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Development of Locomotor Balance Control in Healthy Children

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ASSAIANTE, C. *Development of locomotor balance control in healthy children.* NEUROSCI BIOBEHAV REV 22(4) 527–532, 1998.—A set of experimental studies showing how inter-segmental coordination develops during childhood in various locomotor tasks is reviewed. On the basis of these results and two functional principles (stable reference frame and control of the degrees of freedom of the body joints), we recently proposed an ontogenetic model for the sensorimotor organization of balance control in humans (5). In this model, the hypothesis was put forward that the two main modes of equilibrium control (ascending vs descending temporal organization) operate alternatively and are associated with either of two modes of head–trunk linkage ('*en bloc*' vs articulated) during four successive periods in the course of ontogenesis. The advantage of this model is that it is heuristic and therefore open to further improvements, including the generalization of these balance strategies to most of the posturo-kinetic activities, the comparison between unperturbed natural balance and reactions to postural disturbances. Some improvements are suggested, and are illustrated by the studies of inter-segmental coordination in new experimental tasks such as hops using one foot or two feet and the initiation of gait. These new results are consistent with the idea that mastery of the degrees of freedom to be controlled simultaneously during the movement improves gradually with age. Moreover, they support the concept of multiple reference frames which operate in a complementary manner or in concert to permit the most appropriate organization of balance control, depending on the environmental requirements.

Development Balance control Locomotor activities Kinematic and Electromyographic (EMG) analysis Children

INTRODUCTION

BALANCE CONTROL is required in both posture and locomotion. Maintaining postural balance requires that the center of body mass be kept over the supporting surface (37). Maintaining locomotor balance is a more complex task, since it involves achieving a compromise between the forward propulsion of the body, which involves a highly destabilizing force, and the need to maintain the lateral stability of the body (47). In bipeds, the difficulty of maintaining equilibrium during locomotion is further accentuated by the fact that the weight of the whole body has to be supported by one leg at a time during the swing phase of gait. This is the most difficult balance problem encountered by infants learning to walk (7,17,33,44).

TWO FUNCTIONAL PRINCIPLES

The various balance strategies adopted by children and adults involve two main functional principles. The first concerns the choice of the frame of reference on which the equilibrium control is based. This reference frame can be either the supporting surface on which the subject is standing or the gravitational vector. When the frame of reference is the supporting surface, balance control is temporally organized from the feet to the head (posture), according to an ascending organization. When the frame of reference is the gravitational vector, balance control is temporally organized from the head to the feet, according to a descending organization. However, in the case of intermittent contact, such as during locomotion, it is also possible to consider that another anatomical segment, such as the pelvis, may constitute a reference value. Such a pelvis stabilization based on gravity information is plausible, since the idea has been put forward that graviceptors may be involved at the level of the lower part of the trunk (27,36) or at the level of the joints involved in stance (21). The choice of the segment to be stabilized presumably depends on the dynamic constraints, resulting from the difficulty of the postural or locomotor task. It may be the pelvis, at about the level of the center of gravity, or the head which carries the vestibular system, or both segments. Assaiante and Amblard (5) assumed that the stabilized segment constitutes the origin of the temporal organization of balance control.

The second functional principle concerns the choice of the degrees of freedom of the various body joints, which have to be controlled simultaneously in dynamic equilibrium situations (14), according to the task's constraints and/or the subject's motor ability. Postural control during stance consists of superimposed modules, which can be controlled more or less independently. For example, the control of the composite head–trunk unit can be exerted according to either of the following two main modes. First, the head can be stabilized on the trunk by contraction of the neck muscles, as in the case of the 'strap-down strategy' (38). This is what Assaiante and Amblard (5) called an '*en bloc*' mode of operation. This strategy minimizes the number of degrees of freedom to be controlled simultaneously during the movement (14). Moreover, this '*en bloc*' operation allows more direct and rapid visual and vestibular contributions to balance control. Second, the head can be stabilized in space with the neck structures loose, as in the case of the 'stable platform strategy' (38). This is what Assaiante and Amblard (5) called an articulated operation. This second strategy requires the control of more degrees of freedom by the neck joints and involves also taking into account the orientation of the head and the trunk as a means of accurately interpreting the visual and vestibular messages relating to equilibrium control (35). Obviously, the '*en-bloc*' mode vs articulated mode can be extended to any other couple of consecutive anatomical segments.

