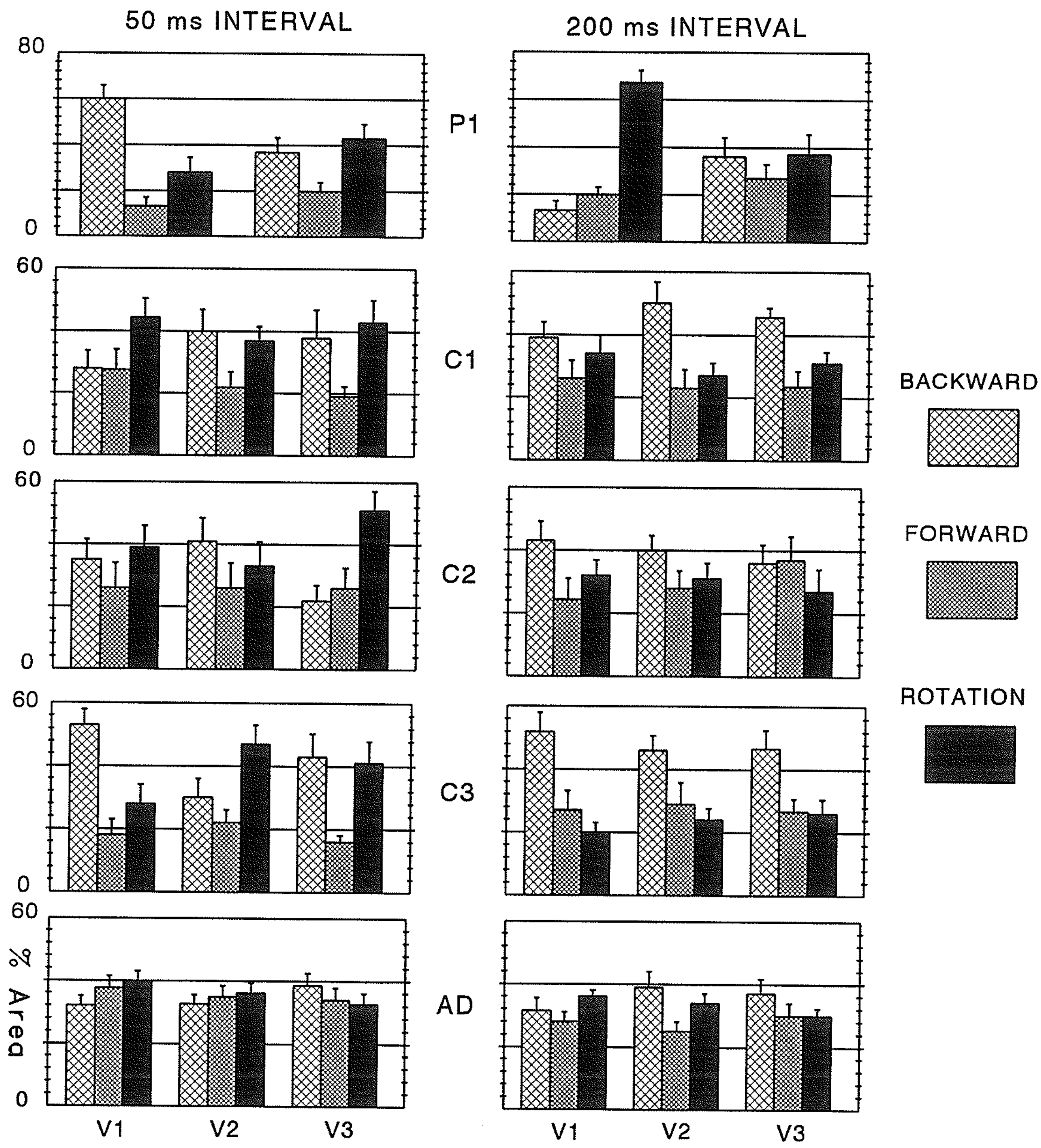


*Fig. 16C* **Same as Fig. 16A, except mean (SEM) normalized EMG area of HAM muscle activity.**

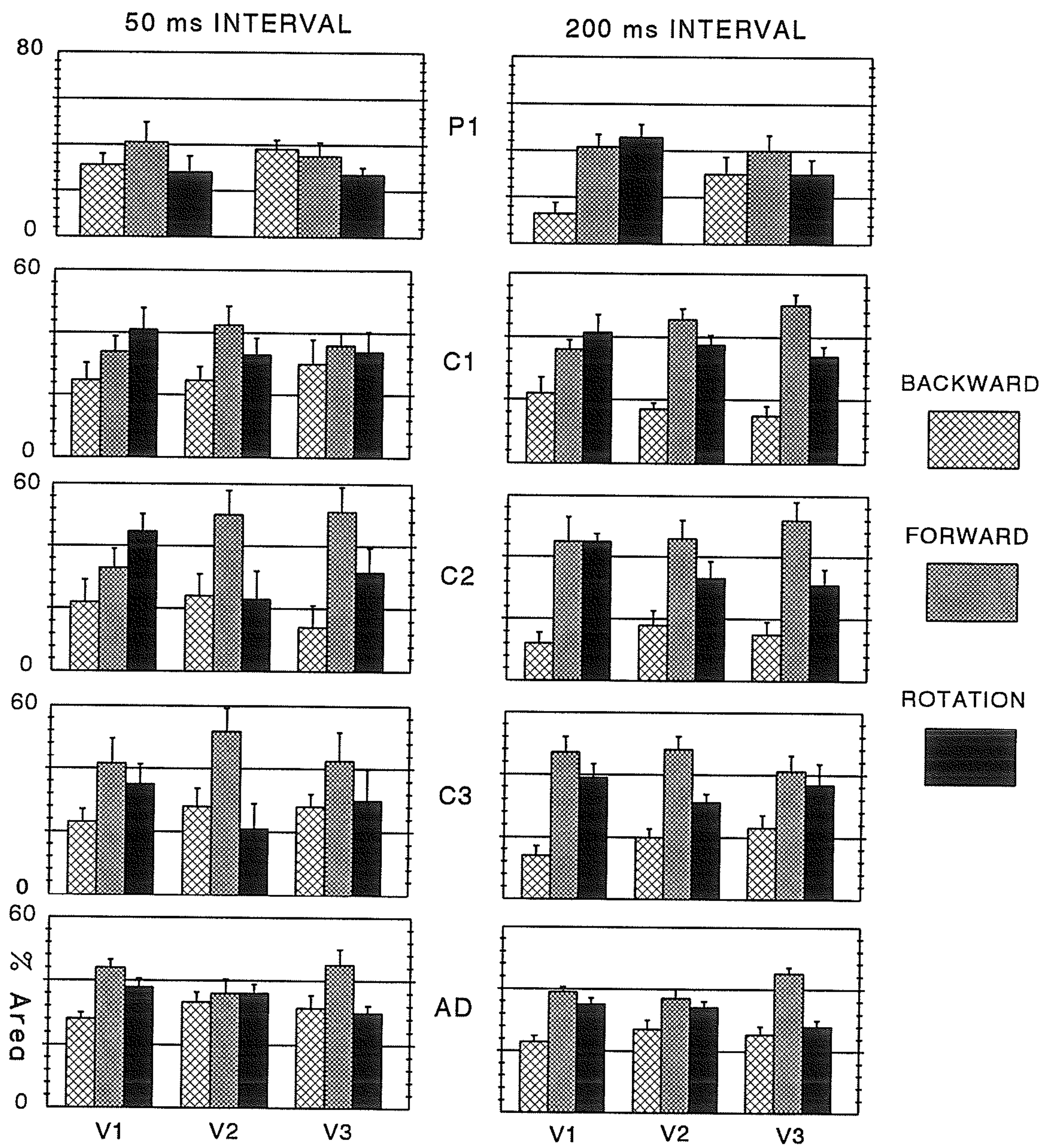


*Fig. 16D* **Same as Fig. 16A, except mean (SEM) normalized EMG area of QUAD muscle activity.**

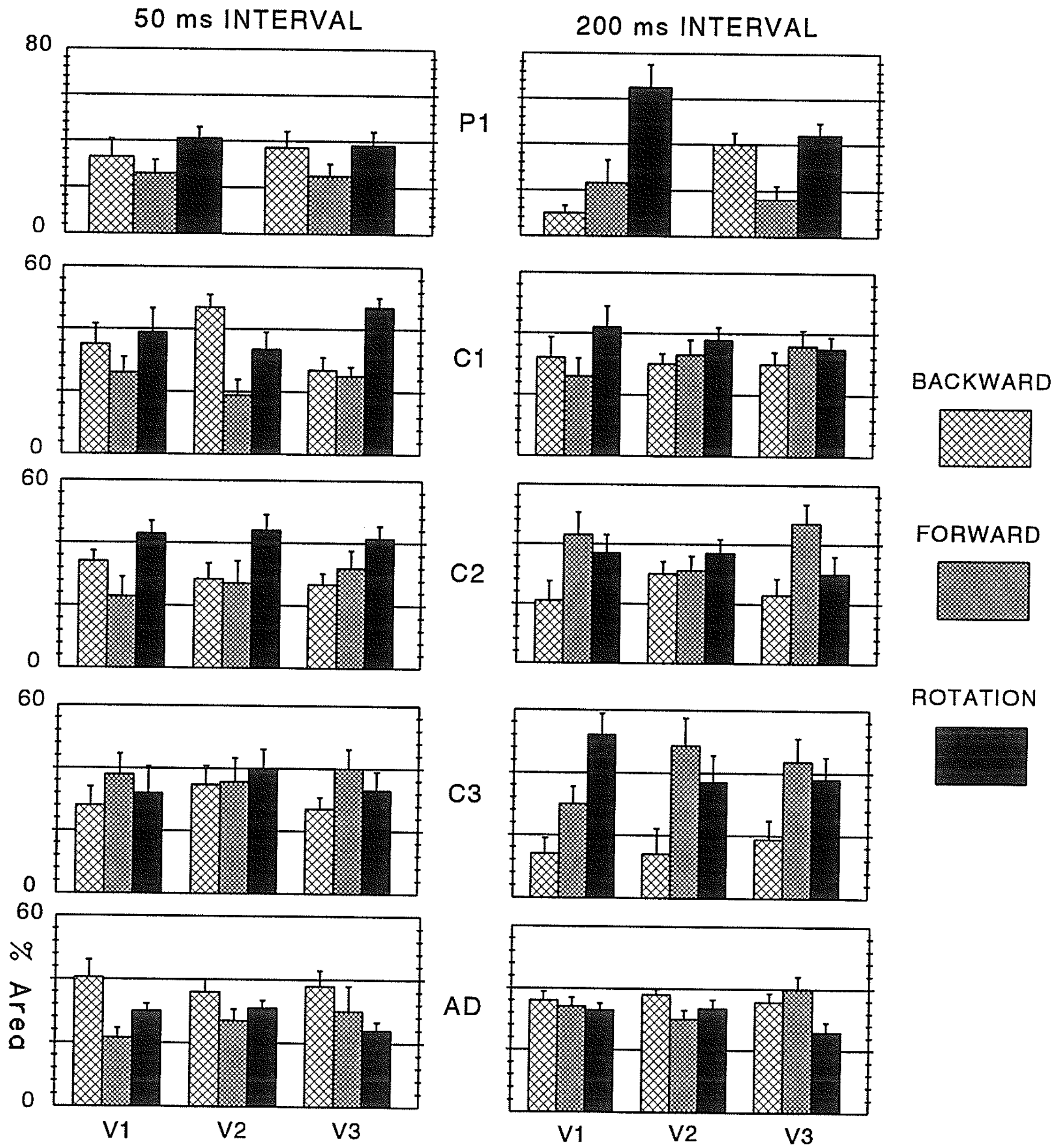


*TABLE 4* **P values obtained form ANOVA - Effect of type of platform perturnation on normalized EMG area of the 50 ms and 200 ms intervals for TA, GA, HAM and QUAD activity.**

| INTERVAL | | TA | | GA | | HAM | | QUAD | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50 | 200 | 50 | 200 | 50 | 200 | 50 | 200 |
| AD | V1 | .001 | .001 | NS | NS | .001 | .001 | .02 | NS |
| | V2 | .004 | .001 | NS | .02 | NS | NS | NS | NS |
| | V3 | .001 | .001 | NS | NS | .01 | .001 | .05 | .01 |
| C3 | V1 | .02 | .001 | .001 | .005 | NS | .001 | NS | NS |
| | V2 | NS | .001 | .02 | .02 | .02 | .001 | NS | .05 |
| | V3 | .05 | .001 | .01 | .01 | NS | NS | NS | .005 |
| C2 | V1 | .001 | .001 | NS | NS | NS | .001 | .001 | NS |
| | V2 | .05 | .001 | NS | NS | .05 | .001 | .05 | NS |
| | V3 | .05 | .001 | ns | NS | .01 | .001 | .05 | .02 |
| C1 | V1 | .01 | .001 | NS | NS | NS | .01 | NS | NS |
| | V2 | NS | .001 | NS | .05 | NS | .001 | .01 | NS |
| | V3 | .005 | .001 | NS | .005 | NS | .001 | .001 | NS |
| P1 | V1 | .005 | .001 | .001 | .001 | NS | .001 | NS | .001 |
| | V2 | .01 | .001 | NS | NS | NS | NS | NS | .005 |

activation in BT and R compared to FT was seen for the 50 ms interval. This was statistically significant in the C3 age group at all platform velocities ($p < 0.01$), and in the P1 age group at the lowest platform velocity ($p < 0.001$).

In regards to the 200 ms interval, analysis of adult results showed a statistically significant difference ($p < 0.02$) only at the middle platform velocity with EMG area for BT > R > FT. As for the C3, C1 and P1 age groups, statistically significant differences were found; in both the C3 and C1 age group, EMG area for BT > FT and R ($p < 0.01$); in the P1 age group, EMG area for R > BT and FT at the lower platform velocity ($p < 0.001$). In the C2 age group, the tendency of EMG area for BT > than FT and R was observed as in the C3 age group (see Fig. 16B)

HAMSTRINGS

Analysis of results of the 50 ms interval revealed that the EMG area of HAM was significantly greater in response to FT as compared to BT and R for: adult ($p < 0.01$ at platform velocities of 15 and 30 cm/s), C3 age group ($p < 0.02$ only at platform velocity of 15 cm/s), and C2 age group ($p < 0.02$ at platform velocities of 15 and 20 cm/s) age groups. No statistically significant effect of platform perturbation type on EMG area was found in the C1 or P1 age groups.

As for the 200 ms interval, a similar pattern of greater HAM activity for FT and R as compared to BT was observed in all age groups. This was with statistical significance in all cases (see Table 4 for p values).

QUADRICEPS

In regards to the 50 ms interval, a large difference between the age groups was found in the relative magnitude of EMG area in response to BT, FT and R. The adult results showed that the EMG area of QUAD activation was significantly greatest in BT as compared to FT and R ($P < 0.02$ at platform velocities of 15 and 30 cm/s). As for the children, in the C2 age group, EMG area was significantly greater for R than FT and BT ($p < 0.01$), and in the C1 age group, EMG area was significantly greater for R and BT than FT ($p < 0.01$ at platform velocities of 15 and 20 cm/s). No statistically significant effects of type of platform perturbation were found in the C3 and P1 age group.

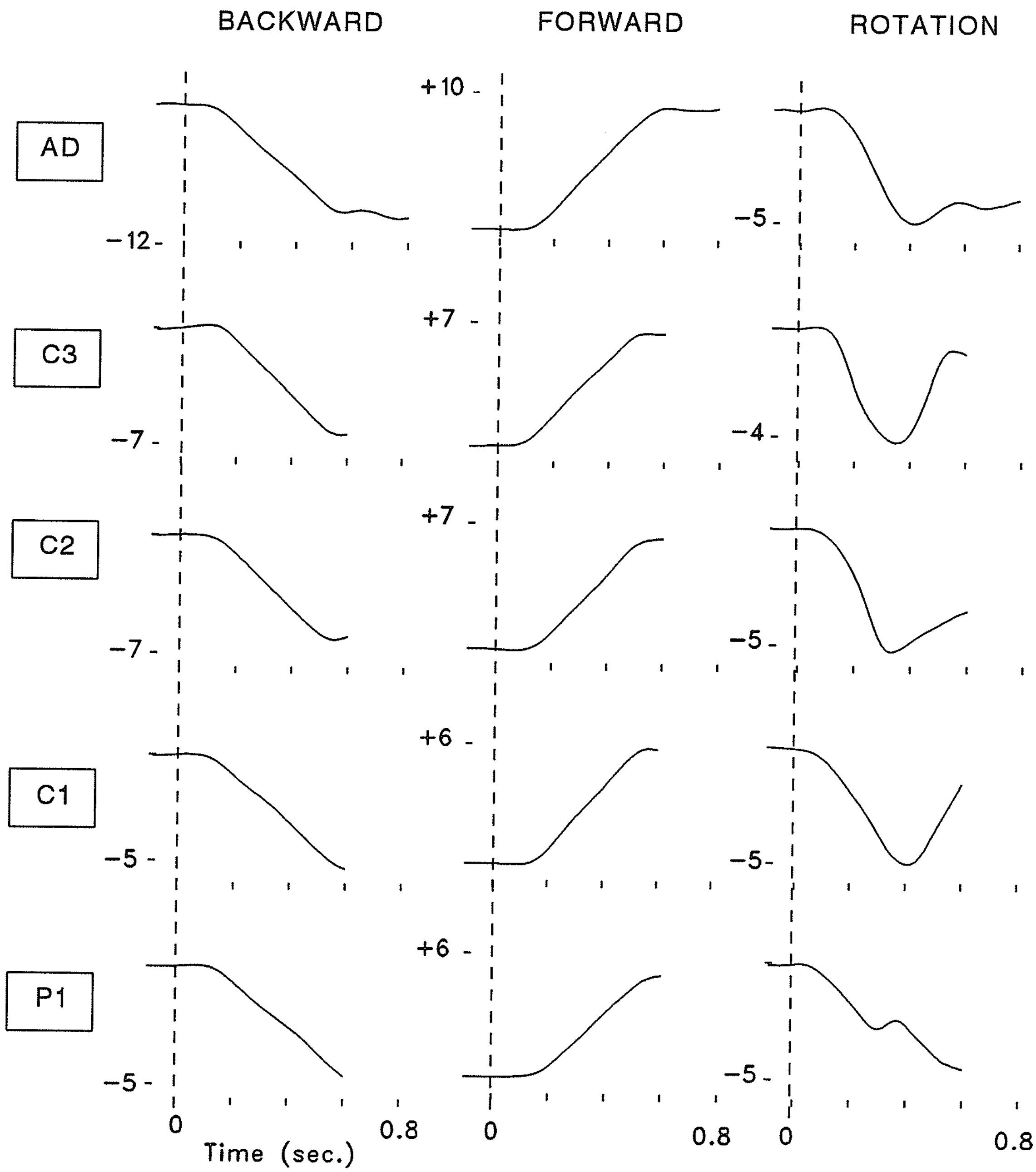
In regards to the 200 ms interval, little difference was found in the adult results, with the exception that at the highest platform velocity where the QUAD EMG area was significantly greater for BT and FT than R ($p < 0.01$). This pattern changed for the children. In the C3 age group a significant effect was found with EMG area for FT > R > BT ($p < 0.05$ at platform velocities of 15 and 20 cm/s). A similar pattern, EMG area of FT > R > BT, was found in the C2 age group, but only statistically significant at the highest platform velocity ($p < 0.02$). As for the P1 age group, statistically significant differences were also found with EMG area, R > BT and FT ($p < 0.005$).

## 3. KINEMATICS

### 3.1. LINEAR DISPLACEMENT OF GREATER TROCHANTER

The linear horizontal displacement (x coordinates) of the greater trochanter marker (GT) shows the travel of the mid-section of the body. Since the human total body center of mass (TCM) is close to the level of GT (L5) (McCollum and Leenq 89), this was chosen to represent the movement of the center of body mass, relative to space, during the platform displacement and the initial stages of balance reaction before any significant angular displacements about ankle, knee and hip joints occurred (see SECTION - ANGULAR DISPLACEMENT, below). It is important to note that although the TCM is close to GT in anatomical position, this is only a valid assumption in the initial stage, since any change in body configuration results in movement of the location of the TCM. In platform translations, as illustrated in Fig. 17, the results showed no passive component to the linear displacement of the GT. This is supported by the comparisons between the onset times for GT displacement (see below and Fig. 18), muscle activity and angular displacement about the ankle, knee and hip. The earliest mean onset of GT displacement in translation backward was found to be 165 ms in platform velocity, 15 cm/s in the P1 age group. This value of 165 ms is much greater than the onset time of CFP displacement which occurred simultaneously with onset of platform motion, and the mean onset time of the passive components of angular displacement about the ankle, knee and hip which occurred within 16 to 64 ms (1 to 4 video frames) after onset of platform motion. Furthermore, since the first muscle activity occurred 80 ms earlier (at 79 ms in GA) and the first mean active angular displacement in the hips at about 166 ms, this would signify that GT or the total body center of mass (TCM) did not move relative to space before the onset of the active, compensatory balance response. In forward translation, the earliest mean onset of GT displacement was 150 ms in the P1 age group (see below and Fig. 19). As for backward translations, CFP displacements were immediate and the passive components of angular displacement about the ankle, knee, and hip occurred within 16 to 64 ms following onset of forward platform motion. Corresponding times for onset of the earliest muscle activity was about 100 ms, and the first mean angular

*Fig. 17* Plots of horizontal (x coordinate linear displacement of GREATER TROCHANTER marker to backward platform translation, forward platform translation and platform rotations for one representative subject from each age group. Platform velocity in translations and rotations for adults (AD) and C3-C1 age groups was 20 cm/s, 50 °/s, and for P1 age group 15 cm/s, 36 °/s. Dashed vertical lines at time zero indicate onset of platform motion. All traces have been offset to zero and positive (+) displacement values are anterior or forward movements, and negative (-) values are posterior or backward movements.

