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The build-up of anticipatory behaviour

An analysis of the development of gait initiation in children

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Abstract This study analyses the anticipatory postural adjustments during the gait initiation process in children aged 2.5, 4, 6 and 8 years. In adults, anticipation during gait initiation includes a shift in the centre of foot pressure (CP) both backwards and towards the stepping foot. Backward displacement and the duration of the anticipation phase covary with the gait progression velocity reached by the subject at the end of the first step. In the present study, the children walked on a force plate that allowed us to calculate the acceleration of the centre of mass and the displacements of the CP. The results showed three main characteristics of the development of anticipatory behaviour: (1) The occurrence of anticipatory displacements of the CP increased progressively with age. Systematic backward anticipation was found for all children except one of the youngest, whereas the lateral displacement was systematically observed later, in the 6-year group; (2) the amplitude of the spatial parameters showed a significant increase with age; (3) contrary to the adult, the amplitude of the backward shift did not covary with the forthcoming velocity in the youngest groups. This covariation became significant at 6 years and remained significant at 8 years. The results showed that even if anticipatory behaviour was present in 2.5-year-old children it is only later that the child is able of more accurate tuning of feedforward control, probably due to better control of the overall postural adjustments.

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Introduction

Anticipation is often viewed as a crucial element in skill (Flowers 1988). It focuses on events that forestall another event. Anticipatory behaviour either forestalls forthcoming problems or modulates current activity to "smooth the way" for upcoming acts. For accurate catching, for example, one must anticipate the trajectory of the ball, the time until impact, the weight of the ball, etc. This kind of "prospective control" of action (von Hofsten 1993) is thus widely found in everyday skills, where ongoing planning and monitoring of movement occurs in a changeable environment. Anticipatory behaviours such as postural adjustments occurring before reflexly triggered reactions appear as an index of feedforward control of movement (Gahery 1987; Requin 1980; Rosenbaum 1984).

Although not in mature forms, anticipation may be observed in some skills from an early age. In prehension movement, for example, Lockman et al. (1984) have shown that as early as 9 months of age children are able to position their hand according to the orientation and/or the form of the object to be grasped prior to actually contacting the object. Von Hofsten and Fazel-Zandy (1984) suggest that anticipation may be observed even earlier, around 18 weeks of age. At this age, infants adjusted their hand orientation to the orientation of a rod, which is presented in front of them, before touching it. Mounoud and Hauert (1982), in a study on weight conservation, showed that children of 14 months adjust muscular force in advance according to their anticipatory evaluation of the weight of the object to lift or to handle. However, these studies are limited because they concern what Konzag and Konzag (1980; cited by Buekers et al. 1988) term "external anticipation", that is anticipation that depends on external events, in contrast to "internal anticipation", which depends only on the performer's own action. External anticipation has been extensively discussed in tasks such as pointing, prehension or catching. Internal anticipation is most often viewed as a way of anticipating the consequence of movement performance (Requin 1980).

Anticipatory postural adjustments would preserve from equilibrium disturbance that could result from the forthcoming movement (Bouisset and Zattara 1981; Massion 1992). However, another purpose of anticipatory behaviour, to our knowledge less discussed in the literature, is to facilitate the set-up of *the necessary condition* of the forthcoming movement. This is clearly the case in gait initiation, during which the propulsive forces necessary to reach the intended gait speed are generated (Brenière and Do 1986a; Brenière et al. 1987). This will be discussed later in the Introduction.