FOUR SUCCESSIVE PERIODS IN THE COURSE OF ONTOGENESIS

On the basis of these two functional principles and a review of the literature including the authors' own experimental studies, Assaiante and Amblard (5) have proposed a set of interpretations as to how balance control develops in humans during their life span (Fig. 1). In their model, the authors hypothesize that the two main modes of balance control (ascending and descending temporal organization) operate alternately and are associated with either of two modes of body joint linkage ('*en bloc*' and articulated) during four successive periods in the course of ontogenesis. It is worth noting that the proposed ontogenetic model can be related to a neurobiological perspective. In motor development, two maturational gradients (cephalocaudal or caudocephalic) operate alternatively during the life span. It could be postulated that the age-dependent ability to develop cephalocaudal or caudocephalic postural responses might be consistent with an alternate predominance of central feedforward postural control mechanisms or peripheral feedback mechanisms, proposed in animals (46) and humans (24).

The *first* period extends from birth up to the acquisition of the upright stance. This period is characterized by the development of postural responses along a cephalocaudal gradient. Adequate control appears first in the muscles of the neck, then in those of the trunk, and finally in the legs (49,51). In infants, head control is generally considered as constituting the beginning of body equilibrium development (32). Head control improves with emergence of reaching (45). Head and gaze stabilizations relative to the target establish a stable reference frame for reaching (15). In the sitting position, recent studies (30) reported the priority of head stabilization in postural control. In response to forward translations of the support, the youngest infants (5–6 months) preferred to activate their neck muscles first with respect to the trunk and leg muscles, suggesting a top-down recruitment, which differs from the bottom-up recruitement normally present in standing and sitting adults (25,31) and sitting children (18). These results, taken together, suggest an articulated operation of the head–trunk unit associated with a descending temporal organization of postural control during the first year of life. It is worth noting that this chronological cephalocaudal progression of the ability to control an increasing number of body segments is consistent with the descending sequential order of postural control.