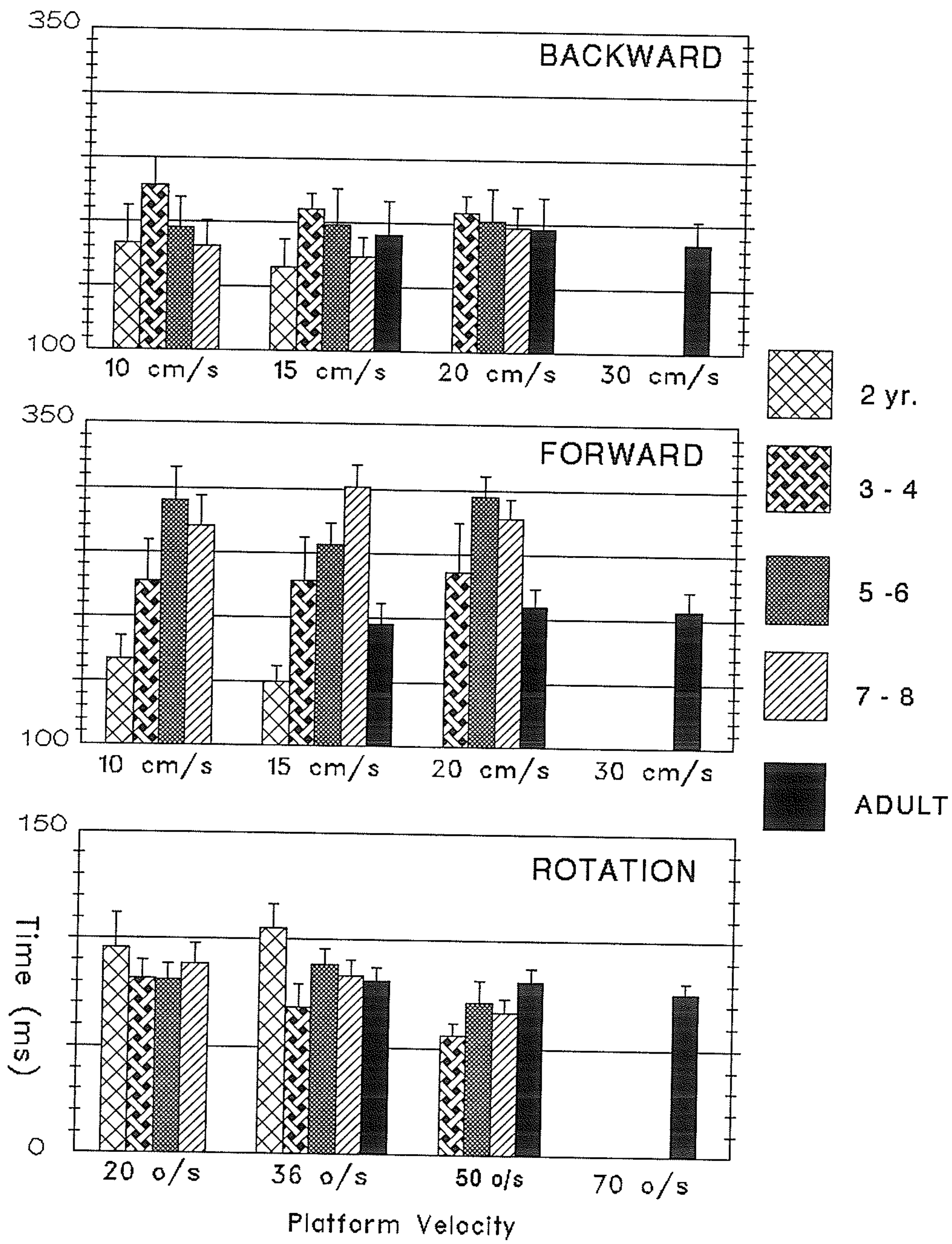


displacement was in the knee at about 150 ms. This demonstrated that the GT (or TCM) did not move relative to space during the passive period of the balance disturbance, that is, no movement of GT before muscle activation or active onset of angular displacement. Thus, in platform translation, the task would be to move the TCM, which has not been accelerated, over the newly located base of support. In rotations, the earliest onset of mean linear displacement of GT occurred within 56 ms in the C1 group in platform velocity 50°/s (see below and Fig. 18). The earliest muscle activity at the same platform velocity in the same age group was 88 ms for GA and 119 ms for HAM and the earliest active angular displacement occurred at 100 ms for the trunk and at 183 ms for the hip. The latest mean linear displacement onset of GT occurred at 105 ms in P1 36 °/s with the corresponding onset of muscle activity in GA at 108 ms and TA and HAM at 161 ms, and the angular displacement at 200 ms in the trunk. When comparing these early onsets of GT displacement to the later onsets of muscle activity and active body displacement, it is reasonable to conclude that the first GT displacement must represent a passive component. Thus, in this situation with the early displacement of the GT (TCM) in backward direction, the platform rotation was functioning as if the subject was "pushed" backwards. The passive component of the GT (TCM), moving in posterior direction corresponded to the passive posterior displacement of the CFP, and the active anterior displacement of GT (TCM) corresponded to the active anterior displacement of the CFP.

### 3.1.1. GENERAL FEATURES

As presented in Fig. 17, the patterns of GT linear displacement to backward and forward translation were almost the same, only mirror images of each other. The

*Fig. 18* **Group means and SEM of time to onset of linear horizontal displacement of GREATER TROCHANTER marker in response to backward platform translations, forward platform translations and platform rotations, at all velocities of platform motion.**



displacement had similar patterns in all age groups, but more frequently fluctuations were observed in the C1 and P1 age groups. In platform rotation, the linear displacement of GT showed the posterior displacement as in backward translation, but in rotation this represented a passive component while in translation backwards an active component. Following the posterior GT displacement during platform rotations, an anterior displacement was observed which would represent the forward movement of the body back over the base of support. Consequently, the active movement of the GT or TCM was in the same direction for forward translation and rotation. In the youngest age group this anterior displacement of the GT or TCM was most often too late to be observed within the digitized frames.

The active component of the GT linear movement was in the same direction as the active component of the CFP displacement, that is; posterior during backward translation and anterior during forward translation.

The early small amplitude anterior displacement of CFP seen in rotation, described above, was not accompanied by a corresponding displacement of the GT or TCM.

### 3.1.2. ONSET OF GREATER TROCHANTER LINEAR DISPLACEMENT EFFECT OF EFFECT OF PLATFORM VELOCITY

Results of ANOVA showed no effect of platform velocity on onset of GT linear displacement in any age group or for any type of platform movement. For illustration of results see Fig. 18, mean (SEM) onset of GT linear displacement for all age groups at all velocities of platform motion.

EFFECT OF AGE

In backward translations the results of both ANOVA comparisons, adults-C3-C2-C1 and C3-C2-C1-P1, showed no significant age effect on active onset of linear GT displacement (see Fig. 18). In forward translation, significant age effect was obtained in the AD-C3-C2-C1 ($p < 0.001$) and the C3-C2-C1- P1 group ($p < 0.001$). Adults' mean onset was earlier (195 ± 16 ms) than in the C3 to C1 children age groups (C3 = 301 ± 17, C2 = 256 ± 17, C1 = 228 ± 33 ms) but later than the P1 group (150 ± 13 ms). Accordingly, in the childrens' groups the onset time of GT displacement increased with increasing age.

In rotation, no significant age effect on onset of GT displacement was obtained in either the AD-C3-C2-C1 comparison or the C3-C2-C1-P1 comparisons (see Fig. 18). It should be noted that comparisons in rotation were made for the passive onset of GT displacement.

3.1.2. PEAK AMPLITUDE OF GREATER TROCHANTER LINEAR DISPLACEMENT

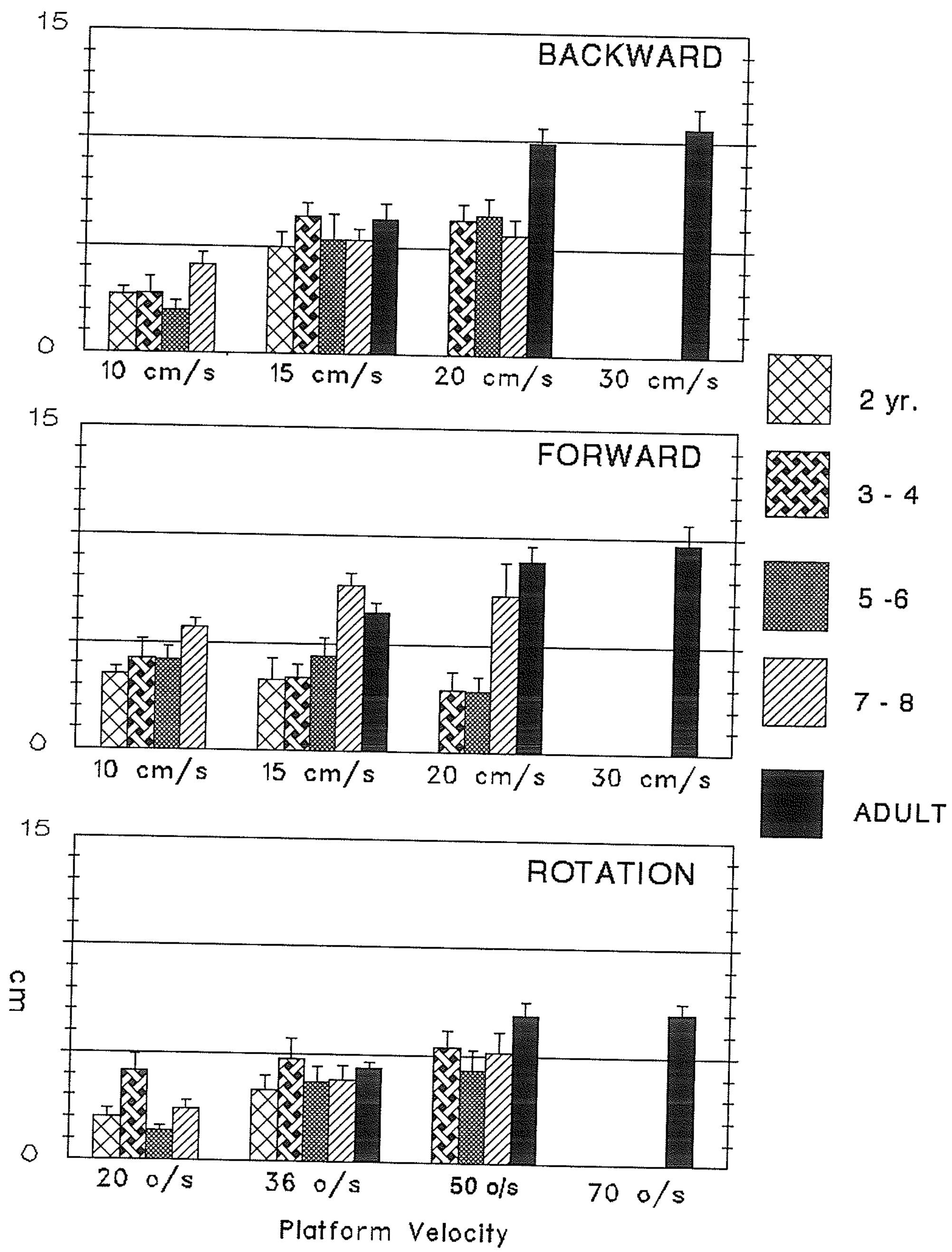
EFFECT OF PLATFORM VELOCITY.

Figure 19 presents the mean (SEM) peak displacement amplitudes for all age groups at all platform velocities.

In backward translation, the results of ANOVA showed a significant effect of platform velocity on peak amplitude of GT displacement for all age groups ($p < 0.01$) except for the C3 age group. The peak amplitude of GT displacement increased with increasing platform velocity.

In forward translation, a significant effect of platform velocity was only observed in the adults ($p < 0.01$), the amplitude increased with increasing velocity.

*Fig. 19* **Group means and SEM of peak magnitude of linear horizontal displacement of GREATER TROCHANTER marker in response to backward platform translations, forward platform translations and platform rotations, at all velocities of platform motion.**



In children, the results were variable and none of them were statistically significant. In fact, the P1, C1, and C2, age groups tended to present smaller peak amplitudes in the highest platform velocity compared to the lowest velocity. The C3 group did show a trend of increased peak amplitude of GT linear displacement with increasing platform velocity like the adults.

In platform rotations, peak amplitude measures represent the magnitude of backward or passive component of GT displacement. It was not possible to quantify the magnitude of the forward or active component of GT displacement for two reasons: (1) because in many records not enough frames were digitized; (2) because the records of a number of subjects did not have a forward component of GT displacement. That is, following the posterior displacement of GT, subjects maintained that position without moving in the forward direction. A trend to increased peak amplitude of GT displacement with increasing platform velocity was present in all groups, but this was only significant in adults ($p < 0.001$), C3 age group ($p < 0.05$) and C2 age group ($p < 0.05$).

EFFECT OF AGE

In backward translation no significant age effect was obtained in either the AD-C3-C2-C1 or C3-C2-C1-P1 comparisons.

In forward translation, a significant age effect was found in the AD-C3-C2-C1 ($p > 0.001$) but not in the C3-C2-C1-P1. On further analysis, it was found that the adults and C3 age group presented larger amplitude than the younger children in all velocities ($p < 0.001$). As an example of this, the peak GT displacement at platform velocity 15 cm/s was about 6.5 cm in adults and 7.7 cm in the C3 group, as compared to the range of mean peak amplitude values of 3.3 cm in P1 and 4.4 in C2.

In platform rotation, no significant age effect was observed in either AD-C3-C2-C1 or C3-C2- C1-P1 comparisons.

### 3.1.3. PEAK VELOCITY OF GREATER TROCHANTER LINEAR DISPLACEMENT

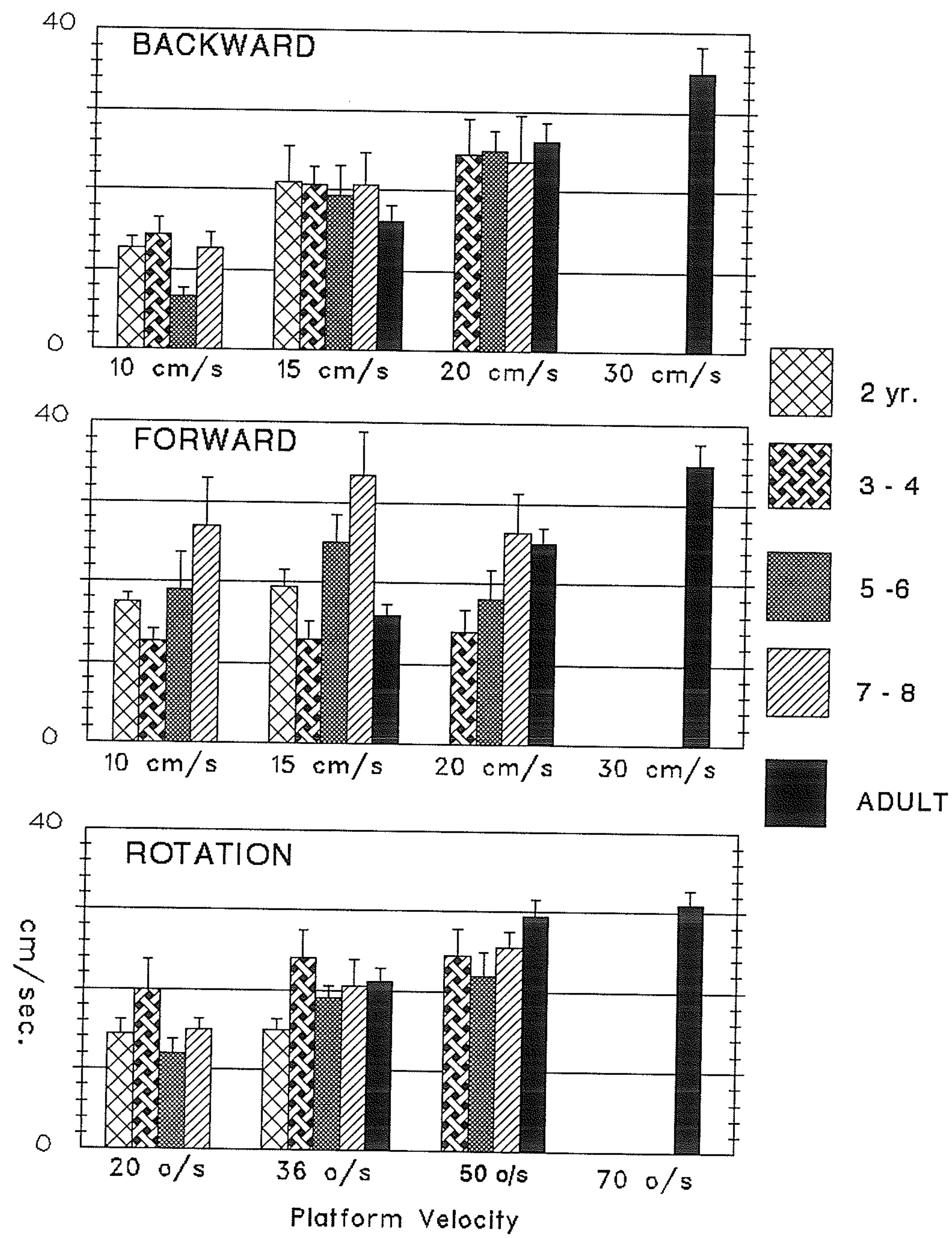
#### EFFECT OF PLATFORM VELOCITY

In backward translation, the effect of platform velocity on peak velocity of GT displacement was found to be statistically significant in the adults ($p < 0.001$) and the C2 age group ($p < .0.001$). As presented in Fig. 20, a clear trend of increased peak velocity of GT displacement with increasing platform velocity was also evident in the other childrens' age groups.

In forward translation, only the adults presented a statistically significant effect of platform velocity ($p < 0.001$) where the peak velocity of GT displacement increased with increasing platform velocity. Unlike backward translation, no tendency of an influence of platform velocity was observed in the responses in the children. In fact, the lowest peak velocity of GT displacement was observed at the highest platform velocity. (see Fig. 20).

In regards to the peak velocity of the passive component of GT displacement in rotation, a significant effect of platform velocity was found in the adults ($p < 0.001$), C3 ($p < 0.05$) and C2 ($p < 0.01$). The peak velocity of GT displacement increased with the increasing platform velocity, in the C2 age group from mean values of 12 to 22, in the C3 age group from 15 to 25.5, and in the adults from 21 to 31 cm/s.

*Fig. 20* **Group means and SEM of peak velocity of linear horizontal displacement of GREATER TROCHANTER marker in response to backward platform translations, forward platform translations and platform rotations, at all velocities of platform motion.**



EFFECT OF AGE.

In backward translation and platform rotations, no significant effect of age on peak linear velocity of GT displacement was found. Neither were any tendencies of age influence observed.

In forward translation, a significant age effect was obtained in the adult-C3-C2-C1 comparison ($p < 0.001$) and the C3 C2-C1-P1 age groups ($p < 0.001$). Here, the peak velocity of GT displacement increased with increasing age, except in the relation between the P1 and C1 group where P1 had higher peak velocity (see Fig. 20).

## 3.2. ANGULAR KINEMATICS

### 3.2.1. PASSIVE COMPONENTS

As described in the METHODS SECTION, and illustrated in Fig. 6, a distinct pattern of passive angular displacement induced by backward and forward platform translation and platform rotation was observed in all age groups. The onset of the passive component of ankle angular displacement occurred within one video frame or 16.67 ms of the start of platform motion. The onset of the passive components for knee and hip angular displacements occurred one to three video frames or 16.67 - 50 ms later than that for the ankle joint. Not all subjects had passive components in each joint. In fact, clearly identifiable passive components were often absent in the knee, hip and hip-trunk (H-T) at the lowest velocity. Also, in backward translations, passive components of angular displacement at the knee where only observed in about one third of the records.

### 3.2.2. ACTIVE MOVEMENT PATTERNS AND ONSET OF ACTIVE ANGULAR DISPLACEMENT IN BACKWARD PLATFORM TRANSLATION.

With respect to each type of platform perturbation, equilibrium was regained by distinct, compensatory movement patterns. As presented in Fig. 21, in backward translation, the adult movement strategy involved hip and hip-trunk (H-T) flexion with maintained ankle dorsiflexion. Later, as hips and H-T continued to flex, the ankles plantarflexed and the knees extended (for times of onset, see velocity effect below). This movement pattern was highly consistent, irrespective of platform velocity. The only exception occurred at the knee joint, where a variable pattern of knee angular displacement of relatively small amplitude knee flexion-extension was observed. Knee extension was observed in 6 of the 13 subjects (Fig. 21, AD), and in the remaining subjects a pattern of flexion-extension was found (see Fig. 6, backward translation). In angular displacement records with an active knee flexion, which was in the order of 3-5 degrees in amplitude, the onset coincided with that of active hip and H-T flexion. This active knee flexion pattern was absent at the lowest platform velocity. A similar pattern of knee flexion-extension has been observed in healthy adult subjects at the onset of fast voluntary trunk flexion movements, but absent during slow movements (Oddson 90).

In all children the hip and H-T flexion was observed as in adults. An occurrence of distinct knee flexion, in the order of 10 degrees, was observed in the children. The frequency of occurrence of this knee flexion increased with decreasing age. Generally, from inspection of the individual results, velocity did not seem to have any influence on the selection of knee flexion/extension pattern as knee flexion was seen in the lowest velocities as well as in the highest velocities.

*Fig. 21* Plots of ANKLE, KNEE, HIP AND H-T angular displacement to BACKWARD platform translation for one representative subject from each age group. Platform velocity in translations and rotations for adults (AD) and C3-C1 subject groups was 20 cm/s, and for P1 subjects 15 cm/s. Dashed vertical lines at time zero indicate onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are flexion/dorsiflexion, and negative (-) values are extension/planterflexion.