While many studies have investigated internal anticipation in adults, especially in preparatory postural adjustments in tasks involving rapid arm movement (Belenki et al. 1967; Bouisset and Zatarra 1981; Lee 1980), or in gait initiation (Brenière et al. 1981; Crenna and Frigo 1991), the developmental basis of such anticipatory behaviour is poorly understood. A recent study from Hayes and Riach (1989) and Riach and Hayes (1990), concerning preparatory postural adjustment prior to the raising of the right arm in children aged from 4 to 14 years, did not find clear evidence of a developmental trend. The study was based on the analysis of the displacement of the centre of foot pressure (CP) prior to the displacement of the arm, considered as indexing anticipatory behaviour. While lateral and antero-posterior displacement of the centre of pressure prior to arm-raising is observed at all ages, the youngest group (4–6 years) showed the same proportion of lateral displacement (characterised by a left followed by a right displacement) as adults, this proportion decreasing in the other two groups (7–10 and 11–14 years). The authors compare this pattern to the pattern observed in anticipatory locomotor movements in adult (see Brenière and Do 1986a; Brenière et al. 1987), suggesting that this left-right pattern may be possibly "part of an innate muscle synergy" (Hayes and Riach 1989). This interpretation is challenging, as a study of gait initiation in children having from 100 to 200 days of independent walking experience showed no anticipatory shift of the centre of pressure prior to gait movement at that early stage of walking (Brenière et al. 1989).

One of the emergent questions is whether the development of internal anticipation depends on neural maturation as suggested by Hirschfeld and Forssberg (1992) and Hamilton (1992) or develops along with the child's mastery of the components of the task (Haas and Diener 1988; von Hofsten 1993). The alternative is that both participate in the development of anticipation, as has been recently suggested concerning the postural responses for sitting (Hirschfeld and Forssberg 1994).

In this paper we focus on the development of internal anticipation in gait initiation in relation to some characteristics of steady-state gait. Gait initiation in the adult is characterised by spatial and temporal components of anticipation that are proportioned to the forthcoming steady-state velocity of walking. The anticipatory movement consists of a backward and lateral displacement of the CP, which precedes the execution of the first step (that is prior to heel-off). The amplitude of the backward displacement is positively correlated with steady-state velocity of the coming sequence of steps, while the amplitude of the lateral displacement is not. The duration of the two phases that characterise gait initiation – an anticipation phase (dynamic events that precede heel-off, HO) and an execution phase, that is the first step – varies in relation to the forthcoming speed of walking, which is reached at the end of the first step. The greater the forthcoming velocity, the longer the duration of the anticipation phase. By contrast, the duration of the execution phase decreases as velocity increases, similar to steady-state gait.

The biodynamical properties of the relative position of the centre of foot pressure and the centre of mass tend to establish that the backward shift of the CP is not a compensation for a forthcoming perturbation but is an *active preparation of this forthcoming movement*. In effect, from a biodynamical perspective, any locomotor task requires the production of propulsive forces that *cause* the displacement of the body, usually along the antero-posterior axis. These propulsive forces are generated by the production and modulation of a distance between the CP – the barycentre of the vertical component of the reactive forces – and the projection onto the ground of the centre of mass (CM), as summarised by the following equations (Brenière et al. 1987):

$$k \cdot x''_G = (x_G - x_P) \cdot W \qquad (1)$$

where x''_G is the value of postero-anterior acceleration of the CM, x_P and x_G the position of the CP and the CM along the antero-posterior axis, W is the subject's weight and k is a constant.

The equation establishes that there exists a dynamic constraint between the acceleration of the CM and the distance between the CP and the projection onto the ground of the CM. It stipulates that the necessary propulsive forces ($x''_G > 0$) – which corresponds to a positive value of the antero-posterior acceleration – requires that $x_G > x_P$ and that the the breaking phase – which corresponds to a negative value of the antero-posterior acceleration – ($x''_G < 0$) requires that $x_G < x_P$. In other words, the backward shift observed during the anticipatory phase in which there is a concurrent forward shift of the CM is the **necessary condition** to set up a given acceleration and consequently a given velocity at the end of the first step. The same principle is used for other movements such as the sprint start (Natta et al. 1991); expert sprinters are able to display a greater backward shift prior to start so that they reach higher velocity.