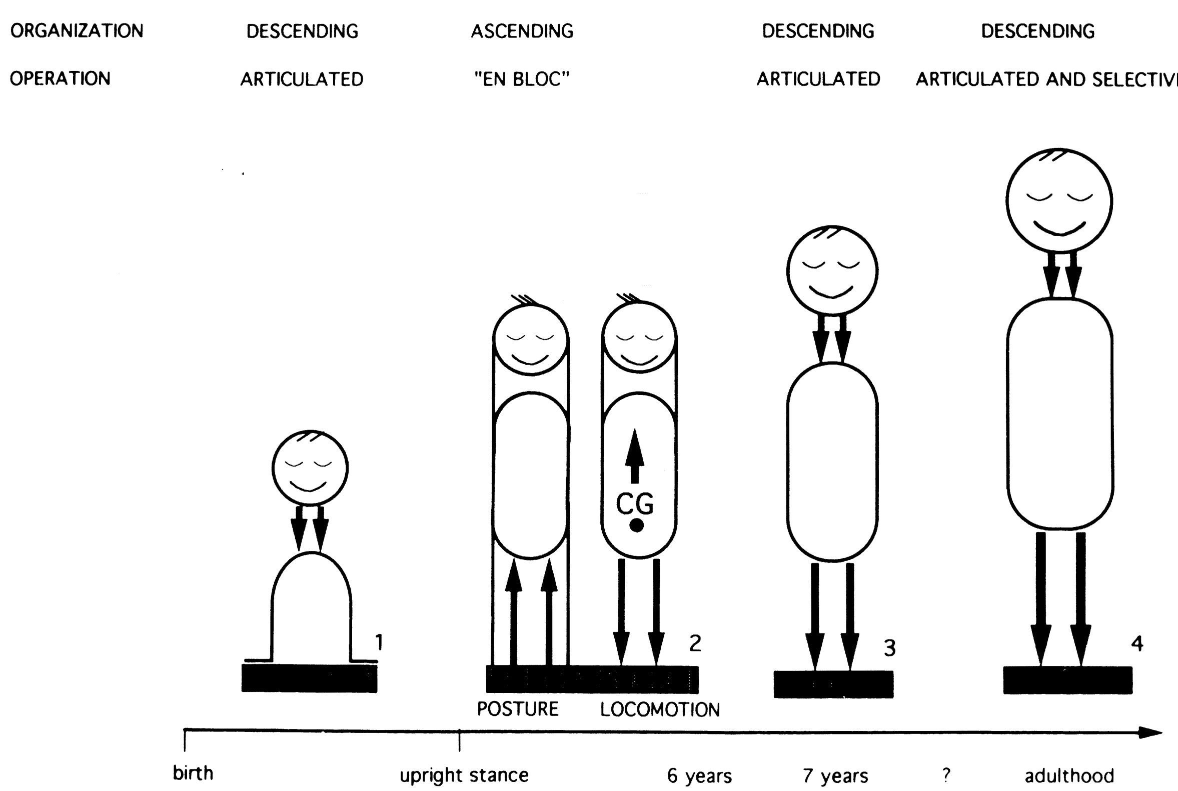

FIG. 1. Ontogenetic scheme of the organization of posturo-kinetic activities during the lifespan. (From: Assaiante; Amblard. An ontogenetic model for the sensorimotor organization of balance control in humans. Human Movement Sci. 11:533–548; 1995.)

With the acquisition of upright posture and locomotion, the balance control is no longer segmental but global. This points towards a new mode of balance organization and to the beginning of the second period.

The *second period* takes place from the acquisition of the upright stance up to around the age of 6 years. This period is characterized by the mastering of the effectors and the development of the coordination between the lower and upper parts of the body. The beginning of locomotion involves solving a number of difficult balance problems (17,44). According to Forssberg (24), the onset of independent walking is probably the result of the maturing postural control system, e.g., the cerebellum and vestibular structures. With the development of independent walking, the locomotor pattern becomes reciprocally organized (11,23,40). Associated with this gradual evolution, an important increase in the gastronemius EMG during the stance phase and the disappearance of monosynaptic reflex potentials were reported (22). The final magnitude of gastrocnemius EMG was established around 5–6 years of age. From about 7 years of life no difference to the adult pattern could be observed (12). The age of 6 years seems to constitute a turning point in both postural (42,50) and locomotor (3,4,11) equilibrium control. In a postural study, Berger et al. (13) have reported that the balance strategy adopted in 2- to 6-year-old children, in response to the horizontal sinusoidal perturbation of the support, consists of blocking the various body joints. The reduced damping in children could represent a strategy which minimizes the number of degrees of freedom which have to be controlled simultaneously during a difficult balance task (4,14,26). In adults, on the contrary, the amplitude of the oscillations decreased sharply from foot to head, suggesting an articulated operation of the whole body.