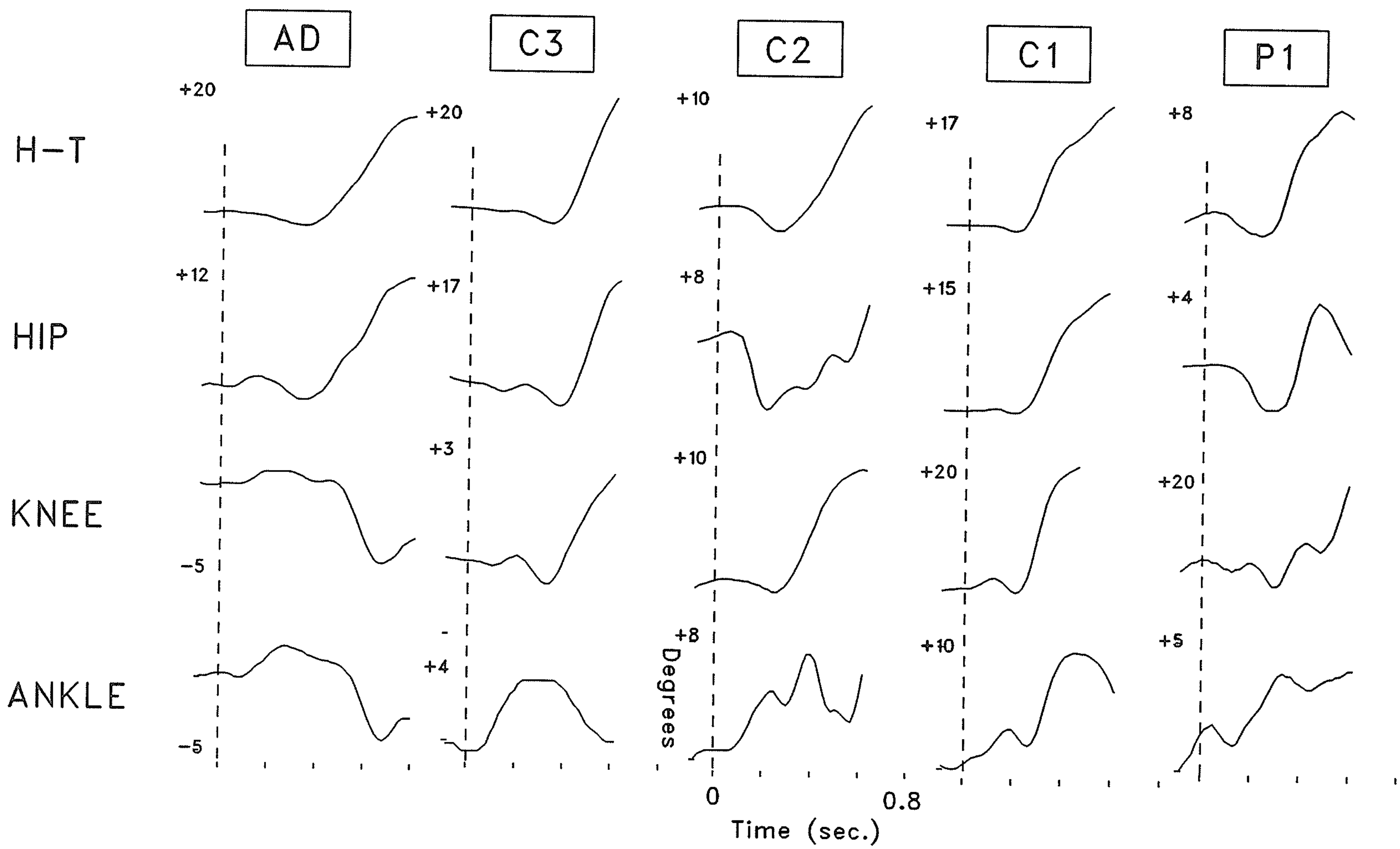
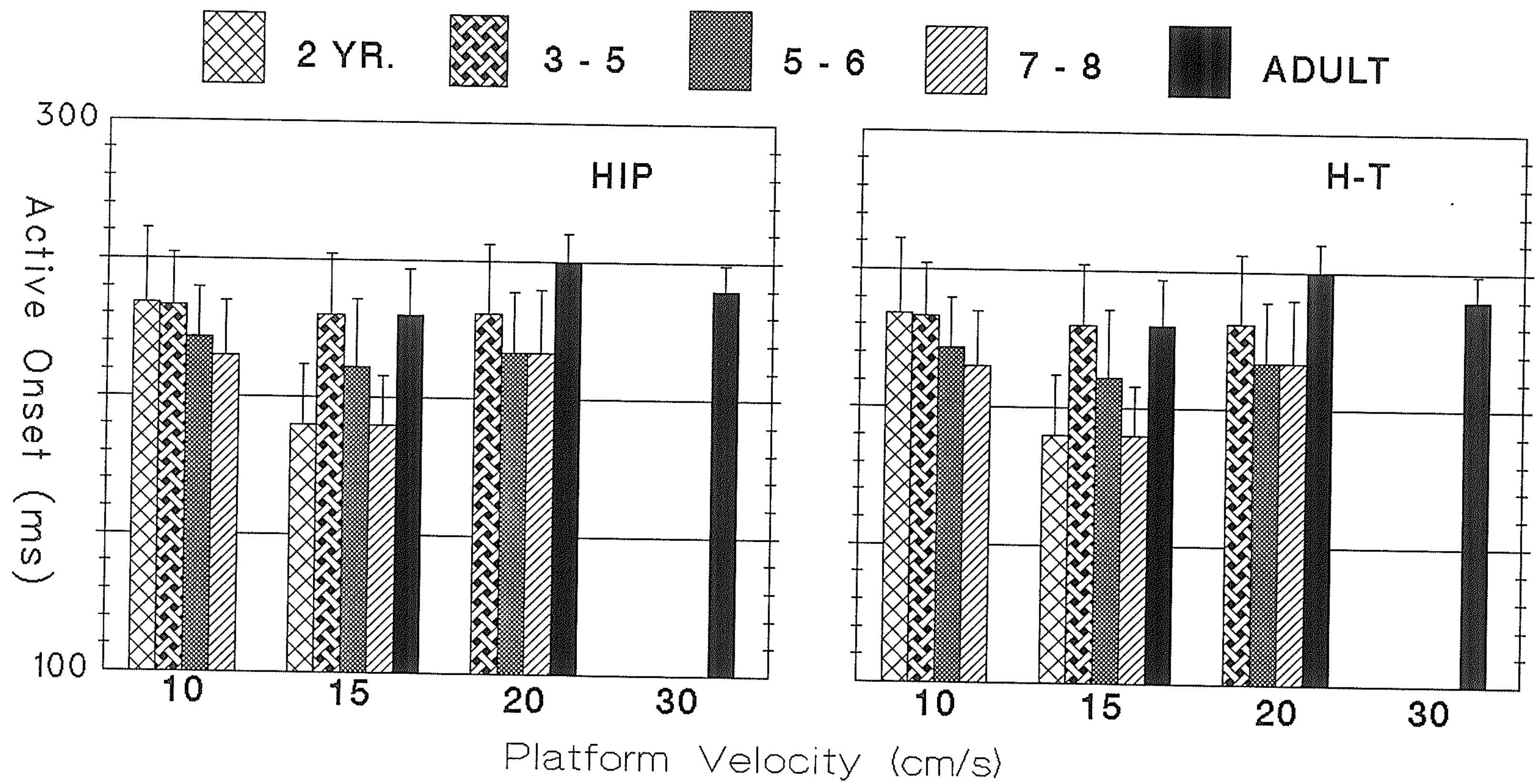


*Fig. 22* Group means and SEM of time to onset of active HIP and H-T angular displacement in response to BACKWARD platform translations at all velocities of platform motion.





## EFFECT OF PLATFORM VELOCITY

In some cases it was not possible to perform statistical analysis of the effect of platform velocity and effect of age on the active onset of angular displacement. This was also true for the peak amplitude and peak velocity of angular displacements which are described below. The reasons for this were: (1) Inconsistency in the direction of active angular displacement as was the case in backward translations where two different movement strategies were observed in the children groups. This rendered sample size too small to perform statistical analysis of knee angular displacement; (2) Difficulty in clearly identifying the onset of the active component of ankle angular displacement in backward translations as many records showed maintained dorsiflexion. A similar situation arose in platform rotations (see below); (3) Missing data points. In some of the angular displacements records, the peak displacements did not end within the time period that the video film was digitized (in the children 583 ms after onset of platform movement). This occurred most often in hip and trunk displacements of the children following forward translations.

To increase the power of ANOVA, the sample size was increased by combining the results of trial 1 and trial 3. Before proceeding, a repeated measures ANOVA was done to determine the effect of trial on the active onset of angular displacement, as well, as on peak amplitude and peak velocity of angular displacement (see below). No significant effect due to trials were found. Thus the data from trials 1 and 3 were combined for all statistical tests presented below which includes active onset of angular displacement, peak amplitude of angular displacement and peak velocity of angular displacement.

EFFECT OF AGE

Statistical analysis was only performed for hip and H-T, as described above. Significant effect of age was seen only for the onset of hip angular displacement between adults and children, the adults showing later mean onset than the children ($p < 0.03$). The mean onset times, in ms, for hip angular displacement at platform velocity of 15 cm/s were: AD = 258, C3 = 235, C2 = 233, C1 = 230, and P1 = 200 ms and for H-T angular displacement: AD = 266, C3 = 223, C2 = 232, C1 = 243, and P1 = 205. No difference in active onset of hip, H-T was significant in the C3-C2-C1-P1 comparison.

The mean onset in ms, of active knee flexion or knee extension at a platform velocity 15 cm/s were respectively: AD = 283, C3 = 292/167, C2 = 235/163, C1 = 238/255 and P1 = 229/228. The amplitude of knee flexion tended to be larger in the two youngest age groups compared to the older children. In C3 age group, the two youngest subjects showed mainly knee flexion, another child in this group had knee flexion in half of the trials and knee extension in the other trials, while six showed mainly extended knees. Fig. 23 presents examples of the different patterns of knee angular displacement in the C3 age group. In the C2 age group, three showed mainly the knee flexion pattern, and five subjects mainly knee extension pattern. The primary active movement in the C1 and P1 age groups was knee flexion, five children in the C1 age group and six in the P1 age group.

From the C2 age group and downwards in age, small amplitude fluctuations in angular displacement were frequently observed. This is illustrated in angular displacement records presented in Fig. 21; C2 ankle and hip records, P1 ankle and knee records, and also presented in Fig. 24 for hip angular displacement of one 3 year old and one 2 year old child.

### 3.2.3. ACTIVE MOVEMENT PATTERNS AND ONSET OF ACTIVE ANGULAR DISPLACEMENT IN FORWARD PLATFORM TRANSLATION

In the adults, the movement strategy consisted of knee flexion followed by hip/trunk extension. At the time the knees started to flex, ankle plantarflexion stopped and dorsiflexion ensued. This basic pattern was present in the majority of the children and at all platform velocities. Figure 25 presents angular displacement records in response to forward translation for one representative subject of each age group. As compared to adults and children in the C3 age group, the younger children (C2, C1 and P1 age groups) frequently presented with a late onset of active hip and H-T extension. In the younger children, the preceding passive hip and H-T flexion lasted for a long time period, with the consequence that, in some of the youngest children, active hip extension started late and this displacement did not peak within the digitized time period (see Fig. 26 for examples).

#### EFFECT OF PLATFORM VELOCITY

No significant statistical effect of platform velocity was found for onset of angular displacement in adults or children in forward translation (see Fig. 27 means (SEM) onset of active angular displacement for hip and H-T in all age groups and velocities).

#### EFFECT OF AGE

Statistical significance was found in the adult-C3-C2-C1 comparisons for; onset of hip extension at both platform velocities of 15 and 20 cm/s ($p < 0.001$), and for onset of H-T extension at the platform velocity of 15 cm/s ($p < 0.001$) and at 20 cm/s ($p < 0.01$). No significant difference in mean of hip or H-T angular displacement was found in the C3-C2-C1-P1 comparison. The mean onset values, in ms, at the platform velocity of 15 cm/s for the hip and H-T extension respectively, were: AD = 225 and 251, C3 = 336 and 338, C2 = 351 and 372, C1 = 362 and 341, P1 = 353 and 333 ms. The difference between adults and children in onset of knee flexion was smaller than that seen for hip and H-T. Mean onset values, in ms, for active knee flexion at a platform velocity of 15 cm/s were: AD = 197, C3 = 171, C2 = 187, C1 = 182, and P1 = 150 ms. No significant effect of age on the onset of knee flexion was found. This was also the case for onset of active ankle plantarflexion. As for active ankle plantarflexion, the mean onset values, in ms, at a platform velocity of 15 cm/s were: AD = 210, C3 = 221, C2 = 235, C1 = 272 and P1 = 205, and at the platform velocity of 20 cm/s, there was practically no difference between adults, C3, and C2 age groups.

The delay between onset of active angular displacement in the knee-ankle-hip was greater in children as compared to adults. In regards to time interval between onset of active angular displacement about the knee and ankle, the adults presented a delay of 13 ms compared to 50 ms for C3 age group, 48 ms for the C2 age group, 90 ms for the C1 age group and 55 ms for the P1 age group. A substantial difference was also present in the time interval between onset of active angular displacement about the ankle and hip, mean time delay values were: 15 ms in the adults, 115 ms in the C3 age group, 116 ms in the C2 age group, 90 ms in the C1 age group, and 148 ms in the P1 age group.

*Fig. 23* Plots of KNEE angular displacement to BACKWARD platform translation for one adult (AD) subject and for two children (S1 and S2) form the C3 age group, which illustrates different patterns of knee flexion/extension. Platform velocity was 20 cm/s. Time zero indicates onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are knee flexion and negative (-) values, knee extension.

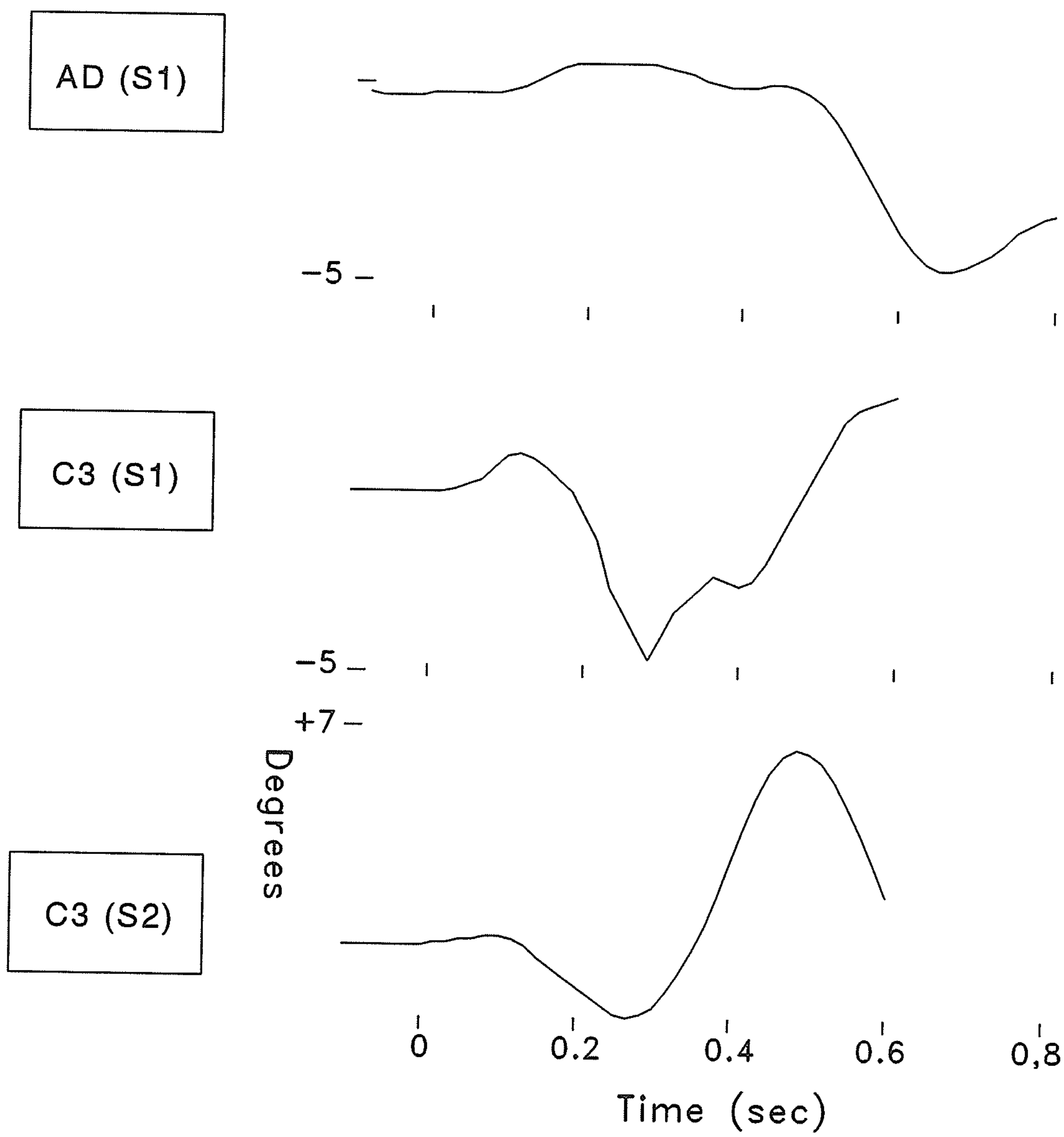


*Fig. 24* Plots of HIP angular displacement to BACKWARD platform translation for one adult (AD) subject and for one child from the C1 and P1 age groups, which illustrates the fluctuations in angular displacement records of the younger children. Platform velocity was 20 cm/s for adult and C1 subjects, and 15 cm/s for P1 subject. Time zero indicates onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are hip flexion and negative (-) values hip extension.

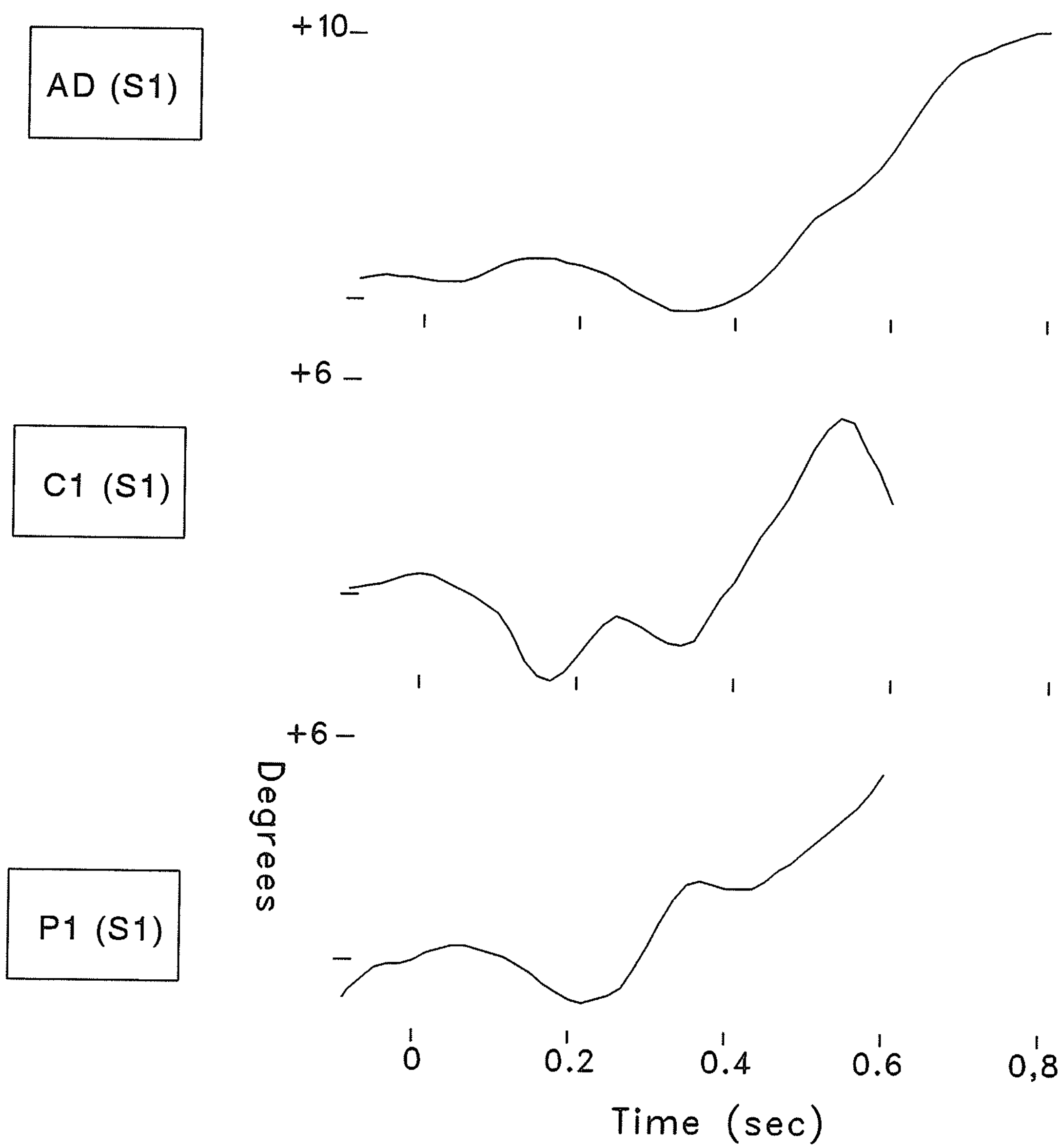


*Fig. 25* Plots of ANKLE, KNEE, HIP AND H-T angular displacement to FORWARD platform translation for one representative subject from each age group. Platform velocity in translations and rotations for adults (AD) and C3-C1 subjects was 20 cm/s, and for P1 subject 15 cm/s. Dashed vertical lines at time zero indicate onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are flexion/dorsiflexion, and negative (-) values are extension/planterflexion.