Very few studies, to our knowledge, have investigated the development of anticipatory behaviour in gait movement. Hamilton (1992), in a study on the effect of optokinetic stimulation on gait initiation in children aged 4–10 years, concluded that younger children use different strategies to adults in gait initiation (timing, different coupling of leg muscle activity). The author suggested that these differences may be due to immature neural functioning (slower peripheral nerve conduction or lack of maturation of central processing). In an experimental study of anticipatory postural control during locomotion in children, Hirschfeld and Forssberg (1992) suggested that the non-mature modulation of postural activity in the youngest group of children (6 years of age) could be due to the neural locomotor network in the spinal cord that "continues to gate the postural responses according to a non-plantigrade pattern several years after transformation to plantigrade gait" (p. 332).

For Hamilton (1992) and Hirschfeld and Forssberg (1992), neural maturation seems to be the decisive element in the development of anticipatory behaviour. Another interpretation is given by Haas and Diener (1988). In their experiment, children had to rise up on their toes as quickly as possible after an acoustic signal and had to remain standing on their toes. The results show that the necessary anticipatory shift of the CP in the anterior direction, prior to heel off, is present in children of 4 years of age (younger children were not able to cooperate sufficiently). They suggest that "children develop and start to apply feedforward control as soon as they are able to maintain a certain posture by means of sufficient feedback control" (p. 57) and that the age-dependent process of the developmental anticipatory behaviour would be shaped through "exercise and training in a specific environment (p. 58)". This study also suggests that anticipatory behaviour is task-dependent and not age-dependent. Anticipatory behaviour may be absent in one task, while it may be present in another task.

In a previous study we showed that none of these characteristics were present in toddlers 200 days after onset of walking (Brenière et al. 1989). At that age it takes more than two steps to reach steady-state velocity; no lateral or backward displacement of the CP was observed prior to the first step, and consequently no anticipatory phase could be seen. A recent study by Malouin and colleagues (1996) has established that children aged 4–6 years do display a backward and lateral displacement of the CP during the initiation phase.

The question was then, how and when does the child become able to perform anticipatory movement to facilitate gait initiation? This question is important, as it will tell about the way children build up feedforward control, which is one of the corner stones of motor control. In our work we hypothesised that anticipation depends on the level of control of the skill. That is, to be cap able of feedforward control of movement, one must have a good mastery of the task at hand. We hypothesise that the anticipatory behaviour in gait initiation does not develop independently of gait, but in sequence with the mastery of steady-state gait.

Previous results from Bril and Brenière (1992) have suggested that walking development undergoes a two-stage process. First, the few months after onset of walking correspond to a process of "integration" of the biomechanical characteristics of the system (Brenière et al. 1989). The end of this period corresponds to a better postural control, when the onset of heel strike emerges (Thelen et al. 1992). A second period, which lasts several years (probably up to 6 or 7 years of age), corresponds to a period of tuning of walking control (Bril and Brenière 1992, 1993).

These results suggest that anticipatory behaviour, which is absent during the first period, develops during the second phase and participate in a finer tuning of postural and locomotor components of gait. To answer this question we investigate, using biochemical methodology, the developmental trend of anticipatory behaviour in children aged 2.5–8 years.

Materials and methods

Subjects

Four groups of children of different ages participated in the study: "2.5 years" (n=6, mean age 2 years 2 months), "4 years" (n=7, mean age 4 years), "6 years" (n=9, mean age 5 years 8 months), and "8 years" (n=7, mean age 7 years 11 months).