In a recent experiment in toddlers, the inter-segmental coordination between head, shoulder and hip were studied in the frontal plane (7,8). The pelvis stabilization was efficiently used as soon as autonomous walking appeared, probably aiming at controlling the lateral excursions of the centre of gravity. Moreover, the emergence of pelvis stabilization while walking clearly preceded that of the shoulder and of the head. These results suggest a caudocephalic progression with age of the ability to control several body segments during locomotion. It is worth noting that this chronological progression is consistent with an ascending temporal organization of balance control with hip movements occurring before shoulder movements and shoulder movements before head movements. Preliminary EMG recordings in infants with 6 months of walking experience showed an anticipatory activation of the hip abductor of the stance leg prior to heel-off. These results, taken together, indicate an anticipatory activity at the hip level with respect both to the upper part of the body (shoulder and head) and the feet movements in toddlers (8). This hip-centered organization of balance control seems to provide a stable reference on which locomotion can develop. The onset of independent locomotion is associated with an '*en bloc*' operation of the head–trunk unit, as attested by the high values of the correlation between head and shoulder movements.

From a kinematic study in children from 3 to 8 years and adults (2,4), it was possible to discern at least three main phases in the development of head–trunk coordinations during locomotion. The first phase included children from 3 to 6 years of age, who adopted a preferred head stabilization in space strategy only while walking on the flat ground without any equilibrium difficulty. When the level of difficulty increased, for example while walking on narrow supports, these children showed an increase in the head–trunk stiffness, as illustrated by the large percentage of cases with positive head–trunk correlations, particularly in 6-year-old children. These results suggest an '*en bloc*' operation of the head–trunk unit. The second phase included children from 7 to 8 years of age, who became able to adopt the preferred head stabilization in space strategy even when balance difficulty increased. This improvement was associated with a large decrease in the correlations between head and trunk movements indicating an articulated operation of the head–trunk unit. In adulthood, the preferred head stabilization in space strategy was systematically adopted, but only in the case of the roll, which is the most relevant component of rotation to control the lateral body oscillations while walking. No correlation between head and trunk movements was observed in adults, at least judging from the roll.

These experimental results on balance control taken together, from upright stance to 6 years of age, are consistent with an ascending temporal organization of balance control, from the feet to the head during postural stance and from the pelvis to the head during locomotion. This ascending organization is associated with an '*en bloc*' mode of head–trunk operation.

The *third period* begins at around the age of 7 years and continues up to an upper age-limit which is as yet unknown. Adolescence might constitute a turning point in the development of balance control. The third period is characterized by the return to an articulated mode of head–trunk operation, whereby the head stabilization necessary for the descending temporal organization of balance control is ensured (4). Lastly, the *fourth period*, which is reached during adulthood, combines the main features of the third period with a new skill involving the articulated operation of the head–trunk unit along with a selective control of the degrees of freedom at the neck level (4).

DEVELOPMENTAL CHANGES IN THE SENSORY CONTRIBUTION TO BALANCE CONTROL

The motor strategies used to maintain equilibrium are dependent upon a number of sensory contributions. Normally, three classes of sensory inputs are available for balance control: visual inputs; vestibular inputs; and somatosensory inputs. Children and adults may use different combinations of these sensory inputs depending on the environmental circumstances. Specific sensory systems, however, seem to predominate at particular stages in ontogenesis. For example, the relative importance of visual contribution to balance control varies during the life span. During babyhood and childhood, it is now well established that visual cues play a prominent role in the control of static postural equilibrium. It has been reported that vision predominates particularly during transitional periods in which infants attempt to master new postural challenges, such as sitting without support (20), independant upright stance (34) and independent walking (43).

Other reports on posture (42) and locomotion (3,6) suggested that this visual predominance is not restricted to infancy, and continues up to about the age of 6 years. Assaiante et al. (3,6) have reported that the peripheral visual contribution to dynamic balance control even increased from 3 to 6 years of age, being maximal in 6-year-old children. A transient disappearance of the peripheral visual contribution to locomotor balance takes place at around the age of 7 years, which corresponds precisely to the beginning of effective head stabilization while walking on narrow supports (line and beam) (4). This new ability is generally assumed to be mainly of vestibular origin (1,19,41). It is therefore possible to interpret these results as indicating actually a transient predominance of the dynamic vestibular contribution to balance control at 7 years of age. Up to now, however, no data are available as to the visual and vestibular contributions to head stabilization in space between the age of 8 years and adulthood. Finally in adults, the three classes of sensory inputs can be coordinated or recruited independently to improve equilibrium control thanks to their specific efficiency, depending on the environmental requirements (5,16,39,48).