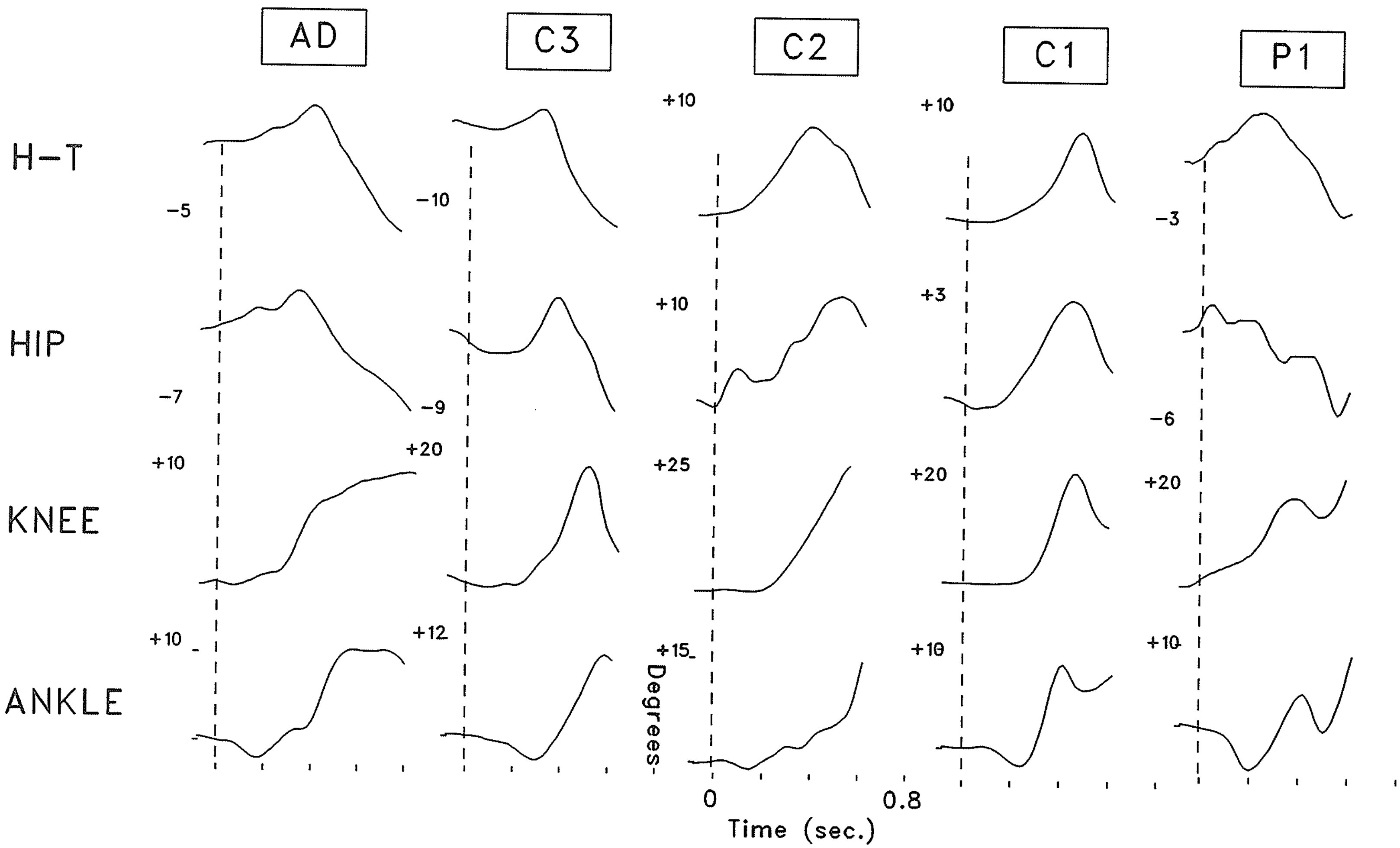


*Fig. 26* **Plots of HIP and H-T angular displacement to FORWARD platform translation for one adult (AD) subject and for one child from the C3 and P1 age groups, which illustrates the late onset of active hip/trunk extension in the youngest children. Platform velocity was 20 cm/s for adult and C3 subjects, and 15 cm/s for P1 subject. Time zero indicates onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are flexion and negative (-) values extension.**

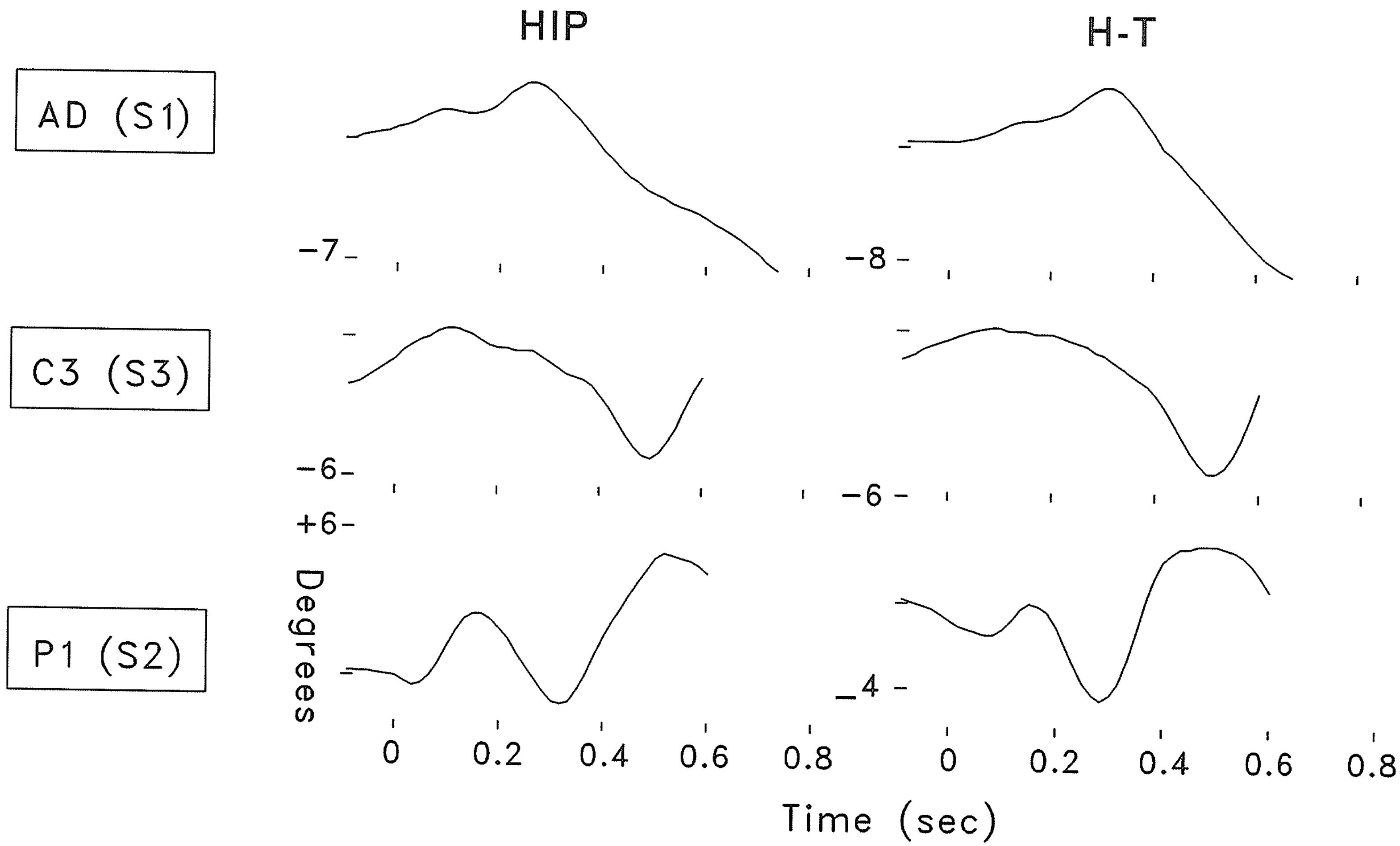
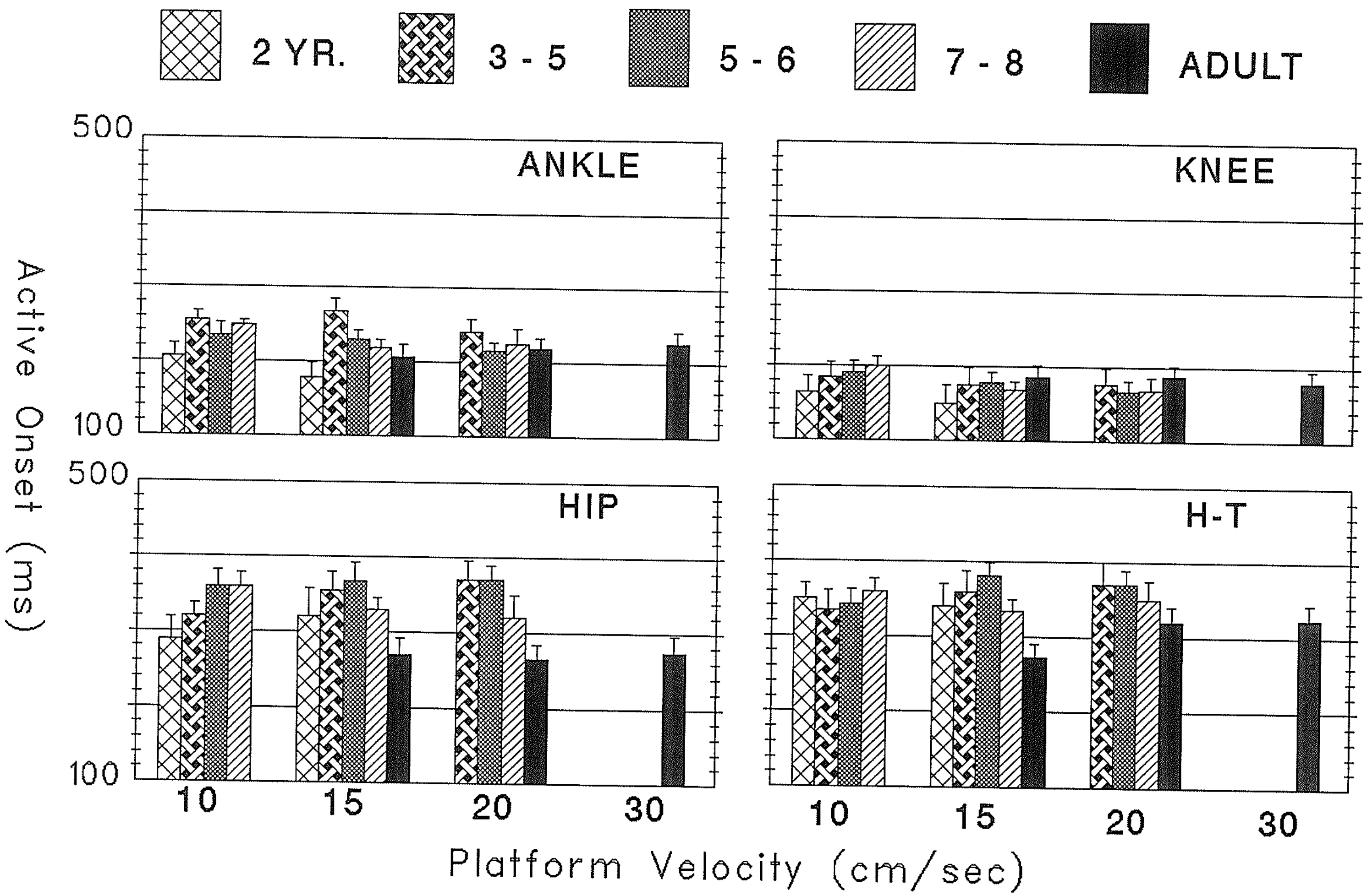


*Fig. 27* **Group means and SEM of time to onset of active ANKLE, KNEE, HIP and H-T angular displacement in response to FORWARD platform translations at all velocities of platform motion.**





Another difference between the adults and the children was that some of the children in the C2 (8 of total 46 trials), C1 (7 of total 48 trials) and P1 (9 of total 33 trials) age groups had to take a step backwards in order to regain balance at the highest platform velocity. This did not occur for adults or for children in the C3 age group. The prolonged period of hip and trunk flexion and late onset of hip extension in the younger children would contribute to their loss of balance and the need to take a step. This would be consistent with earlier EMG onset in HAM, in adults, as compared to children and the earlier onset of QUAD in children as compared to the adults (SECTION - EMG 2.1.2). Figures 28 and 29 present angular displacement records of two children illustrating the pattern of knee, hip and H-T angular displacement when a step was taken. One example is from a child in group C1, who most of the time, had to take a quick backward step. Here, the onset of active hip extension and active knee flexion, respectively, were 476 ms and 256 ms, as compared to mean onset of C1 age group of 336 ms and 165 ms.

Like that observed for backward translation, a general feature in the angular displacement records of the children, especially below 4 years of age, was the presence of small fluctuations which were most evident in hip and H-T angular displacement records. See Fig. 25 (C2 and P1) and Fig. 29 for examples of angular displacement.

### 3.2.4. ACTIVE MOVEMENT PATTERNS AND ONSET OF ACTIVE ANGULAR DISPLACEMENT IN PLATFORM ROTATION

The components in the adult movement strategy started with hip/trunk flexion, followed by knee flexion. The ankle angular displacement showed a prolonged dorsiflexion, in some cases interrupted by a small amplitude, short duration plantarflexion, before continuing into dorsiflexion. Since the active onset of dorsiflexion was in the same direction as the passive component of angular displacement caused by direct platform rotation, it was not possible to identify the end of the passive component and the onset of the active component. After the period of active hip and trunk flexion, a further compensatory movement strategy was seen, while the ankles remained in dorsiflexion and knees in slight flexion, the hips and H-T shifted into extension. Figure 30 presents angular displacement records in response to platform rotations for one representative subject of each age group.

Basically, this movement pattern was seen in all children but, larger variations in onset times and occurrences of movement fluctuations in ankle, knee and hip joints were found in the younger age groups. Figure 31 presents mean (SEM) onset of active angular displacement for platform rotations. For examples of fluctuations in angular displacement records see Fig. 30 (C2 and P1) and Fig. 32.

In the children below 7 years of age, hip and H-T flexion were prolonged as compared to the adults and most of the 7-8 years old children (see Fig. 33 for example). As described below, the amplitude of active knee flexion was large in children, and the occurrence of ankle plantarflexion was more frequently seen in the children below 6 years of age.

## EFFECT OF PLATFORM VELOCITY

In rotation, (Fig. 36) no statistical significant effect of platform velocity was shown for mean onset of active angular displacement in adults. Whereas for the children, significant differences were found in mean onset of knee flexion, hip and H-T

*Fig. 28* **Plots of ANKLE, KNEE HIP and H-T angular displacement to FORWARD platform translation for one adult (AD) subject and one child from the P1 age groups. Notice large amplitude knee, and hip/trunk flexion in the child records, who took a step backward in order to regain balance. Platform velocity was 20 cm/s for adult and 15 cm/s for P1 subject. Time zero indicates onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are flexion and negative (-) values extension.**

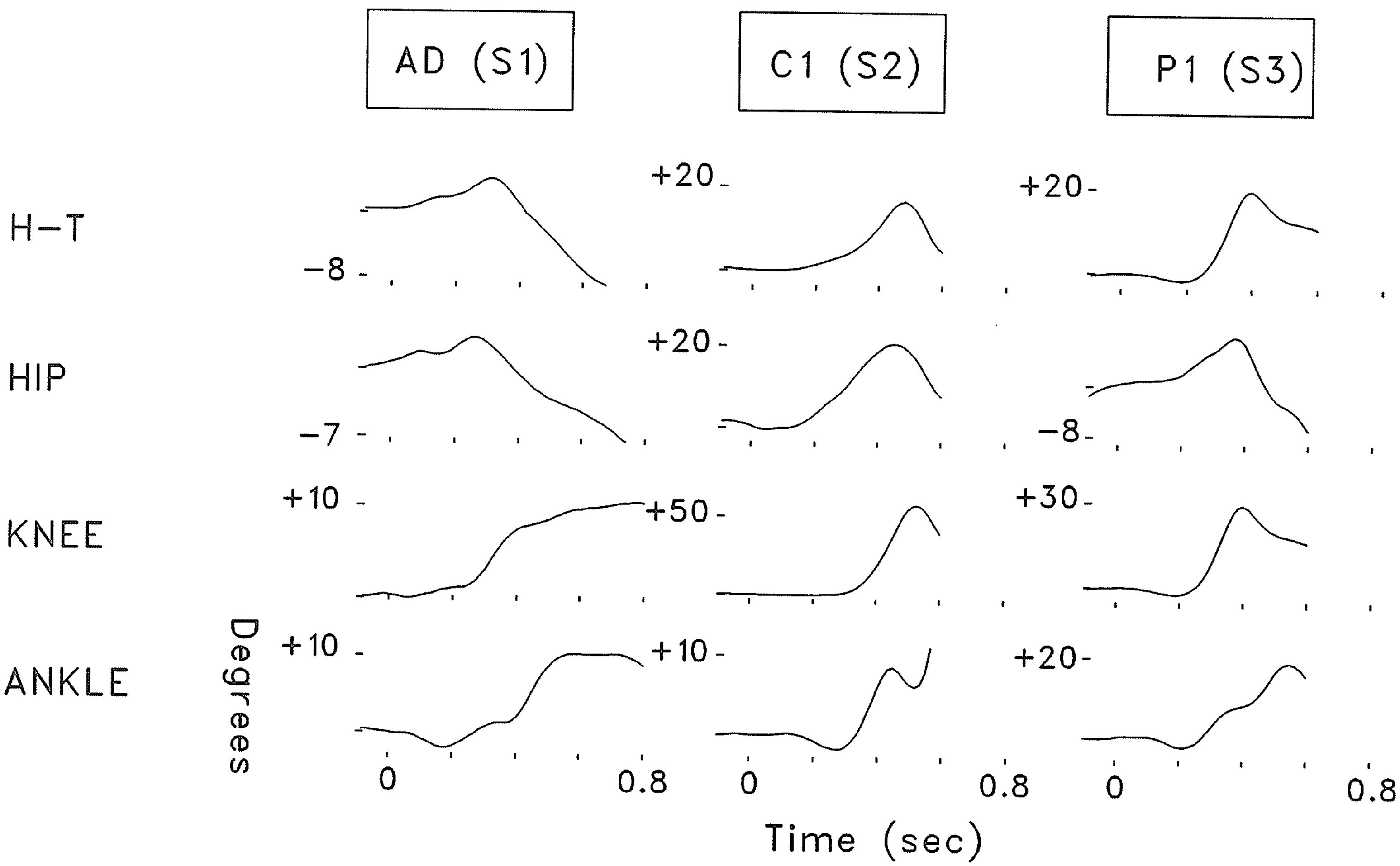


*Fig 29* **Plots of ANKLE, KNEE, HIP and H-T angular displacement to FORWARD platform translation for one adult (AD) subject and one child from the C1 age group, which illustrates the fluctuations in angular displacement records of the younger children. Platform velocity was 20 cm/s. Time zero indicates onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are hip flexion and negative (-) values hip extension.**

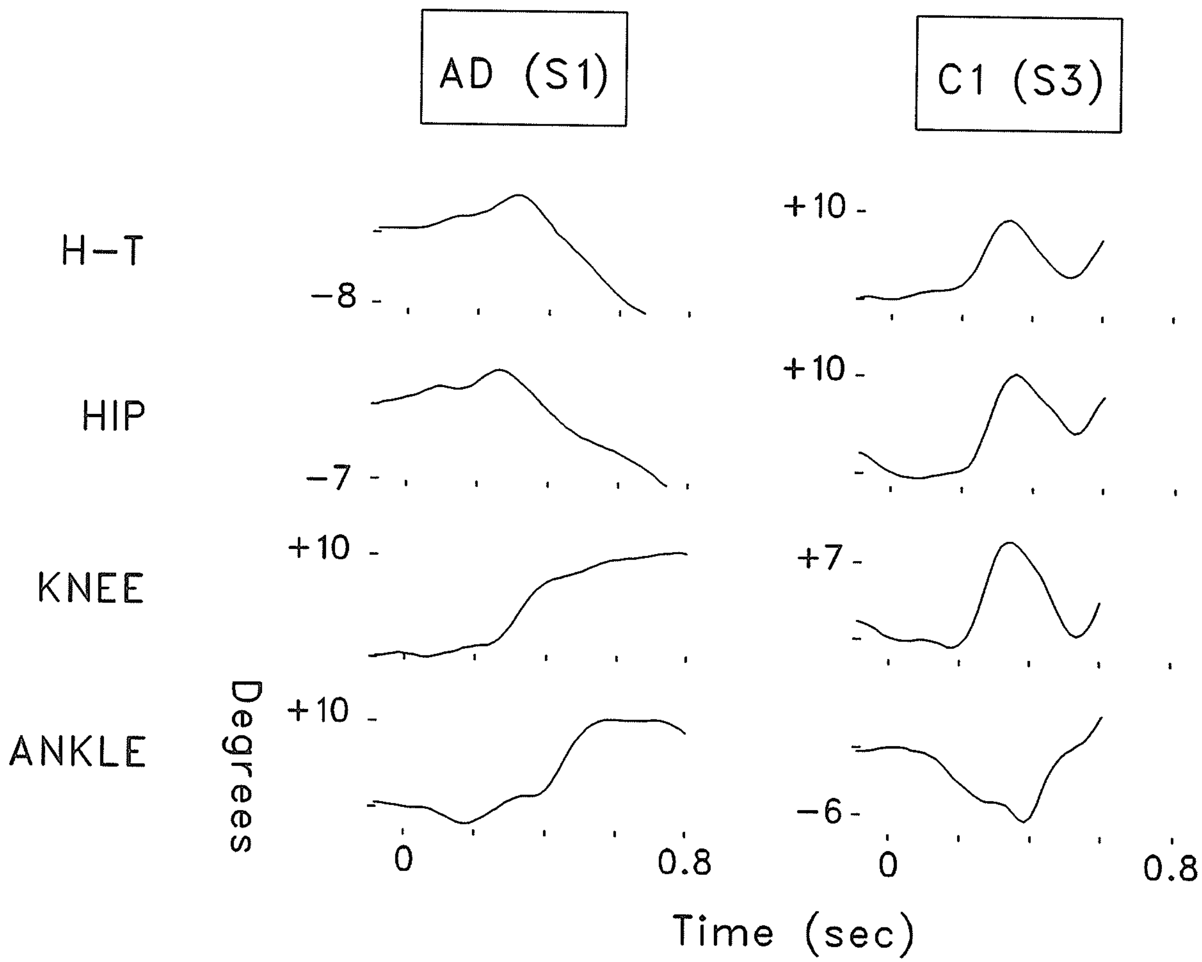
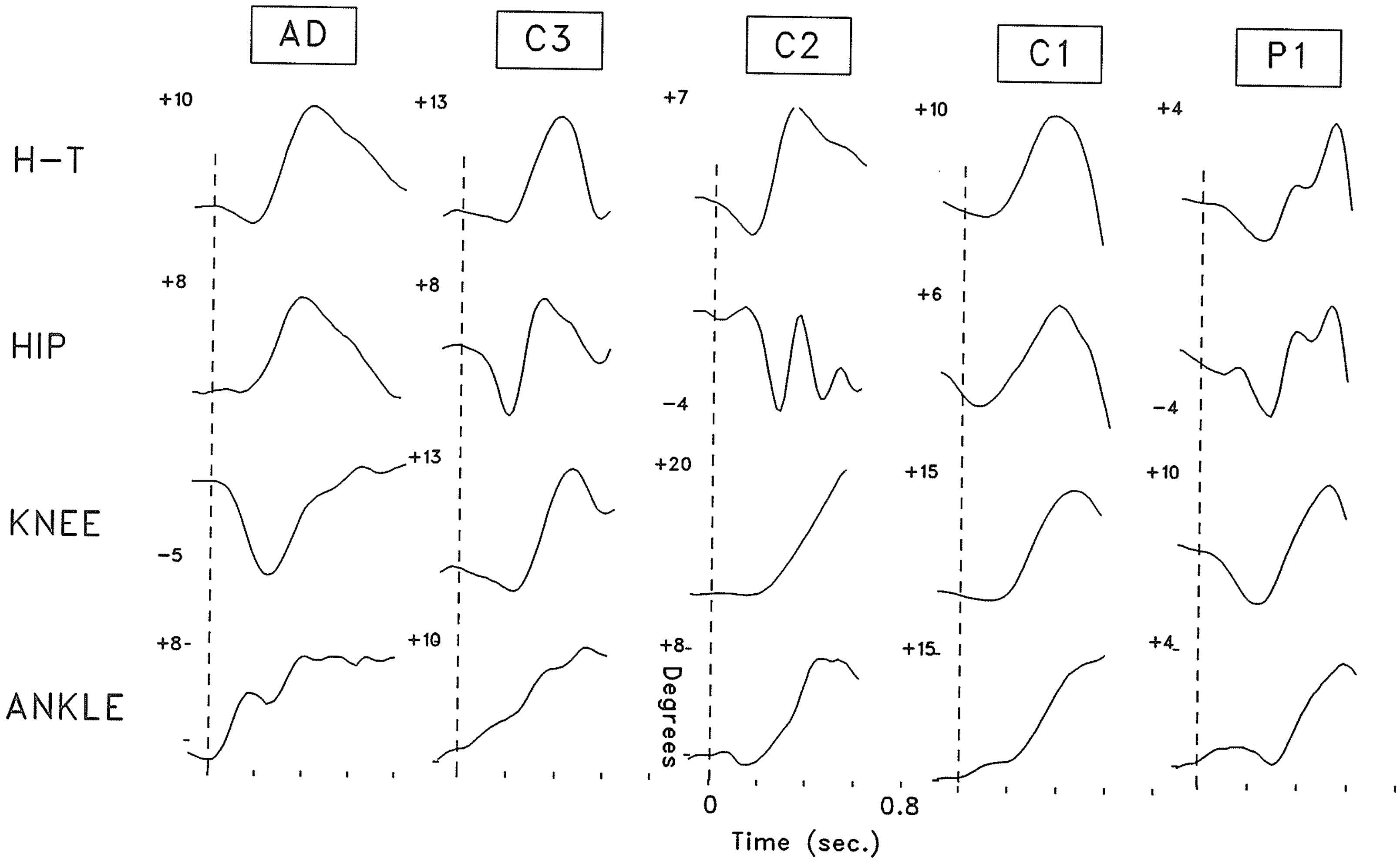