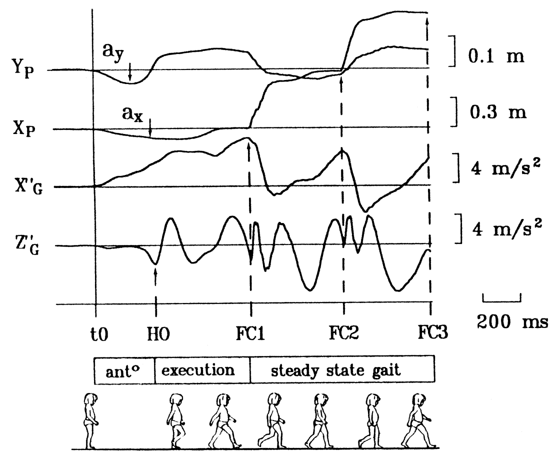


Fig. 1 Recordings from the force plate of the displacement of the centre of foot pressure (CP) and the acceleration of the centre of mass (CM) during gait initiation of a sequence of steps made by a child. At the beginning of the traces, before t_0, each curve is on the base line. This confirms that the subject is standing relatively still with his weight equally distributed on both feet. For the X_P curve, the *traces above the base line* indicated a forward displacement of the CP. On the contrary, the *traces under the base line* indicated a backward displacement of the CP. For the X''_G and the Z''_G curves, the *traces above the base line* indicated positive (respectively forward and upward) accelerations and the *traces under the base line* indicated negative (respectively backward and downward) accelerations of the CM. The initiation phase begins at the instant of onset of the dynamic phenomena t_0 and ends at the instant when the antero-posterior acceleration curve X''_G changes in sign. The heel-off of the foot executing the first step (*HO*) is located by a negative peak of the vertical acceleration curve Z''_G (Brenière et al. 1987). The anticipatory phase begins at t_0 and ends with the *HO*. The end of the first step is the instant of foot contact (*FC*). This instant is located owing to two simultaneous indications: abrupt changes in the X_P and a change of direction of the X''_G curve (X_P and Y_P displacement of the centre of foot pressure, respectively, along the antero-posterior and lateral axis, X''_G and Z''_G antero-posterior and vertical acceleration of the centre of mass, respectively; a_x and a_y maximum backward and lateral shifts of the CP, respectively)

Experimental device

A force plate (data sampling interval 5 ms) was used the same experimental technique as in our previous research on gait initiation in children (Brenière et al. 1989). From the step sequences executed on the force plate, ground reaction forces and the instantaneous position of the CP (that is the application point of the vertical component of these forces) were recorded.

Procedure

Each child walked about 20 sequences of steps on the force plate. A sequence of steps consisted of two to three steps on the force plate and several steps on the walkway ahead (the number of steps executed on the force plate depended on the child's step length related to their height). Each subject began all sequences standing in a still, relaxed manner at the upper edge of the platform; they were then asked to walk forward.

Recorded and calculated data

The force plate data were used to calculate (Fig. 1, from bottom to top): (a) the vertical and antero-posterior components of the acceleration of the CM (z''_G and x''_G) were computed from the components of the ground reaction resultant R (R_z and R_x) and from Newton's principle ($m \cdot z''_G = R_z - W$ and $m \cdot x''_G = R_x$, m being the subject's mass and W the subject's weight); (b) the instantaneous co-ordinates of the CP with respect to the antero-posterior axis (O_x) and lateral axis (O_y), x_P and y_P.

Anticipation and movement parameters

The initiation phase, which is composed of an anticipatory phase and the execution of the first step (Brenière et al. 1987), is followed by the second and third steps. Parameters were considered from the mechanical traces for each of the three phases (the indexes utilised to compute the parameters are indicated in the legend of Fig. 1):

A. *The anticipatory phase* begins at the onset of the dynamic phenomena (t_O) and ends at the instant of HO. It is characterised by the displacement of the CP with respect to the antero-posterior and lateral axis (Brenière et al. 1981). According to this characteristic the parameters utilised were: **duration of the anticipatory phase** (t_{HO}); **maximum backward shift of the CP** prior to the HO (a_x); **maximum lateral shift of the CP** prior to the HO (a_y).

B. *The first step, execution phase,* begins at the instant of HO and ends at the first contact of the foot with the ground (FC1). Global parameters were computed: velocity of the first step (V_1), and length and frequency of the first step.

C. *The second step* corresponds to the movement performed between the first and second foot contact (FC1 and FC2) and the third step, between the second and third foot contact (FC2 and FC3). Global gait parameters were computed for the two steps together when three steps were available, otherwise, it was done only for the second one: mean velocity of the second and third steps (V); mean length of the second and third steps mean frequency of the second and third steps.