NEW FINDINGS THAT EXTEND THE MODEL

In a recent study aiming at testing the generalization of our ontogenetic model (5), to new motor skills, the development of head–trunk coordination was studied during single hops using one foot or two feet in 6- and 7-year-old children and in adults (9). It was reported that during flight, in both types of hopping, the head and trunk remain stabilized in space along the pitch axis both in children and adults. This suggests an articulated operation of the head–trunk unit. In contrast, during landing, head stabilization tended to disappear while trunk stabilization in space was still present, suggesting an '*en bloc*' operation of the head–trunk unit. On the other hand, stabilization of the pelvis about the roll axis occurred in all subjects during both flight and landing under uni-pedal conditions where lateral balance control is of primary importance. Taken together, these results suggest that head stabilization in this task is phase dependent, while trunk stabilization is phase independent. The trunk, including the pelvis, may thus constitute a stable reference frame from which antero-posterior and lateral balance control are organized during hops. It is also interesting to note that during both flight and landing, children differed from adults (higher amplitude of head and trunk oscillations) but not from each other. Other parameters such as vertical forces and EMG recordings at the lower limbs suggested that the transition in the organization of balance control is particularly prominent between 6 and 7 years in the coordination of the lower limbs during the preparatory phase of the take-off.

Coordination between posture and movement implies anticipatory postural adjustments aimed at minimizing the postural and balance disturbance due to the movement. The development of anticipatory postural adjustments associated with the initiation of gait in young children was recently investigated with two complementary kinematic and EMG analyses (10). Kinematic analysis indicated that preparatory postural adjustments preceding the first step were the first to emerge. For example, there was a clear preparatory lateral tilt of the pelvis and of the stance leg in order to unload the opposite leg shortly before its swing phase. This developed concomitantly with the emergence of independent walking. Despite their early emergence, preparatory postural adjustments took time to mature and most of them did not appear consistently until 4–5 years of age. Indeed, it was reported that a decrease of the segmental oscillations occurred across the ages, indicating a better control of the inter-segmental coordination in the frontal and sagittal plane during the postural phase of gait initiation. The young walkers presented preparatory postural adjustments involving movements of both upper and lower parts of the body. However, in the youngest autonomous walkers, in the period from 1–4 months of walking experience, only movements of the lower part of the body were included in preparatory postural adjustments while movements of the upper part were not yet efficiently oriented. Later, with more walking experience, in the period from 9 to 17 months, the control of both upper and lower parts of the body was efficiently organized. This contributed to produce adequate preparatory postural adjustments, thus showing an '*en bloc*' mode of segmental organization. From 4 to 5 years, children were able to shift lateraly only the pelvis and the stance leg, and to keep the trunk and the head more vertical, thus showing an articulated mode of segmental organization similar to the behavior observed in adults.

The development of EMG response patterns during the initiation of gait shows a similar developmental course. EMG analysis indicated that preparatory postural adjustments emerge very early in the development of gait initiation. Indeed, there was an anticipatory activation of hip abductor of the leg in stance phase prior to heel-off, suggesting pelvis stabilization. This was found in all age groups, including pre-walkers. This indicates that pelvis stabilization is present before independent walking and provides a stable reference frame for the development of locomotion. This is further substantiated by activation patterns in hip, knee and ankle muscles in young independent walkers. In contrast, older children (4–5 years of age) and adults showed lower activation levels of hip and knee muscles, but higher activation at the ankle level. The explanation might be that anticipatory postural adjustments in the adults and 4 to 5-year-old children are mainly focussed on the lower limbs whereas in younger children these include the whole body. These results taken together suggest a clear developmental sequence from an '*en bloc*' operation of the body through an articulated operation with maturation and/or walking experience.