*Fig. 30* Plots of ANKLE, KNEE, HIP AND H-T angular displacement to platform ROTATIONS for one representative subject from each age group. Platform velocity in translations and rotations for adults (AD) and C3-C1 subjects was 50 °/s, and for P1 subject 36 °/s. Dashed vertical lines at time zero indicate onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are flexion/dorsiflexion, and negative (-) values are extension/planterflexion.



flexion; C1 in hip and H-T flexion ($p < 0.01$), C2 in knee flexion ($p < 0.003$), C3 in knee flexion ($p < 0.004$), and in hip flexion ($p < 0.04$). In all these cases, active onset decreased with increasing platform velocity. (see Fig. 31).

EFFECT OF AGE

Results of ANOVA showed significant differences only at the hip; for the adult-C3-C2-C1 comparisons at both platform velocities of 36°/s and 50°/s ($p < 0.01$), and for the C3-C2-C1 P1 comparison only at the platform velocity of 36°/s ($p < 0.03$). Here, at the platform velocity of 36°/s, onset of active hip angular displacement, in ms, were: AD = 159, C3 = 160, C2 = 191, C1 = 197 and P1 = 227 ms. The C2, C1 and P1 presented the latest onsets. In regards to onset of active H-T angular displacement, the P1 age group tended to show a later onset than the other age groups, although not statistically significant. The C1 age group did show a shorter time to onset of H-T angular displacement than the older age groups (see Fig.31).

3.2.5. PEAK ANGULAR DISPLACEMENT IN PLATFORM TRANSLATIONS AND ROTATIONS EFFECT OF PLATFORM VELOCITY

As described above, statistical analysis in backward translation were only performed in hip and H-T due to the different strategies employed by children. The adult subjects presented statistically significant effect of platform velocity on mean peak angular displacements in all joints in response to platform translation ($p < 0.001$). The mean peak angular displacement increased with increasing velocity. In the children, no significant effect of platform velocity on peak angular displacement was seen. However, in the results of the C3, C2 and C1 age groups, there was a clear

*Fig. 31* **Group means and SEM of time to onset of active KNEE, HIP and H-T angular displacement in response to platform ROTATIONS at all velocities of platform motion.**

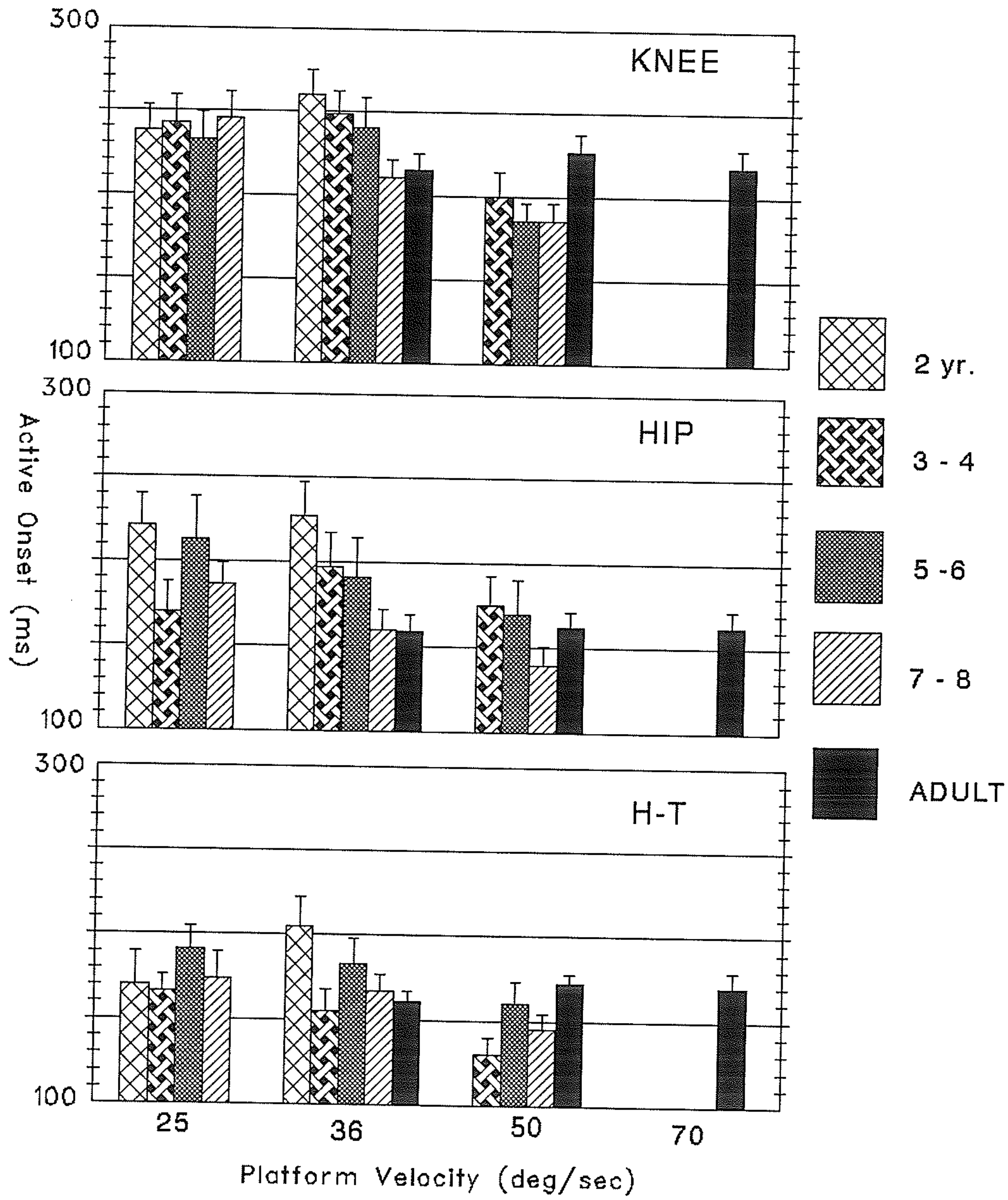


*Fig. 32* **Plots of angular displacement to platform ROTATIONS for one child from C1 age group (ANKLE and KNEE) and one child from P1 age group (HIP and H-T) which illustrates the fluctuations in angular displacement records of the younger children. Platform velocity was 50 °/s for C1 subject, and 36 °/s for P1 subject. Time zero indicates onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are flexion/dorsiflexion and negative (-) values hip extension//planterflexion.**

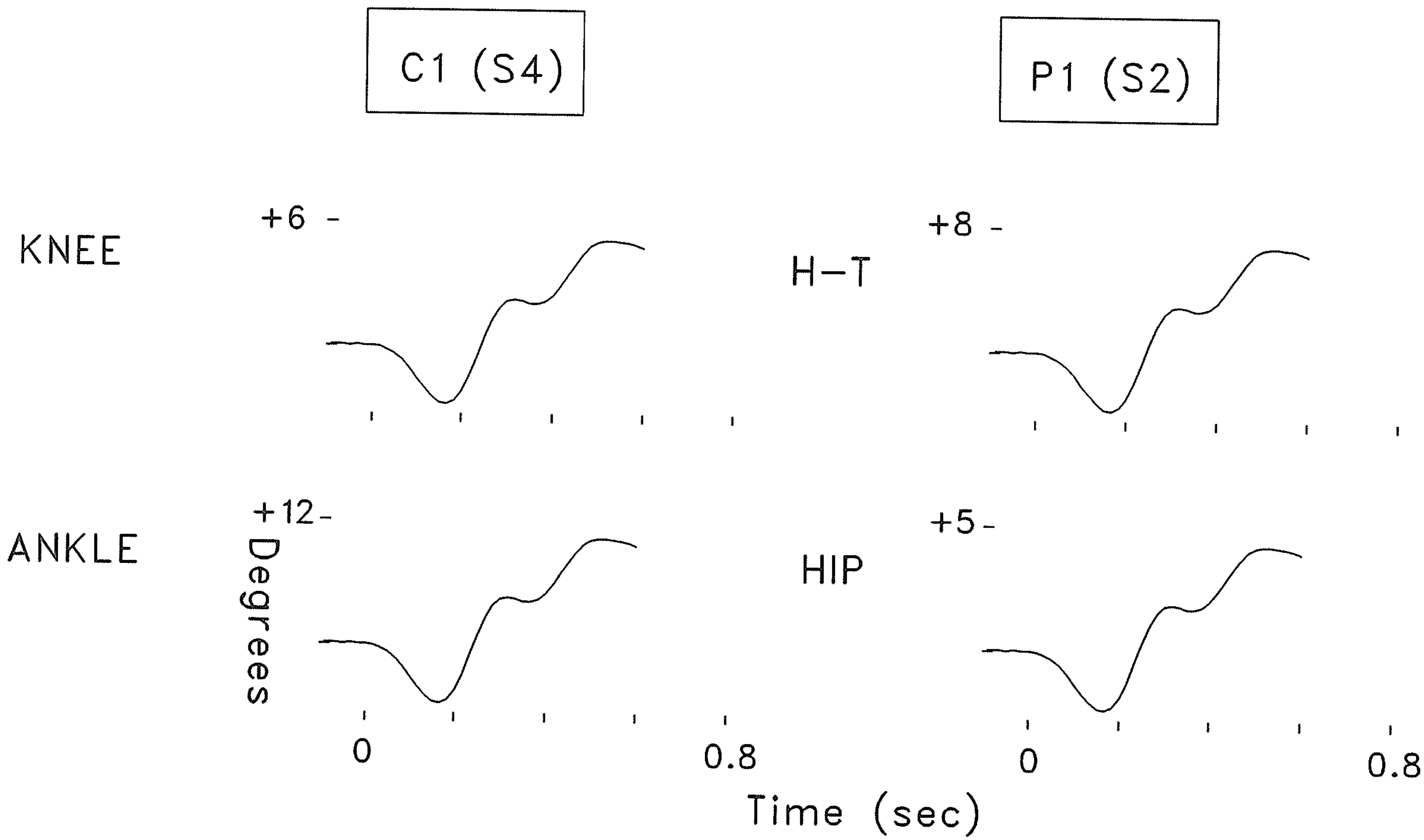
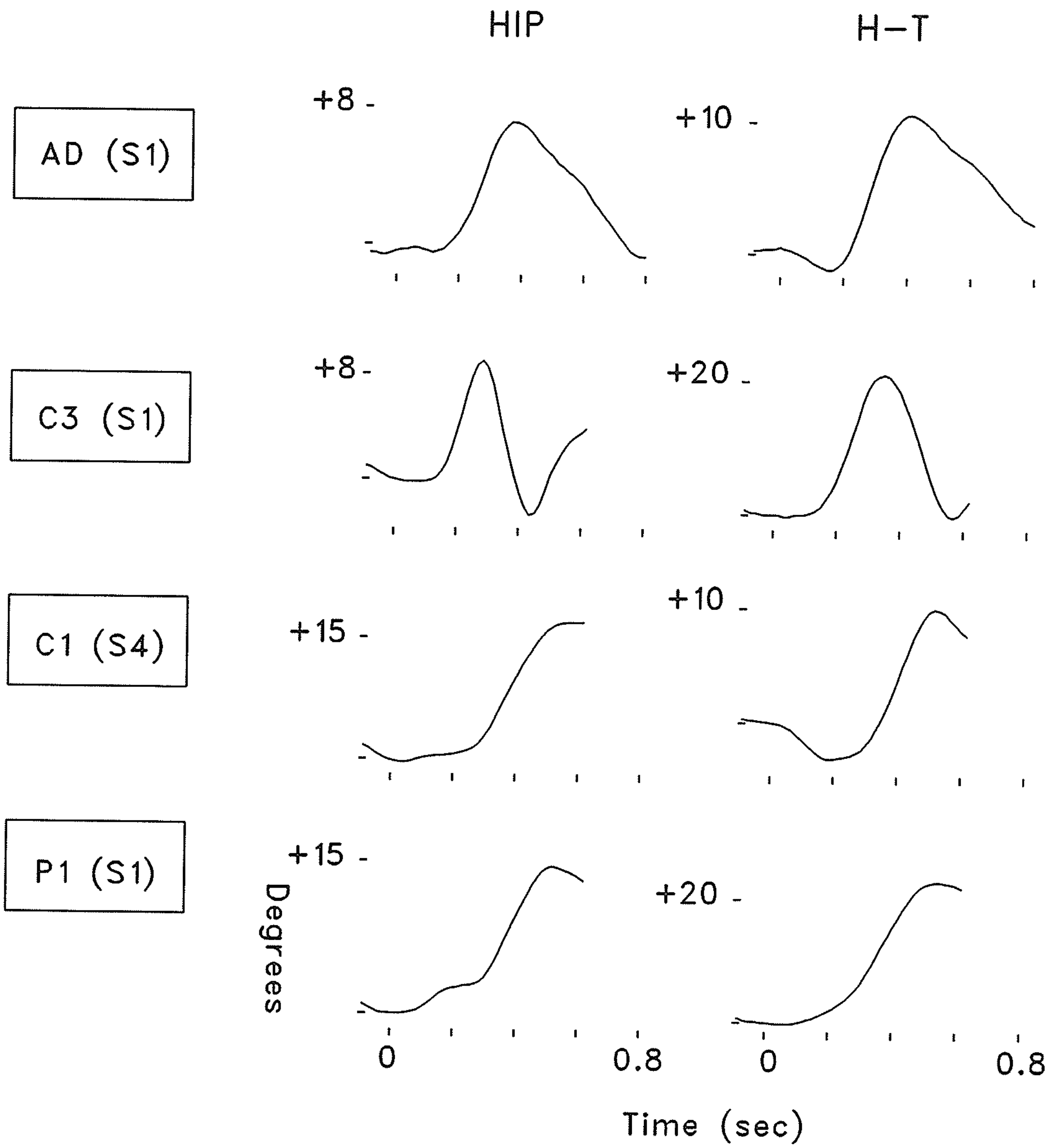


*Fig. 33* Plots of HIP and H-T angular displacement to platform ROTATIONS for one adult (AD), one child from C3, C1 and P1 age groups, which illustrates prolonged hip/trunk flexion in the younger children. Platform velocity was 50 °/s for AD, C3 and C1 subjects, and 36 °/s for P1 subject. Time zero indicates onset of platform motion. All traces have been offset to zero and positive (+) angular displacement values are flexion and negative (-) values extension.



trend towards increased peak angular displacement with increasing platform velocity for hip and H-T (see Fig. 34 - means (SEM) peak angular displacement for hip and H-T in all age groups and velocities). No such tendency of velocity influence was seen in the P1 group.

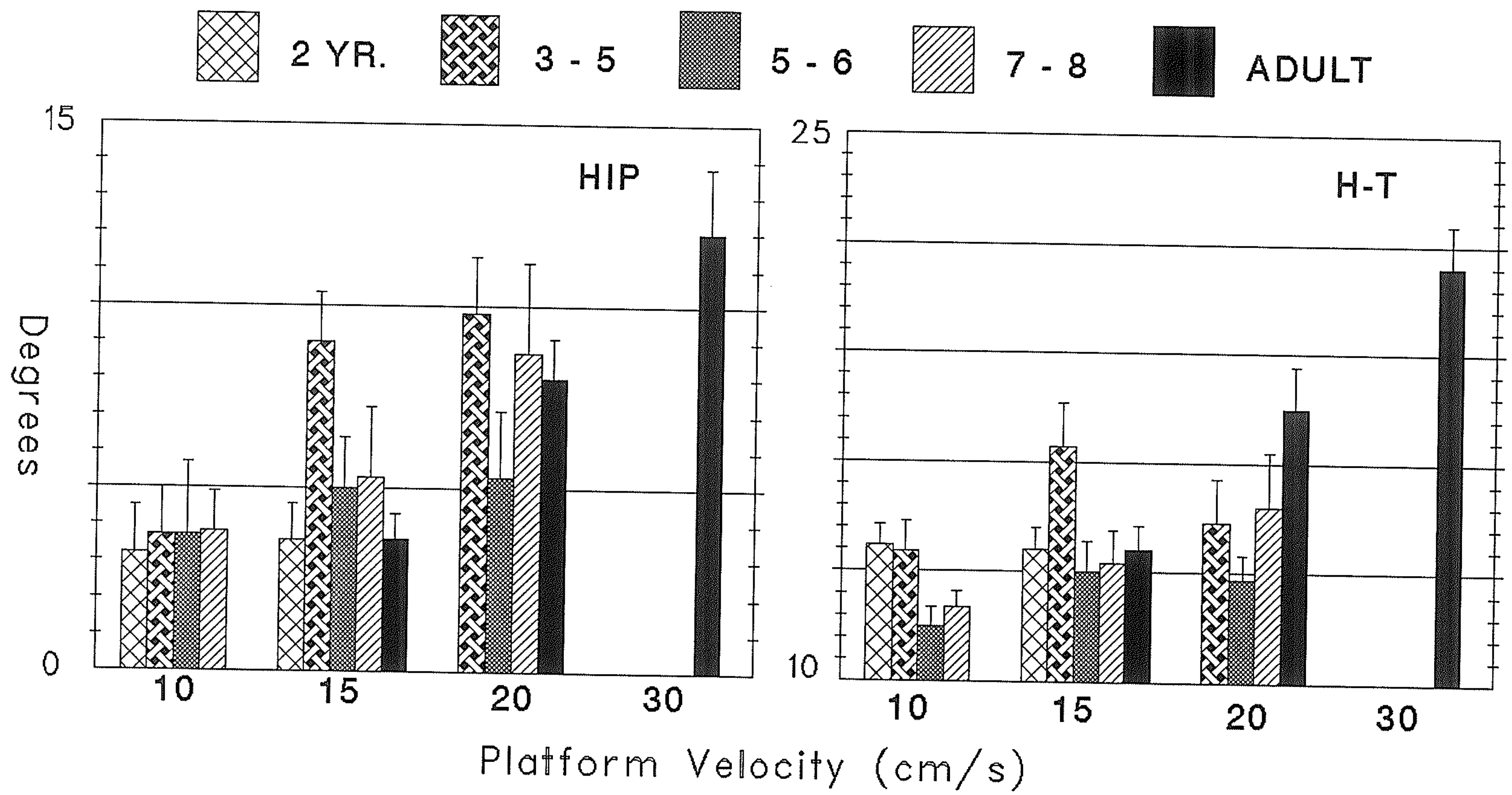
In forward translation, adults presented statistically significant effect of platform velocity on peak angular displacement at all joints ($p < 0.001$). In the children, statistically significant effect of platform velocity was seen for the C3 at the ankle ($p < 0.03$) and at the knee ($p < 0.01$). In all cases the peak angular displacement increased with increased velocity. In the other childrens' groups, a trend towards increased peak angular displacement with increasing platform velocity was seen in the knees (see Fig. 35 - means (SEM) peak angular displacement for ankle, knee, hip and H-T in all age groups and velocities). Only the P1 age group, showed this tendency of velocity influence in hips and H-T too, although not statistically significant.