Statistical analysis

Only sequences of steps leading to regular and stationary velocity were incorporated into the study, i.e. a total of 218 sequences of steps. The traces of the youngest children were very difficult to analyse because they were less stable at the beginning of the sequences (n=34 at 2.5 years; n=54 at 4 years; n=69 at 6 years; n=61 at 8 years).

Descriptive data were derived for all subjects. Analysis of linear correlation between the considered parameters were done within each age group. The influence of age on the different variables was computed by an analysis of variance (ANOVA).

Results

Initiation phase

Occurrence of anticipatory behaviour

Figure 2a shows the frequency of antero-posterior backward shift and lateral shift for each age group. All children but two of the 2.5-years group showed systematic anticipatory backward shift of the CP. For the two young children with no systematic backward shift, we observed, instead of the backward displacement, either a forward displacement (in five cases) or absence of any kind of displacement of the CP (in two cases). Lateral shift appears systematically only in the 6-years group: at 2.5 years lateral anticipatory displacement was absent in 21 sequences (for six subjects); at 4 years, in seven sequences (for four subjects); and at 6 years, in 1 sequence.

Maximum backward shift of the centre of foot pressure during the anticipatory phase

The mean values of backward shift showed a significant increase with age (Fig. 2b; $F_{(3,206)}$=12.292, P<0.0001; excluding the sequences with no backward displacement).

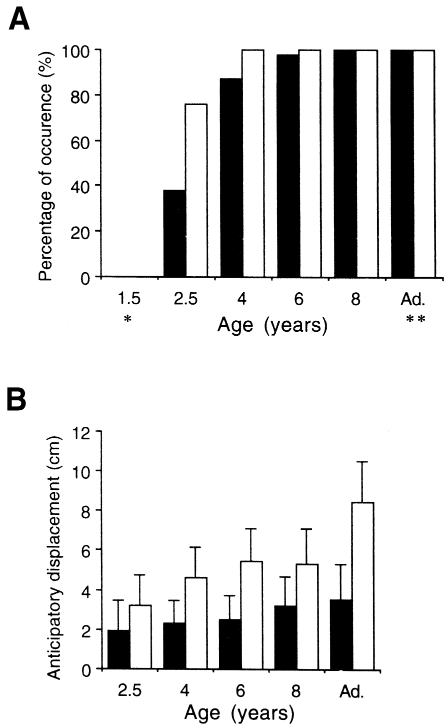


Fig. 2A Percentage of occurrence of backward (*in white*) and lateral (*in black*) shift of the centre of pressure for each age group. To give an overview of the developmental trend, results for toddlers (*Brenière et al. 1989) and adults (**Brenière and Do 1986a, b) are shown. **B** Amplitude of the maximum lateral (*in black*) and backward (*in white*) anticipatory displacement of the centre of foot pressure

When the amplitude of the backward shift was normalised with respect to the subject's foot length, however, the effect of age disappeared.

Maximum lateral shift of the centre of foot pressure during the anticipation phase

The mean values of lateral shift increases significantly with age (Fig. 2b; $F_{(3,185)}$=6.512, P<0.001; excluding the sequences without any lateral shift of the CP). The effects of age disappeared when the amplitude of the lateral shift was normalised with respect to the body height of each subject (excluding the sequences with no lateral shift).

Duration of the anticipatory phase

The mean durations of the anticipatory phase were: 325±127 ms at 2.5 years, 385±86 ms at 4 years, 363±78 ms at 6 years, and 378±77 ms at 8 years. These means were not significantly different ($F_{(3,214)}$=3.63).

Velocity of the first step

At 2.5 years, the mean value was 0.51±0.16 m/s at 4 years, 0.89±0.18 m/s; at 6 years, 0.88±0.19 m/s; and at 8 years, 0.97±0.24 m/s. The mean values of velocity of the first step significantly increased between 2.5 and 8 years ($F_{(3,214)}$=41.69, P<0.0001). The effect of age remained when the velocities were normalised with respect to the body height ($F_{(3,214)}$=20.271, P<0.0001).