CONCLUSION

It seems that the two functional principles at the basis of our ontogenetic model (5) hold up well, as they can be generalized across other posturokinetic activities such as initiation of gait or hopping in which equilibrium control is essential for the transition between different phases of movement. The improvement of the preparatory postural adjustment seems consistent with the gradual mastery of the many degrees of freedom to be controlled simultaneously during the movement (14). In addition, it appears that the stabilization of the head is task-dependent while the stabilization of the pelvis is task independent. In other words, the

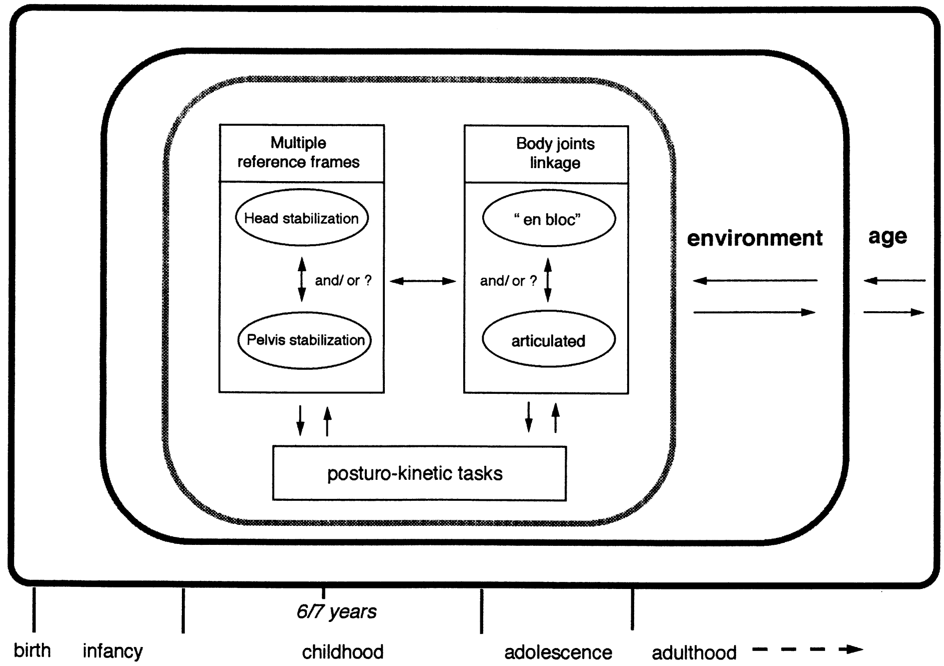

FIG. 2. Schematic diagram of the development of balance strategies showing the multiple interactions between the two functional principles (reference frames and body joints linkage) and the constraints of the posturo-kinetic task, the environment and the various periods of ontogenesis.

stabilization of the head appears to be more sensitive to the dynamic characteristics of the activity being performed than the pelvis. In contrast, pelvis stabilization appears to be a reference base inherent to most posturokinetic activities. These last results support the concept of multiple reference frames which operate in a complementary manner or in concert to permit the most appropriate organization of balance control during movement, depending on the environmental requirements. A summary of the multiple interactions between the organization of balance control and the constraints of the posturokinetic task, the environment and the various periods of ontogenesis is proposed in Fig. 2.

This is precisely the choice of the reference frames that children must learn to organize during development. The challenge of research in the next years should be to better understand how children select the proper reference frame (anatomical segment and sensory inputs) with respect to the various periods of ontogenesis, the posturokinetic tasks and the environmental context. Taking into account the complexity of the parameters to control, it is not surprising that the development of balance control continues up to late periods during childhood. The recent development of the functional neuroimaging tools allows non-invasive studies of several aspects of human brain functional development. The transition between 6 and 7 years of age, reported in many sensorimotor activities (4,9,28,29,42), should help us in future studies to better understand the late maturational process of the central nervous system.

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