In rotation, (Fig. 36) the adults showed a significant effect of platform velocity on peak angular displacement only at the hip ($p < 0.01$), whereas for the children, a significant effect of platform velocity was found at the H-T peak displacement: C1 $p < 0.01$, C2 $p < 0.01$, C3 $p < 0.001$. Ankles were not tested because of difficulties in defining active onset of displacement (see above).

EFFECT OF AGE

In backward translation comparisons were limited due to the different strategies employed by the children. Only hips and H-T were tested for significance. No real difference were found in the adult-C3-C2-C1 group (Fig. 34). The results from the C3-C2 C1-P1 comparison showed difference in both hip ($p < 0.005$) and H T ($p <$

*Fig. 34* **Group means and SEM of peak magnitude of active HIP and H-T angular displacement in response to BACKWARD platform translations at all velocities of platform motion.**



0.001). Mean peak amplitude was mainly increased in the C1 age group compared to other age groups. It has to be noted that the results were varying between the velocities and should be regarded as tendencies.

In forward translation, (Fig.35) a statistically significant effect of age on mean peak displacement amplitude was only found in velocity 15 cm/s in the adult-C3-C2-C1 comparison, for the ankles ($p < 0.01$), knees ($p < 0.01$) and hips ($p < 0.04$). The mean peak angular displacement was larger in children than adults. At ankles, mean value for adults was 3 degrees, whereas all childrens' groups were between 6 and 7 degrees. In the knees, the values in adults were 5.3 and 10 degrees in age group C1, to 10.8 degrees in C2 and C3, respectively. In hips, the differences were smaller and more variable between groups: AD = 2.7, C3 = 4.3, C2 = 5.6, C1 = 3.4 degrees. P1 ankle and knee peak displacement amplitudes were not different from the rest of the children (NS). It has to be noted that some of the large displacement values were missing in the younger children because the displacement ended outside the digitized frames.

In rotation, the peak angular knee displacement was significantly larger in C1, C2 and C3 age group children to adults in both platform velocities ($p < 0.001$). As illustrated in Fig. 36 means (SEM) of peak angular displacement at the knee, hip and H-T at the platform velocity of 36°/s, the childrens' age groups were similar in mean peak displacement, between 10-11 degrees, except the C3 age group (8.8 degrees), as compared to 5.4 degrees for the adults. At the platform velocity of 50°/s, the C1 age group showed a mean peak displacement of 17 degrees, which was larger than the rest of the age groups; C3 = 11 and C2 = 9.6, or the adults = 5.7 degrees. In the C3-C2-C1-P1 comparison for the knee, statistical significance was found at only

*Fig. 35* **Group means and SEM of peak magnitude of active ANKLE, KNEE, HIP and H-T angular displacement in response to FORWARD platform translations at all velocities of platform motion.**

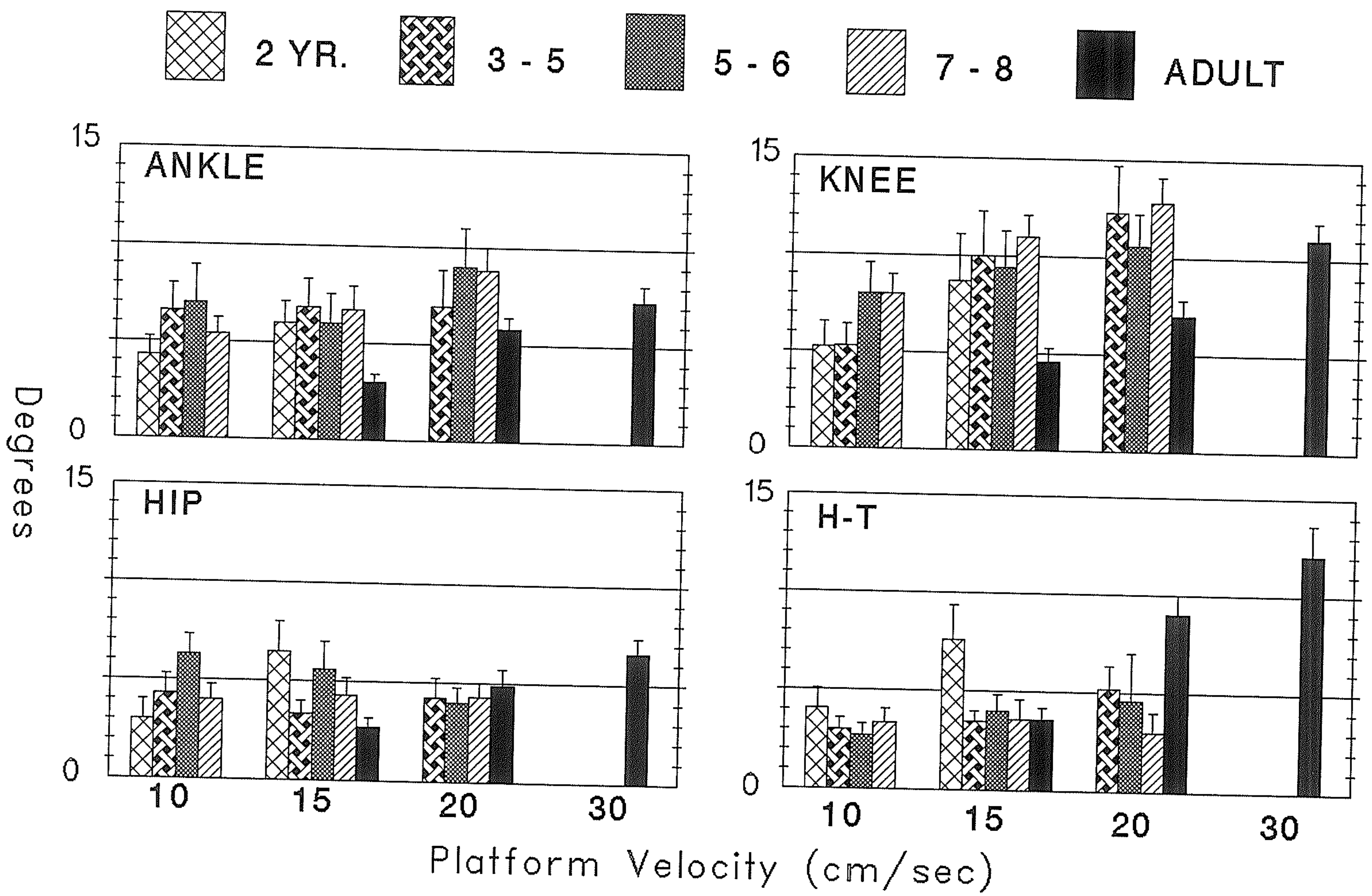
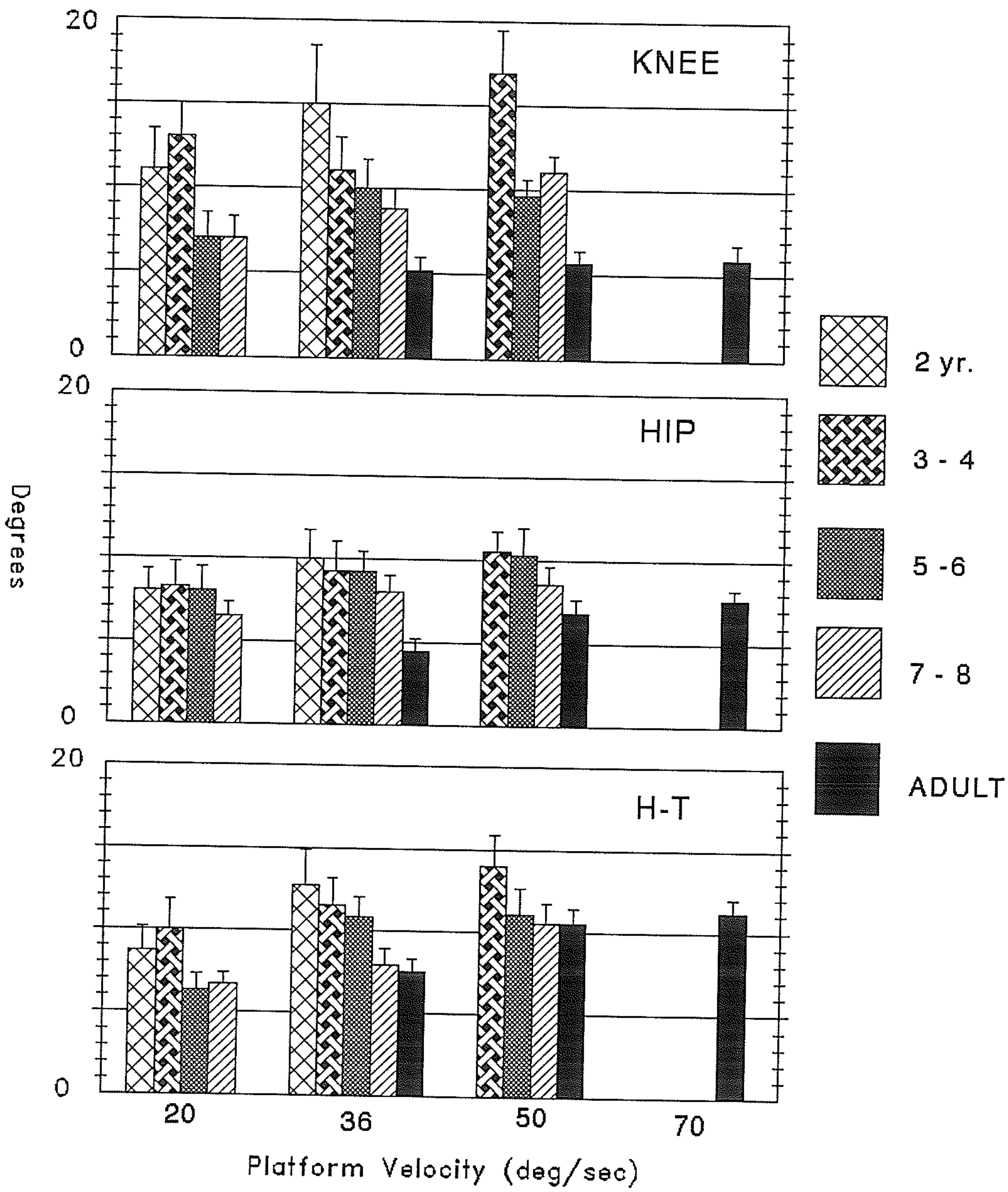


***Fig. 36*** **Group means and SEM of peak magnitude of active KNEE, HIP and H-T angular displacement in response to platform ROTATIONS at all velocities of platform motion.**



a platform velocity of 20°/s ($p < 0.01$). The mean peak angular knee displacement for the C3 and C2 age groups were smaller than for the two youngest groups; C3 = 7.3, C2 = 6.7 and C1 = 14, P1 = 11. In regards to the results of H-T peak displacement, the adult-C3-C2-C1 comparison proved to be significantly different at only the platform velocity of 36°/s ($p < 0.05$), and in the C3 C2-C1-P1 comparison, a significant age effect was only found at the platform velocity of 20°/s ($p < 0.05$). The mean peak H-T displacement at the platform velocity of 36°/s was: adult = 7.5, C3 = 7.9, C2 = 10.8, C1 = 11.5 and P1 = 12.7 (see Fig. 36). Thus, the C3 age group peak H-T displacements were similar to the adults. The same peak displacement-age relationship was also observed for the hip, that is an increase in peak hip angular displacement with decreasing age (see Fig. 36), although this was not statistically significant.

### 3.2.6. PEAK ANGULAR VELOCITY IN PLATFORM TRANSLATIONS AND ROTATIONS

EFFECT OF PLATFORM VELOCITY

In backward translation, the mean peak angular velocity for the adults significantly increased with increasing platform velocity; hip = $p < 0.01$, all the other joints = $p < 0.001$. Fig. 37 presents means (SEM) of peak angular velocity for hip and H-T in all age groups and platform velocities. As for the childrens' groups, no significant effect of platform velocity on peak angular velocity at the hip and H-T was found. However, a tendency for increased peak H-T angular velocity with higher platform velocity was observed for the C3 and C2 age groups.

In forward translation, the effect of platform velocity was statistically significant in adults for all joints ($p < 0.001$). The peak amplitude increased with increasing velocity. No significant effect of platform velocity was seen in the children due to the large variations in the results. However, a clear trend of increased knee angular velocity with increasing platform velocity is evident in the C3, C1 and P1 groups (see Fig 38 means (SEM) of peak angular velocity for ankle, knee, hip and H-T in all age groups and velocities).

In rotation, the adults presented a significant effect of platform velocity on peak angular velocity in hip ($p < 0.01$) and H- T ($p < 0.02$). In children, a significant influence of velocity was seen in the C3 group in the H-T angular velocity ($p < 0.02$), and in the C2 group for knee ($p < 0.01$) and H-T angular velocity ($p < 0.01$). As illustrated in Fig. 39 means (SEM) of peak angular velocity for knee, hip and H-T in all age groups and platform velocities - angular velocity increased with increasing platform velocity. No such tendencies were observed in the C1 and P1 age groups.

EFFECT OF AGE

In backwards translations, the adult-C3-C2-C1 comparison, an age effect on peak angular velocity was found statistically significant for the hip ($p < 0.001$) at both platform velocities of 15 and 20 cm/s velocities. For the H-T movement, significance was only seen at the platform velocity of 15 cm/s ($p < 0.001$). As for the C3-C2-C1-P1 comparison, a significant age effect was also found at the hip ($p < 0.001$) and at the H-T ($p < 0.001$). For all cases, the peak angular velocity increased with decreasing age (see Fig. 37). Mean values for the hip at the platform velocity of 15 cm/s were in adult = 24, C3 = 34, C2 = 44, C1 = 67 and P1 = 67 cm/s.

In forward translation, adults had significantly lower peak angular velocity than C3, C2, and C1 age groups; ankle ($p < 0.001$ at the platform velocity of 15 cm/s and

$p < 0.005$ at 20 cm/s), knee ($p < 0.001$), and for hip and H-T ($p < 0.01$) only at platform velocity of 20 cm/s, greater in young children than older children and adults. As for the C3-C2-C1-P1 comparison, no significant differences between children groups were obtained (see Fig 38).

In rotation, the peak angular velocity was significantly higher in the children compared to adults in both platform velocities in knees ($p < 0.001$) and hips ($p < 0.001$ at the platform velocity of 40 0/s and $p < 0.002$ at 50 0/sec). For H-T, a significantly greater peak angular velocity in children compared to adults was only found at the platform velocity of 50°/s ($p < 0.004$). No significant difference between C3, C2, C1, and P1 age groups was found. (see Fig. 39).

*Fig. 37* **Group means and SEM of peak velocity of active HIP and H-T angular displacement in response to BACKWARD platform translations at all velocities of platform motion.**



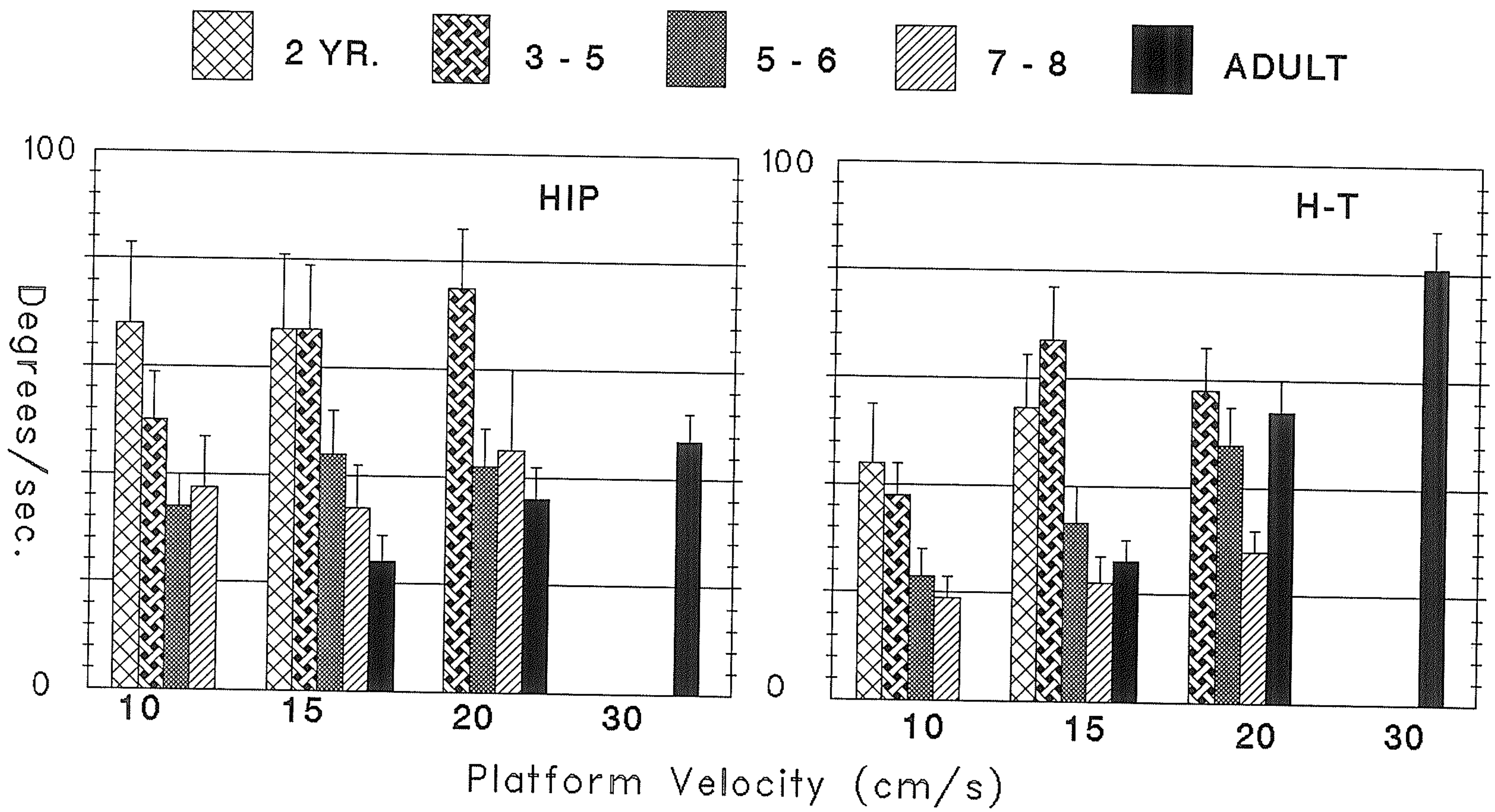


*Fig. 38* **Group means and SEM of peak velocity of active ANKLE, KNEE, HIP and H-T angular displacement in response to FORWARD platform translations at all velocities of platform motion.**