The second and third steps

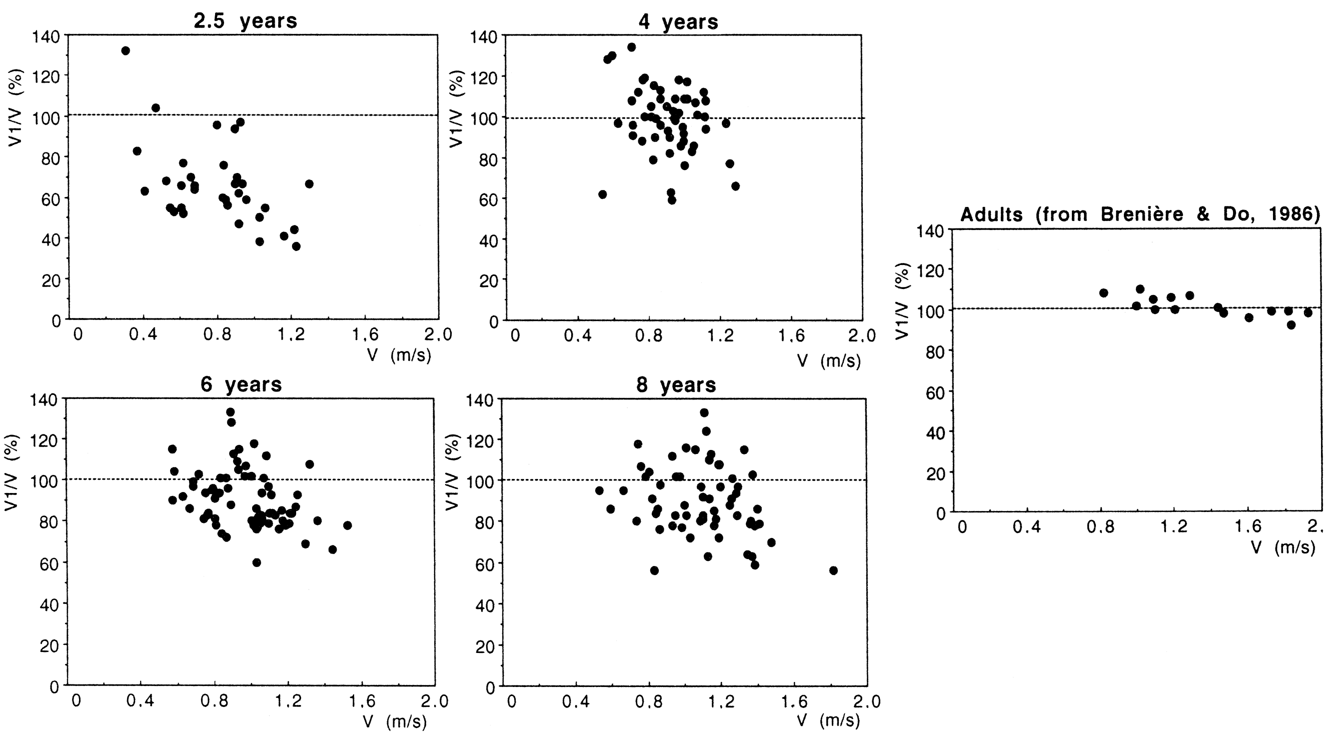
The developmental trend of the gait parameters measured here (mean displacement velocity, frequency and step length during the second and third steps of the sequences of steps) confirms results usually described in the literature (Sutherland et al. 1988). The mean velocity and step length significantly increased from 2.5 to 8 years, while frequency of steps slightly decreased.

The velocity of the first step divided by the mean velocity of the second and third steps (Fig. 3) revealed that the children in the 2.5-years group reached, on average, 66±20% of their steady-state velocity during the first step. In the 4-years, 6-years and 8-years groups, the children had the ability to reach a large part of the mean velocity of the steady-state gait during the first step (98±16% at 4 years; 90±14% at 6 years; 90±17% at 8 years).

Correlation between parameters

The correlations were computed with all the values (absolute and normalised) for each group to analyse the developmental trend of the covariations between parameters with age. No significant correlation was found between the maximum backward shift and the velocity of the first step at 2.5 years (r=–0.21) and at 4 years (r=–0.30), but

Fig. 3 Percentage of steady-state gait velocity during the first step for each age group (*V1* velocity of the first step, *V* mean velocity of the second and third steps for the children and for the second step for the adult). The value *100* indicates that the steady-state gait velocity has been reached at the end of the first step. For the children, each *dot* corresponds to one sequence of steps; for the adults, each *dot* corresponds to the mean value of several sequences



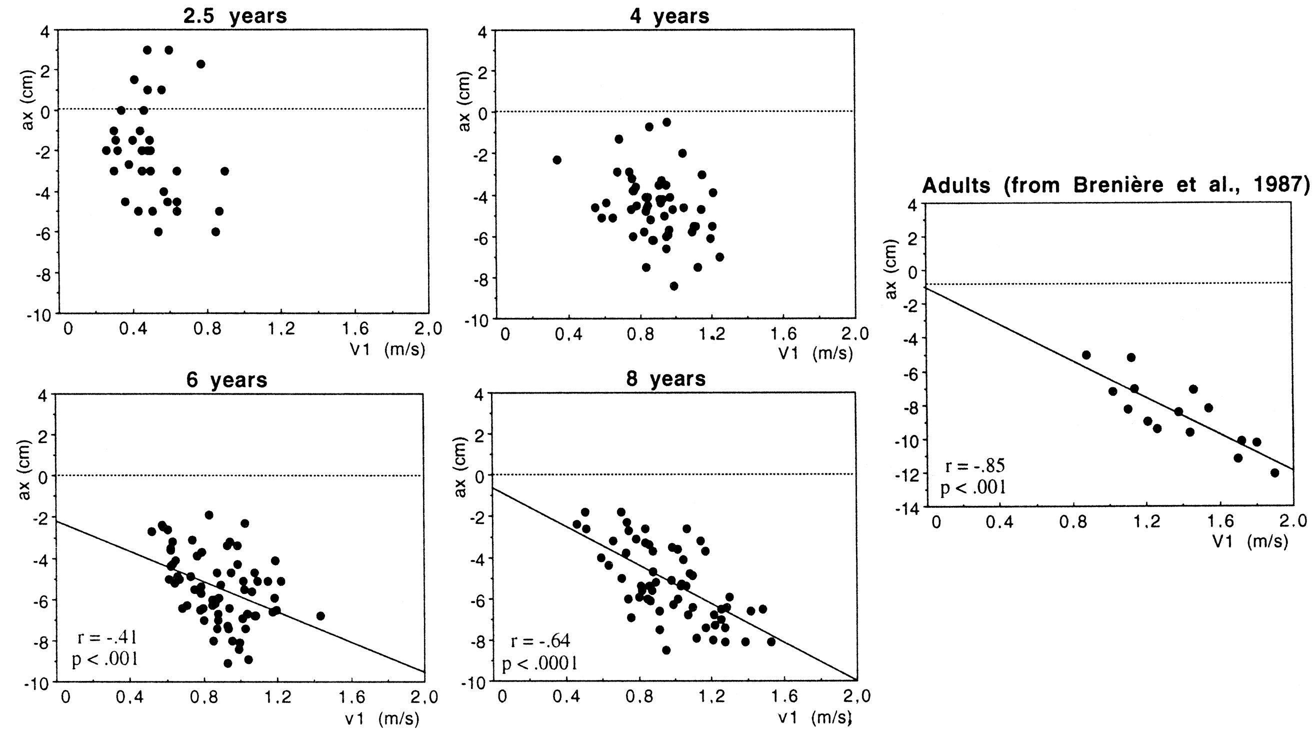


Fig. 4 Relationship between maximum backward shift (indicated by the negative values) of the centre of pressure (a_x) and progression velocity during the first step (v_1)

the correlation became significant at 6 years (r=–0.41, P<0.001) and its value increased at 8 years (r=–0.64, P<0.0001; Fig. 4). The same results were obtained with the normalised values of the backward shift (with respect to foot length) and the velocity (with respect to height).