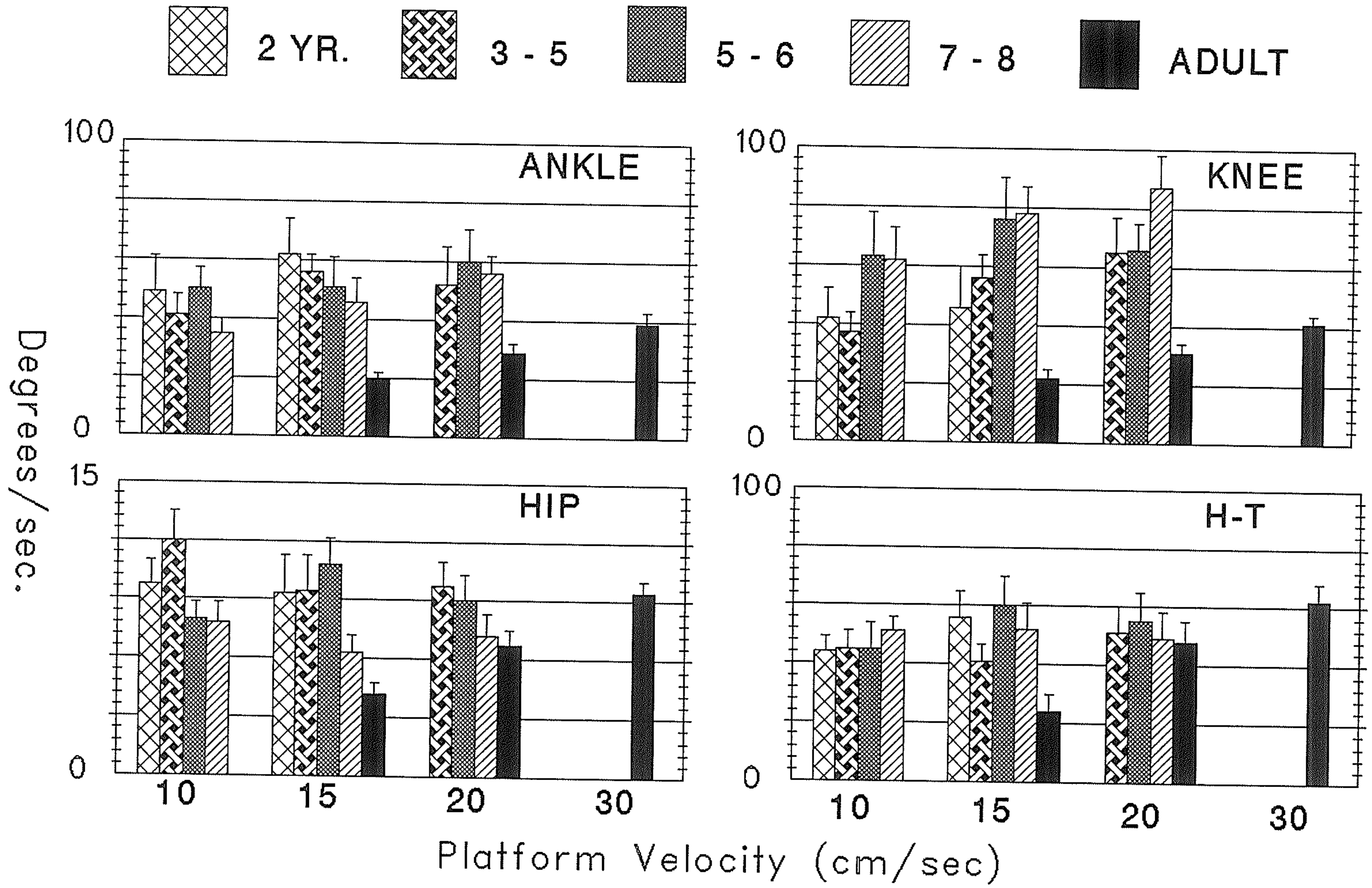
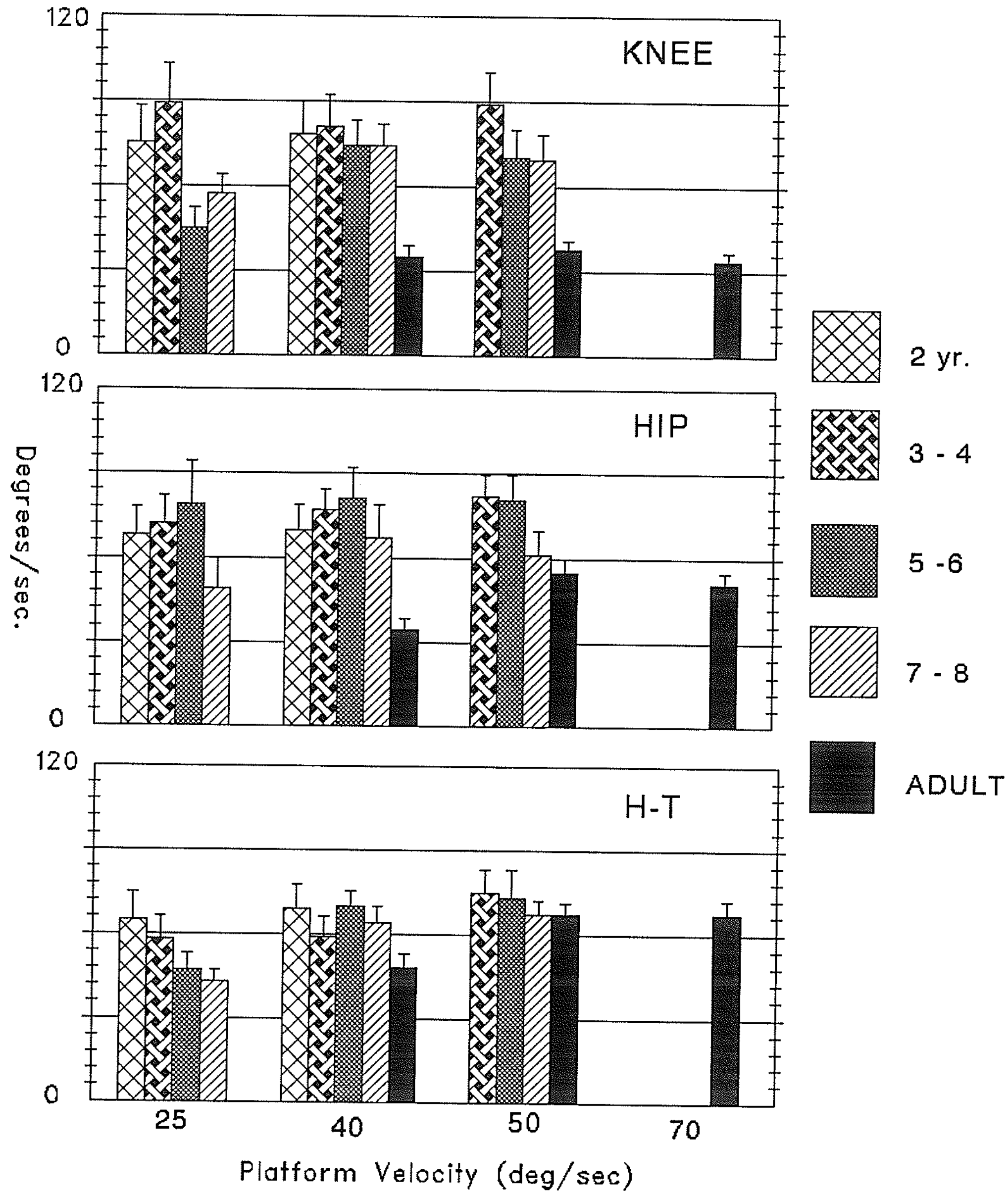


*Fig. 39* **Group means and SEM of peak velocity of active KNEE, HIP and H-T angular displacement in response to platform ROTATIONS at all velocities of platform motion.**



# *CHAPTER 6 DISCUSSION*

The purpose of this study was to examine the movement strategies employed in restoring postural equilibrium in response to sudden disturbances of standing balance in children and adults, and to identify differences between adults and children in the regulation of standing balance by the motor control process. According to the objectives of the study, the main findings were:

(1) Sudden platform displacements induced a consistent balance disturbance in subjects of all age groups. The type of disturbance or balance requirement for platform translations was fundamentally different than that for platform rotations. The linear displacement of GT did not move in space during platform translation as opposed to in toes-up platform rotation, where GT was displaced backwards. Stating that the backward translation and toes-up rotation perturbation, although both provoke a stretch of the dorsal leg muscles, do contain a different somatosensory input requiring different response by the subject.

(2) Recovery of equilibrium, in response to forward platform translations, backward platform translations, and toes-up rotations, was achieved by different multi-link movement strategies involving activation of all lower limb muscles and motion of all body segments. The main components of the adult or mature compensatory movement strategies were observed in children of all age groups.

(3) Platform velocity had no significant effect: (i) On the onset or pattern of active

angular displacements (except for onset in platform rotation in children) (ii) Onset of linear displacement of the GT (iii) On the onset time or pattern of muscle activation.

(4) A significant effect of platform velocity on magnitude of the muscle response was revealed in specific muscles, which was dependent on the type of platform disturbance. In rotation, this effect was not seen in children below 7 years.

(5) For adults, the magnitude and peak velocity of active angular displacement and of GT linear displacement generally increased with increasing platform velocity. This was not seen in children below 7 years of age for forward translation, and not seen for children below 5 years of age for platform rotation.

(6) Each movement strategy was associated with a unique temporal pattern of activation in all lower limb muscles tested, although the muscle activation pattern of lower limb muscles and pattern of active angular displacement did not always follow the same distal to proximal order in children and adults.

(7) In both backward translations and platform rotations, all age groups responded with an early stretch-evoked burst of muscle activity in GA which was followed by a long duration GA response. In backwards translation, all age groups modulated the magnitude of muscle activity as a function of platform velocity. This was not observed in platform rotations in children below 7 years.

(8) In regards to magnitude of muscle activation as a function of type of platform

perturbation; (i) In all age groups, TA and HAM showed statistically significant greater percentage of activity in forward translation and rotation as compared to backward translations and (ii) As opposed to older children and adults who showed greater percentage of GA activity in backward translation, the P1 group showed a greater percentage of GA activity in platform rotations.

## 1. BALANCE REQUIREMENTS AND SENSORY INPUTS

The balance disturbances induced by platform translation and rotation were fundamentally different. In translation, the base of support was moved relative to the TCM which remained stationary in space. The requirement of this task was to rapidly move the TCM back/forward over the displaced base of support. On the other hand, platform rotation resulted in a backward displacement of the TCM with a stationary, yet tilted support base. The requirement of this task was to halt the motion of the TCM.

In regards to sensory inputs which would contribute to the selection and generation of the appropriate balance reaction, each type of platform displacement resulted in a different pattern of stimulation of somatosensory receptors. As illustrated in Fig. 6, the pattern of early proprioceptive inputs (muscle spindles, joints afferents and golgi tendon organs) may have varied between forward translation, backward translation and platform rotation. For the passive components of ankle angular displacements, forward translation showed plantarflexion, while backward translation and rotations showed dorsiflexion. In response to backward translations and rotations, ankle dorsiflexion did evoke a short latency burst of activity in GA in all age groups, which would represent a segmental stretch reflex. Although it has to be noted that in order to have similar magnitude and velocity of ankle dorsiflexion in backward translation and rotations, one would have to compare the lowest velocity of rotation to the two highest velocities of translation. This is based on the study by Nardone et al (1990) who found comparable ankle angular velocity and amplitude at 21°/s of platform rotation, with 3 degrees displacement and 21 cm/s of translation with 3 cm displacement. For the passive components of knee angular displacement, forward translation and rotation showed extension while backward translation showed flexion or no movement. For the hip/trunk, backward translation and rotation showed extension while forward translation showed flexion. As illustrated in Fig. 3 and Fig. 7, the pattern of early exteroceptive sensory inputs from foot pressure receptors, also varied between the different types of platform displacements. CFP displacement for forward and backward translation showed a similar pattern but opposite in direction. The displacement of CFP following platform rotations was more complex, the pattern in the first 90-100 ms was similar to that observed for backward translations, but then, as the body was thrust backwards, the pattern of CFP was similar to forward translation. It is not possible to determine the contribution of different sensory inputs in generating the varied movement strategies employed during translation and rotations. Although, due to the fact that certain sources of sensory inputs were the same in the different platform displacements, this would argue against a single source of sensory input, for example, that proprioceptive inputs arising from ankle angular displacements would trigger the balance reactions.

## 2. MOVEMENT STRATEGIES

Contrary to early studies of healthy adult subjects, which reported that in response to platform displacements, equilibrium is restored through single-link movement strategies, in particular angular displacement only about ankle joint with no or minimal knee or hip angular displacement, evidence from recent studies has revealed that the body responds to balance disturbances with motor strategies involving motion of multiple body segments. The results of this study clearly demonstrate that in response to sudden platform displacements, equilibrium was restored by multi-link movement strategies, movement patterns which were fundamentally distinct for forward platform translation, backward platform translations and toes-up platform rotations. The pattern, direction and order of active ankle, knee and hip/trunk angular displacements of the adult movement strategies were present in children of all ages. However, one major difference between adults and younger children was the increased time delay between onset of the initial angular displacement and succeeding angular displacements about proximal and distal joints. This delay onset sequence seemed to play a critical role in the ability to effectively regain balance.

## 2.1 FORWARD TRANSLATION

Immediately following onset of forward platform translation the CFP was passively displaced in the posterior direction but as evidenced from analysis of GT linear displacement, the TCM remained stationary, relative to space, for approximately 190 ms, at which time the TCM was displaced forward over the base of support as a result of the active compensatory response of the body.

Subjects of all ages employed a movement strategy which involved knee flexion, followed by ankle dorsiflexion and then hip/trunk extension. Although the onset of knee and ankle angular displacement was similar in all age groups, the onset of active hip/trunk extension was considerably later in children under 7 years of age as compared to adults and 7-8 year old children. Horak and Nashner (1986) have described a hip movement strategy employed by adult subjects in response to forward translations. The movement pattern consisted of hip extension and ankle dorsiflexion with no angular displacement at the knees. However, this was only observed when restrictions were placed on the length of the support surface, that is, the hip strategy was observed only if subjects stood on a narrow beam as opposed to a normal support surface where the single-link movement pattern of only ankle dorsiflexion was observed. In another investigation, Nardone et al (1990) reported that adults employed a multi-link movement strategy in response to small amplitude (3 cm) forward translations. They showed similar passive and active angular displacements of ankle, knee and hips as in the current study. Although not examined in their study, from inspection of the angular displacement records it appears that the temporal order of angular displacements was knee flexion then ankle dorsiflexion and hip extension. The only study in children which has examined movement patterns was the study by Shumway-Cook and Wollacott (1985), who presented the results of only one 5 year old subject. They showed knee flexion and ankle dorsiflexion but no hip angular displacement in the active response to forward translation. It should be noted that lack of hip movements could be due to the small amplitude of forward translation which was 2 cm as compared to 6 cm used in the present study.

The adults and, for the most part, the 7-8 year old children, started the compensating movement earlier, and reached an equilibrium position within a shorter time period than the younger children. This is supported by the following list of time-related parameters which were reduced in adults and 7-8 year old children as compared to the younger children:

1) The onset of TCM (GT) displacement.

2) The onset of compensatory, anterior displacement of CFP.

3) The time to reach the CFP equilibrium position.

4) Onset time of active hip/trunk extension.

This is evidence that adults and 7-8 year old children were more effective in their efforts to restore equilibrium to forward translations than the younger children.

Although the pattern and timing of the body's compensatory response to forward translations did not vary with platform velocity in any age group, the younger children were generally unable to scale the magnitude of the balance reaction to the magnitude of the stimulus (platform velocity). Clearly, the adults and 7-8 year children were able to modulate the magnitude of their balance reactions as a function of platform velocity or degree of difficulty as follows:

1) Increased peak velocity of TCM displacement, not seen in younger children.

2) Increased magnitude and peak velocity of ankle, knee and hip/trunk angular displacement, not seen in younger children.

3) Increased magnitude of muscle activity (except for TA and GA in the 50 ms interval). Increased muscle activity was also seen in children but not in all muscles. No children except the P1 age group showed effect of platform velocity on magnitude of TA activity of the 50 ms interval. The younger children, P1 and C1 age groups, showed no effect of platform velocity on magnitude of proximal muscle activation.

The inability of the younger children, below the age of 7 years, to adjust their postural response to increasing velocity of forward translation is also evident from the finding that some of these children had to take a step backwards during the compensative response in order to regain balance. The onset of the initial active angular displacement of the forward translation movement pattern, knee flexion, was earlier or at the same time in younger children as compared to the adults and 7-8 year old children. This information indicates that knee flexion was not a crucial response in actually moving the TCM back over the new position of the base of support. However, a striking difference was seen in the time delay in onset of succeeding active angular displacement of the movement pattern. The delay between onset of knee flexion and ankle dorsiflexion was longer in children as compared to adults, whereas small differences were seen between childrens groups. Furthermore, a large delay in onset between ankle dorsiflexion and hip/trunk extension was seen in the younger children as compared to adults and 7-8 year old children (115 and 15 ms respectively). This delay was increased in the P1 age group (148 ms) as compared to the older children.

Another age related difference observed in the kinematic results was related to the magnitude and peak velocity of angular displacement. In the children, the magnitude and peak velocity of angular displacement about various joints was greater as compared to adults. For the peak magnitude, this age difference was true for knee flexion and ankle dorsiflexion, but not true for the hip/trunk extension. The increased amplitude of ankle and knee angular displacement could be due to increased delay in onset of active hip/trunk extension. In the children, the compensatory knee flexion response was accompanied by a prolonged period of hip flexion. Biomechanically, this allowed the center of mass to stay behind the knee, and with the action of the gravitational force, this would contribute to further knee flexion. It was approximately 180 ms (range 162 to 189 ms) after onset of knee flexion, hip extension ensued (which would result in the forward displacement of the TCM) as compared to the delay in adults of 85 ms. Small amplitude fluctuations in the direction of active angular displacements observed in both knee and hip displacements of the younger children would also contribute to an increased time to compensate for the perturbation. The fluctuations acted as small abrupt changes in the direction of movement during the balance reactions. This is consistent with the results of the CFP displacement, which showed fluctuations, and increased time to reach CFP equilibrium position.

It has been stated by Riach and Hayes (1987) and Forssberg and Nashner (1982), that children, as compared to adults, would exhibit greater velocity of displacement or body sway, due to the fact that children are shorter, have less mass and consequently, less moment of inertia. This may be the reason why children often generally exhibit higher peak velocity of angular displacement than adults. However, movement velocity is not only dependent on the moment of inertia to be overcome, but on the force generated by muscle activation and also by the timing of muscle activation, and consequently of succeeding movements of the respective body segments, or motor coordination. These factors are all important for effectively restoring equilibrium position. The difference in temporal sequencing of motion of multiple body segments and its relationship to balance performance has only been and can only be inferred from analysis of the temporal sequencing of muscle activation patterns (Forssberg and Nashner 82, Shumway-Cook and Wollacott 85).

The magnitude of the balance disturbance in forward translation reached the limits of stability of the younger children, even at the lowest platform velocity. This could be due to: (1) the lack of maturation or fine tuning of the postural control system in the younger children, and/or (2) biomechanical considerations, such as age differences in foot size as suggested by McCollum and Leen 89. Although, the pattern and timing of the response did not vary with platform velocity, as observed in the adults, the variation in temporal order of succeeding knee, ankle and hip/trunk angular displacements in the younger age group and the inability of the younger children to scale or modulate the magnitude of the balance response to the magnitude of the stimulus (platform velocity) is evidence in support of a neural mechanism as the main reason for the age differences and poor performance of the younger children.

These results demonstrate that the recovery of postural equilibrium following forward translation is not fully developed in children below the age of 7 years of age, and that it is a more difficult task than for backward translations or platform rotations (see below).

According to the studies which have evaluated the ability of young children to maintain a standing balance position during sensory conflict situations (Forssberg and Nashner 82, Nashner et al 83, Shumway-Cook and Wollacott 87), children did maintain balance when the support surface was stabilized, and thus, somatosensory input from platform movement gave conflicting or misleading information. In the present study, all children were able to regain balance in response to platform rotations. The results indicate that sudden platform rotations, suggested to represent a sensory conflict, are solved by children down to 2 years of age, but not as effectively as in adult subjects. The evidence of reduced performance in the younger children was demonstrated by: the large variability in time for CFP to return into equilibrium position, delayed onset of active hip flexion in children below 4 years of age. When the difficulty of the task was increased (increasing platform velocity), the children below 4 years of age did not modulate the response to the increased requirements, but they demonstrated the same increased activity of TA and HAM muscles in rotation compared to forward platform translation as did the adults. It should be noted that children had more difficulty restoring balance to forward translations than to platform rotations, and the difference in performance between adults and children was much greater.

## 2.2 BACKWARD TRANSLATION

Immediately following onset of backward platform translation the CFP was passively displaced in the anterior direction but as evidenced from analysis of GT linear displacement, the TCM remained stationary relative to space for approximately 180 ms, at which time the TCM was displaced back over the base of support as a result of the active compensatory response of the body. In response to backward translation, the movement strategy employed observed to compensate for the disturbance induced was hip/trunk flexion, ankle plantar flexion, and a variable, small amplitude knee extension or flexion. This is similar to the hip movement strategy of adult subjects in response to sudden backward translations described by Horak and Nashner (1986). The movement pattern consisted of hip flexion and ankle plantarflexion with no angular displacement at the knees. But as stated above for forward translation, this was only observed when restrictions were placed on the length of the support surface. That is, the hip strategy was observed only if subjects stood on a narrow beam as opposed to a normal support surface where the single-link movement pattern of only ankle dorsiflexion was observed. In another investigation, Nardone et al (1990) have also examined movement strategies in adults in response to small amplitude (3 cm) backward translations. They reported that adults employed a multi-link movement strategy with similar passive and active angular displacements of ankle, knee and hips as were observed in the present study. No information on the movement patterns of children is available.

Based on the analysis of CFP displacement; time to peak CFP displacement and time to reach CFP equilibrium position was increased in children as compared to adults, which would indicate that adults restored equilibrium earlier than children in backward translation as in forward translation. The finding that time to onset of GT (TCM) linear displacement and the onset of active hip/trunk flexion was increased in the adults as compared to the children demonstrates that childrens' compensatory response began earlier than the adults. However, there was no significant difference in: (1) the magnitude or peak velocity GT linear displacement (TCM) between children and adults, and (2) the magnitude and peak velocity of hip/trunk flexion between adults and children (except for an increase in hip/trunk flexion of the C1 age group). Thus, the task of regaining balance seemed to differ less between adults and children in backward translation as compared to forward translation.

There were also less age related differences in the effect of platform velocity on the CFP parameters and movement parameters to backward translation than forward translations. In this regard, increased platform velocity had no significant effect on:

(1) time to onset of GT linear displacement.

(2) time to peak CFP displacement (except C2 for time to peak CFP displacement), or time to reach CFP equilibrium in any group.

(3) time to onset of hip/trunk flexion in any age group. In regards to the effect of platform velocity on the amplitude or extent of the balance reaction, adults and children showed similar modulated response to increasing challenge or balance

requirements, which included:

1) increased magnitude of GT linear displacement in all age groups.

2) increased peak velocity of GT linear displacement in adults, and although not statistically significant, clear trends of increased peak velocity of GT linear displacement was observed in all children age groups.

3) increased magnitude and peak velocity of hip/trunk flexion in adults, and although not statistically significant, clear trends of increased magnitude of hip/trunk flexion was observed in C3, C2, C1 age groups and increased peak velocity observed C3 and C2 age groups.

4) increased magnitude of muscle activation in adults and children (although in fewer muscles in children).

Thus, in comparing children to adults, the task of regaining equilibrium in response to backward platform translation was achieved in a similar manner with relatively small differences. Also, children above the age of 3 years were able to scale response magnitude in accordance with the requirements of the task, increasing platform velocity. The fluctuations observed in angular displacement records of the younger children, seen as small amplitude adjustments of flexion and extension may increase the time to reach equilibrium.

The direction of active knee angular displacement varied within and between groups. Knee extension was primarily observed in the adults and older children, whereas knee flexion showed an increasing incidence in the younger age groups. When knee extension occurred, the magnitude was small, in the order of 1-3 degrees. Knee flexion responses were of greater magnitude, (3-8 degrees) especially in the P1 and C1 age groups. Although knee flexion was found in about half of the adults in the highest velocity, in general, knee flexion in the children was more pronounced and of longer duration. Thus, the presence of small amplitude knee extension versus knee flexion seems to depend on age. Biomechanically, when the base of support was moved posteriorly, the TCM remained in the starting position. Flexing the knees would result in a posterior displacement of the TCM, back over the base of support, only if the ankles plantarflexed. If dorsiflexion occurred at the ankle, then this would cause increasing knee flexion and a anterior shift of the TCM. Our results showed that ankle movements varied between plantarflexion and dorsiflexion, and knee flexion did not seem to be clearly associated with increased ankle plantarflexion. The role of muscle activity is important to clarify this situation and will be discussed below.

## 2.3 PLATFORM ROTATION

Due to the toes-up rotation of the platform, CFP was initially displaced, for a short period, in the anterior direction. This was immediately followed by a posterior displacement of the CFP, which coincided with an early backward displacement of the TCM as evidenced from the analysis of GT linear displacement. The TCM was moved backwards during the platform perturbation and actively moved forward over the base of support again by the body's compensatory response. Thus, unlike platform translations, balance reactions to platform rotation must function to halt the backward motion of the TCM and regain an equilibrium position. In regards to onset, magnitude, or peak velocity of this early, passive component of GT linear displacement, no differences were observed between adults and the children.

In response to platform rotation, the movement strategy employed to regain balance consisted of ankle dorsiflexion, hip/trunk flexion and knee flexion. This movement pattern was evident in subjects of all ages. Nardone et al (1990) have examined movement patterns in response to platform rotations. Their results showed hip flexion and ankle dorsiflexion response as in the present study, but no movements in the knees were observed. This could be due to the smaller amplitude of platform rotation - 3° compared to the present study in which there was 9° in adults, and 7° in children. Allum et al (1990) have also examined balance reaction in healthy adults subjected to platform rotations. They described a "stiffening" response strategy. Although trunk flexion was observed, they stated that the perturbation was mainly absorbed by the ankle joints. However, their method did not directly record the knee or hip angular displacements, rather, only angular motion of the trunk and the lower leg, and not the thigh segment, which was recorded with the use of angular accelerometers. The results of the present study demonstrate that the balance disturbance imposed by toe-up platform rotations was not absorbed by the ankle joints, as the TCM was thrusted backwards within 100 ms of onset of platform rotation, and the "stiffening" strategy does not reflect the compensatory movement pattern, as a combination of hip/trunk flexion, ankle dorsiflexion and knee flexion was employed to halt the backward motion of the TCM. In many of the subjects, both adults and children, the backward displacement of GT was only halted and maintained in the posterior position without being moved forward again. When the GT is displaced backwards, a forward movement of the trunk is an effective way of quickly compensating for the posterior displacement of TCM. Haas et al. (1986) reported that in response to toes-up platform rotation, children below 3 years of age did not show hip flexion in contrast to older children. However, Haas et al. (1986) did not report on how this was measured and only muscle activity and displacement of CFP were recorded. These findings are not in agreement with the kinematic results in the present study. In fact, these results show that the amount of knee flexion was considerably greater in the younger children than the adults and 7 to 8 year old children: about 5° for adults as compared to 10°-17° in the children. The magnitude of hip/trunk flexion, also, was greater in the younger children. Those below 5 years of age showed the greatest amount of angular displacement. The amount of hip/trunk flexion of the 7-8 year old children was similar to the adult values. Concerning peak velocity of knee, hip, and H-T angular displacement, all children presented higher velocities than adults. No significant age difference was observed in time to peak CFP displacement or time to reach equilibrium position, although a trend towards increased time to reach equilibrium for the younger children was evident. However, the onset of hip, H-T and knee angular displacement increased with decreasing age, the P1 age group showed the latest onset. There were few age-related differences in the effect of platform velocity on the CFP and movement parameters to platform rotations. The time to peak CFP displacement was not affected in any age group, and the time to reach CFP equilibrium position tended to increase with increasing platform velocity in all groups. Platform velocity had no effect on magnitude or peak velocity of knee flexion in any age group. The magnitude of hip flexion in adults and H-T flexion in children increased with increasing platform velocity. These include: (1) an increased peak velocity of angular displacement was observed in adults and children above 5 years of age, and (2) only adults and 7-8 year old children showed significant influence of platform velocity on magnitude of muscle activity: GA and QUAD muscle activity in the 200 ms interval increased with increased platform velocity. Thus, the task of regaining equilibrium in response to platform rotations was achieved with relatively small differences between children and adults. Also, the children above 5 years, with the few exceptions noted above, demonstrated the ability to scale response magnitude in accordance with the requirements of the task, increasing platform velocity.

The results of analysis of CFP velocity ratio, which gives information about the rate of balance compensation relative to the rate of the balance disturbance, showed significantly higher values in the younger children as compared with the adults and 7-8 year old children. Since the magnitude and peak velocity of the passive component of GT linear displacement or TCM (balance disturbance) was similar in adults and children, and since no significant age related difference were found in the time delay between onset of hip and knee angular displacement, the increased velocity ratio would be the result of the increased magnitude and peak velocity of active hip and knee flexion with decreasing age.

## 3. MUSCLE ACTIVATION PATTERNS AND RELATIONSHIP TO PATTERNS OF ACTIVE ANGULAR DISPLACEMENTS

The comparison between the kinematic and EMG results suggest that interpretations of muscle response patterns alone, especially onset latency, does not automatically allow conclusions to be made about the resulting movement strategy. For instance, in response to platform rotations, the distal to proximal order of muscle activity did not give an unambiguous pattern of angular ankle movement as the first response to platform perturbation. Another example can be found in the comparison of the role of GA muscle activity to backward translation and platform rotations where

GA was the first muscle to be activated and where the onset latencies were identical. In the adults, the percentage of GA activity in the 50 ms or 200 ms interval did not show any significant differences between the different platform translations. This did not result in the same movement about the ankle or the knee joint. In platform translations, the ankles plantarflexed and the knee tended to extend, while in platform rotations, the ankles dorsiflexed and the knee flexed. This is also consistent with the different multi-link movement patterns which were observed, where movements about the ankles or the knees were not the initial movement or not the primary movement leading to compensation of the balance disturbances in the mature adult. In the children, GA activity tended to be increased in translation compared to rotation, except for the P1 group which showed increased activity in rotation. This might suggest that the youngest children show less specificity and are not able to suppress a non-functional stretch-evoked GA activation which would move the lower leg segment backwards. But since knee flexion was large in rotation in the younger children, GA might play a considerable role in this flexion of the knee to prevent the TCM from moving further backwards (see under rotation). The angular displacement showed a mixed pattern of knee flexion and extension in translation and only knee flexion in rotation. Thus no age related differences were seen in the angular displacement pattern between the perturbations, only in the performance: the delayed onset and increased amplitude in hip flexion in rotation in the children.

The TA presented increased activity in the 50 ms and the 200 ms interval in rotation as compared to translation in all subjects. In the 200 ms interval HAM was more involved in platform rotation than platform translation for all age groups. Thus, even the youngest age group showed a specific pattern of the relative magnitude of

TA activation to the type of perturbation. Although, when comparing platform translation and rotation, the latter seemed to require increased activity of all muscles in P1 age group. The role of temporal sequence (for translation: adults = GA-QUAD-TA HAM, child = GA-HAM/TA-QUAD and for rotation: adults = GA-TA-QUAD HAM, child = GA-HAM-TA-QUAD) has to be evaluated together with information related to magnitude of muscle activity and to the resulting angular displacement in order to determine the motor consequences of various sequences.

## 3.1 FORWARD TRANSLATION

The sequencing of knee, hip/trunk and ankle angular displacement in adults, as described above, was associated with a near synchronous activation of TA, GA, HAM and QUAD. Although the temporal sequence of muscle activation was similar in 7-8 year olds, they presented with longer delays between onset of knee, ankle and hip/trunk angular displacements. Thus, a difference in the temporal pattern of body segment motion still exists between 7-8 year old children and adults. As described above, the temporal delay between onset of ankle dorsiflexion and hip/trunk extension observed in the 7-8 year old children was in the same range as in the C2 and C1 year old children; about 100 ms longer compared to adults. This difference between adults and the 7-8 year olds was not as distinctly reflected in the CFP records, where the performance of 7-8 year olds was similar to adults, and unlike the younger children the 7-8 year old children did not take steps backward in order to regain balance. Onset of muscle activity did start distally in children with TA activity as the first response followed by: GA, HAM and QUAD in the C3 age group; QUAD, GA, and HAM in C2 age group; and HAM, QUAD and GA in the C1 and P1 age groups. Nevertheless, the knee flexion preceded ankle dorsiflexion. Thus, it would appear that TA activity rotates the lower leg forward, resulting in knee flexion due to gravitation weight and to the relatively large moment of inertia of the segments above the knee joint. This mechanism was also suggested by Oddson (1990) who observed knee flexion in response to fast backward trunk movements. Relative to the other perturbations, TA presented stronger activation in forward translation. It should also be noted that activation of HAM occurred within 24 ms (P1 the latest) of TA activation. This likely would contribute to the rapid active knee flexion. In all age groups except in the P1 age group, the percentage of HAM activity was greatest in forward translation for both the 50 ms and 200 ms interval relative to rotation or backward translation. In the P1 age group, the percentage of HAM activity in forward translation was the same as backward translation and greater than rotation.

A clear difference in the child-adult comparison was the late onset of GA activation in children below 7 years of age. The increased early knee flexion in children combined with increased delay of GA onset, implies that GA was not functioning as a knee flexor. Rather GA activity would contribute to decelerate the active ankle dorsiflexion and to stabilize the ankle joint in preparation for the hip/trunk extension period. The early onset of GA in adults coincided with a smaller amplitude of ankle dorsiflexion in adults and also the earlier onset of active hip/trunk extension as compared to the children. This supports the idea that the main function of GA contraction is not knee flexion but is to stabilize the ankle joint and to decelerate ankle dorsiflexion. The shorter delay observed between activation of TA and GA in adults and older children as compared to younger children is not in agreement with Forssberg and Nashner (1982) who reported a increasing degree of co-activation between TA and

GA in the younger children as compared to children above 7 years of age and adults. The reason for this disagreement is difficult to explain. The velocity stimulus employed in their study was similar to the parameters used in the present study (15 - 25 cm/s as compared to our 10, 15, 20, 30 cm/s, the last velocity only in adults) and their displacement amplitude was even smaller in the youngest children; a range of 3.75 to 6.25 cm compared to our 6.1 cm in children and 8.3 cm in adults. However, platform accelerations or time period to constant velocity were not provided in their study. Forssberg and Nashner (1982) inferred a single-link ankle movement strategy from their results of EMG and CFP recordings. In the single-link ankle strategy it would be expected to see different temporal patterns of muscle activation than for a movement pattern involving a combination of knee, ankle and hip/trunk angular displacements. If the platform accelerations used in the study of Forssberg and Nashner (1982) were relatively small, then this would result in less disturbance to balance and may explain why only a single-link movement pattern was required.

As for the role of QUAD activation in the multi-link movement pattern, it is most likely that QUAD activation is responsible for braking of the knee flexion and maintenance of knee position while the hips are extended and the TCM moved forward. This role would also be assisted by activation of GA to decelerate the forward displacement of the lower leg. The activation of GA for the purpose of braking the forward rotation of the lower leg may be influenced by peripheral feedback and is for this reason not observed in studies where no knee flexion is reported. The later onset and large variation (SEM) of muscle activity in HAM in the younger children would also contribute to the increased temporal delay in onset of hip extension observed in the youngest age group as compared to the adults and 7-8 year old children.

## 3.2 BACKWARD TRANSLATION

The patterns of muscle activation showed a distal to proximal temporal order, starting with GA, which probably represents the segmental stretch reflex as described by Diener et al (1984a) and Nardone et al (1990). This was followed by activation of TA and then QUAD and HAM. The results of the kinematic analysis revealed that hip flexion was the initial active response and later knee extension/flexion. The onset time of active hip flexion and onset time of QUAD muscle activity was not significantly different in children as compared to adults, but the temporal sequence of HAM and QUAD was reversed in the children as compared to the adults. HAM most often responded first in the children (less frequent in 7-8 year olds). Furthermore, in the children below the age of 5 years, the percentage of HAM activation at the 50 ms interval was greater in backward translation relative to the forward translations and rotations, whereas in adults the percentage of QUAD activity was stronger in backward translation relative to forward translations and rotations. These age-related differences, the reversal in order of QUAD-HAM activation, and the relative magnitude of HAM and QUAD activation in the different platform displacements coincides with the finding that knee flexion was observed in increasing frequency and in increasing magnitude and duration in the children aged 2-6 years. Thus, the reversed temporal order of activation of HAM and QUAD indicates that HAM worked as a knee flexor in children, possibly together with activation of GA. In the adults and 7-8 year old children, it is likely that QUAD activity would function to extend the knee and/or maintain the knee in a stable locked position, allowing the pelvis, and consequently the TCM, to be thrust backwards over the base of support. In this regard, the QUAD would function to assist rapid hip flexion. Thus, an early and strong QUAD activity may restrict knee flexion which results in the smaller amplitude knee flexion seen in adults. It seems likely then that GA activity would function to plantarflex the ankles as the hips are flexing in order to achieve backward displacement of the GT or pelvis.

Even though the movement pattern employed by the adults was observed in the youngest age group (P1) the interpretation of the function of muscle activity is more difficult to determine since following GA activation, TA, HAM and QUAD muscles were near synchronous in onset.

Generally, an increase in platform velocity was followed by an increase in the magnitude of muscle activation in adults in both the 50 and 200 ms intervals (except TA in 50 ms interval). This coincided with the significant increase in magnitude and peak velocity of hip and trunk flexion with increasing platform velocity and is consistent with the findings of Diener et al (1988). In the majority of the children, the EMG area of the 200 ms interval and not the 50 ms interval was influenced by platform velocity, except in C1 age group where only GA activity showed an effect due to platform velocity. The fact that this age group presented a large hip flexion at higher platform velocities could be due to lack of modulation of magnitude of hip muscle activity at the higher platform velocities. Modulation of HAM activity to decelerate the hip flexion would influence hip flexion.

### 3.3 PLATFORM ROTATION

The movement pattern employed to restore equilibrium consisted of hip and H-T flexion followed by knee flexion and continued ankle dorsiflexion. The temporal order of muscle activation followed distal to proximal GA-TA-QUAD-HAM in the adults, but in children, the order of onset was GA-HAM-TA-QUAD. The onset of TA activation was earlier in adults as compared to children. The finding of early activation of TA and QUAD in adults has been reported by Allum et al (1989). Since it was not possible to clearly distinguish between the onset of compensatory ankle dorsiflexion and the passive ankle dorsiflexion due to toes-up platform rotation, the effect of delayed TA activation in the children on ankle angular displacement could not be determined. Haas et al (1986) also reported that onset time of TA activation in response to platform rotations decreased from 1 year old to the oldest group of 10 to 15 years old, which was found to be statistically significant. Although the present findings did show a clear trend towards decreasing TA onset latency with increasing age, due to the large variation, an ANOVA revealed no significant effect of age on TA onset latency. This discrepancy could be attributed to the fact that Haas et al (1986) employed higher platform velocity of 50°/s in the youngest children where the platform velocities in the present study were 20°/s and 36°/s. As in backward translation, a reversed temporal order of HAM and QUAD activation between adults and children was observed, HAM being the first response in the children. This would account for the increased magnitude and peak velocity of knee flexion seen in the children as compared to adults.

In all age groups, the percentage of TA activity activation was the same in platform rotation relative to forward translation, but significantly stronger relative to backward translation. This was also the case for HAM activation. Only the P1 age group presented stronger QUAD activation in platform rotations relative to platform translations. The adults presented no difference in relative amount of GA activity of the 50 ms or the 200 ms interval in any type of platform displacement. However, in regards to EMG area in the 200 ms interval, only the P1 age group (below 3 years) showed more GA activity in rotation relative to backward translation, whereas the other older children showed greater amount of GA activity in backward translation relative to rotation.

## 4. NEURAL MECHANISMS UNDERLYING REGULATION OF BALANCE REACTIONS

Since head displacement was not analyzed, it is not possible to estimate the exact movement of the head. However, based on the finding that the GT marker was not displaced until 100 ms after onset of platform rotation and about 180 ms after onset of platform translations, then no head motion due to platform displacement could occur before this time. For this reason it is unlikely that vestibular inputs played a significant role in the determination or the triggering of the balance reactions. Although no attempt was made to evaluate the effect of visual input on balance reactions, the visual conditions were the same for all subjects.

As described above, each balance disturbance was associated with a different pattern of somatosensory inputs, both proprioceptive and exteroceptive, which could be utilized by the CNS to determine the appropriate balance reactions. In order to restore postural equilibrium in response to the different types of platform displacements, a distinct pattern of angular displacement and muscle pattern activity was seen in all age groups. It should be noted that the different platform displacements were presented in a random order and at an unexpected time, so that no directional anticipation was possible.

The hypothesis that the postural control system utilizes triggered central programs to restore balance was tested in adults by systematically varying platform velocity and amplitude in backward translation by Diener et al (1988). Varying platform velocity was used to change the peripheral somatosensory input, while responses in the lower limb muscle were recorded to examine its impact. They observed that different velocity stimuli did not influence which muscles were activated, neither the onset or sequencing of muscle activation, and it was concluded that balance reactions are centrally determined. They also observed that the magnitude of muscle activation increased with increasing platform velocity, and they thus indicated that this modification of the magnitude of muscle activity was due to the increased peripheral drive from proprioceptors suggesting that short latency segmental reflexes mediated by peripheral inputs contribute to this amplitude modulation. The present results demonstrate that for backward translations as well as for forward translation and rotations, platform velocity did not affect the pattern or timing of muscle activation, nor the pattern and timing of active ankle, knee, and hip/trunk angular displacement (except in rotation for children where increasing velocity gave earlier onset of angular displacement but the movement pattern did not change). For a number of reasons, the results of the present study support the view that postural equilibrium is restored through centrally determined motor strategies based on the pattern of sensory inputs. First of all, for adults and the majority of the children, it was found that the onset of TA activation in rotation and forward translations was similar, and that the percentage of TA activity in rotation and forward translation was the same. Although it could be true for forward translation, TA activation in rotation cannot be explained by a simple stretch reflex mediated by proprioceptive inputs because the ankles were dorsiflexed.

Rather, it is most likely that TA activation in rotation is influenced by the pattern of somatosensory inputs specific to this type of balance disturbance, and is thus centrally determined. A similar argument can be made for activation of the thigh muscles, HAM and QUAD. As described above, each balance disturbance was associated with a different pattern of somatosensory inputs, both proprioceptive and exteroceptive. Increasing platform velocity did not change the pattern of somatosensor inputs, rather it resulted in an increase in peripheral input. A segmental reflex mechanism, such as the short latency stretch reflex, and a centrally determined motor response would both respond to increased peripheral input or balance requirements with an increase in the magnitude of muscle activity. Thus, increasing proprioceptive or tactile inputs with increasing platform velocity, cannot be used to distinguish between the effect of short latency reflex contractions and centrally determined motor responses. The ankle dorsiflexion induced by backward translations and platform rotation did evoke a short latency burst of activity in GA in all groups, which would represent a segmental stretch reflex. With the exception of the adults in backward translation and the C3 and C2 age groups in rotations, the magnitude of GA activity in the 50 ms interval did not increase with increasing platform velocity as would be expected due to increased proprioceptor activity from ankle dorsiflexion. Furthermore, in a comparison of the balance reactions to backward translation and platform rotations, equilibrium was restored through different multi-link movement strategies, where the movement began with hip/trunk flexion and not with motion about the ankle joint. In fact, while ankle plantarflexion was observed in backward translations, ankle dorsiflexion was observed in rotations. These finding argue against an amplitude modulation of balance reactions solely by short latency reflexes mediated by increased activation of proprioceptive inputs. Thus, the present results support the view that the stretch reflex does not make a significant contribution to the multi-link movement pattern that compensated for the disturbance in backward translation or rotations. In a comparison between backward translation and platform rotation, a similar pattern of proprioceptive inputs from ankle and hip displacement as well as a similar pattern of early foot pressure information occurred during the balance disturbance, however other sources of peripheral information arising from knee displacement were different. In order to identify the central neural mechanisms involved in the selection and regulation of movement strategies for different types of balance disturbances further analysis of the differences and similarities in peripheral inputs from stretch of muscles, angular displacements and tactile information is required.

# *CHAPTER 7 - CONCLUSION*

As described and discussed above, a multi-link strategy was universally employed to restore equilibrium unlike the findings of others which have implied that a single-link movement strategy is employed. The essential corrective body movements which moved the TCM back over the support and restored postural equilibrium, were mainly the timely motion of the hip/trunk and the thigh body segment and not ankle angular displacement. The main features of the multi-link movement patterns employed by adults were present in children as early as 19 months of age. These findings indicate the presence of an organized balance control system, even in the 2 year olds. Although the highly advanced balance control system as observed in adults were not seen until the age of 7-8 years. The sequence of muscle activation in response to the different balance disturbances showed a distal to proximal pattern in all age groups. However age-related differences were observed. In response to backward translations and rotations, a different temporal order of thigh muscle activation was observed between adults and the children. In forward platform translation a shorter time delay in activation of the lower limb muscles was observed in adults as compared to children. Based on the kinematic results, and pattern of CFP displacement, the distinct patterns of muscle activity were interpreted to have different functions of moving, decelerating or stabilizing the various body segments.

The results of this study demonstrate a number of age-related differences between adults and children which summarized are:

(1) Increased time to onset and to reach equilibrium position of CFP displacement

in response to forward and backward platform translation.

(2) Pronounced knee flexion in the younger children in response to backward platform translation.

(3) Increased duration to onset of hip/trunk flexion in forward translation, probably causing the difficulty of the younger children to regain balance in response to forward platform translation.

(4) Increased magnitude and peak velocity of angular displacement with decreasing age in forward translation and platform rotations.

(5) Greater fluctuation in angular displacement and in CFP records.

(6) Delayed onset of specific muscles in children below 7 years in forward translation and platform rotation.

(7) Reversed temporal order of thigh muscle activation in backward translation and platform rotation in children below 7 years compared to adults.

(8) Age-related differences in the effect of platform velocity on the response parameters as follows: a) In response to forward translations, time to reach equilibrium position only showed an increase with increasing platform velocity in children below 7 years, and at the higher platform velocities some children 2-6 years

of age needed to take a step backward in order regain balance, b) In response to platform translations, adults showed a significant increase in the magnitude and peak velocity of active angular displacements with increasing platform velocity about all joints, whereas, in the children 2-6 years of age this relationship between the requirement of the disturbance and the extent of the compensatory movements was lacking, c) The number of muscles that increased activity with increasing platform velocity was reduced for platform translations in all children groups, and was lacking in platform rotation in children below 7 years.

It is concluded that these differences reveal an immature control system in children, which needs further development and refinement of motor coordination to function at the level of a mature adult. The different types of platform displacements represent a different level of challenge to the children. Backward platform translation was the least demanding as less difference between adult and child responses and performance measures were seen. Forward platform translations were the most difficult task, which, in a number of younger children required a stepping strategy to restore balance.

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