There was no significant correlation between the duration of anticipation and the velocity of the first step, but the value of the correlation slightly increased with age (r=0.22 at 2.5 years; r=0.09 at 4 years; r=0.23 at 6 years and r=0.32 at 8 years).

Discussion

The purpose of this study was to analyse anticipatory behaviour in gait initiation, in children aged 2.5–8 years. The development of anticipatory behaviour is explicitly viewed here as indexing the construction of feedforward control of gait (Hayes and Riach 1989).

These results clearly show that, when anticipatory behaviour (i.e. backward and lateral shift of the CP) first appears, it is observed only now and then, and, above all, it is not organised. That is, the behaviour is there, but it is not used as an anticipatory behaviour: the characteristics of the behaviour are not linked with the forthcoming event. It is only when the child is able to display systematic anticipatory behaviour that he starts to organise it in relation to the characteristics of the velocity. We shall discuss this developmental trend, looking successively at three main characteristics of the development of anticipatory behaviour.

First, the percentage of occurrence of the anticipatory behaviour. Totally absent after 6 months of independent walking (Brenière et al. 1989), anticipatory spatial parameters were present in all age groups, but at first haphazard and disorganised. It appears that the two spatial characteristics of the mature pattern of anticipation are developing in a serial manner with age. Systematic backward anticipation was found for all children except one of the youngest (2.5-year group), whereas the lateral component of the anticipation was systematically observed later, in the 6-year group. This result indicates that anticipation emerges between 1.5 years, where no anticipation was found (Brenière et al. 1989), and about 2.5 years. Concerning the temporal parameter of gait initiation, the duration of the anticipatory phase was never equal to zero even in the cases with no anticipatory backward shift of the CP. So the phase that precedes the HO does not correspond necessarily to an effective anticipatory phase, as is the case in adult.

It appears that this phase can be present independently of spatial anticipatory phenomena. This phase of the movement could be a biomechanical constraint during which the body is falling forwards before the HO. This interpretation suggests that the gait initiation movement is that of a compound, but inverted, pendulum (Brenière and Do 1986a, b; Ledebt and Brenière 1994; Lepers and Brenière 1995). What interests us about the control of movement here is the way those biomechanical constraints are used by the walker to optimise the movement (Bernstein 1967). As shown by Lepers and Brenière (1995), in adult, muscle forces prescribed by the central nervous system are not the only forces that produce the movement during gait initiation. In fact, the ankle musculature controls body balance before the HO, but afterwards the principal force acting during step execution is gravity. So, it is during the anticipation phase that the postural and dynamic conditions for reaching the target velocity at the end of the first step are set up. In the present study, the remaining question is: is the lack of anticipatory behaviour in young children due to poor muscular control and/or to a lack of using the destabilising forces created by the gravity moment about the ankle joint?

Two factors could account for the low percentage of occurrence of anticipatory behaviour in the youngest children: either a less stable initial posture characterised by important oscillations of the body or a lack in cognitive control of the movement, or both.

The lack of anticipatory behaviour in the youngest children could be due to a different relative posture of the body segments at the onset of the initiation phase. As a matter of fact, the initial posture induces postural constraints for the movement executed from this posture (Lipshitz et al. 1981). With an initially forward tilt of the trunk, for example, there would be no anticipatory backward shift of the CP. The youngest children could have a different initial posture to the oldest, due, in part, to their postural instability. As a matter of fact, there are age-related differences in postural stability measured as the time-varying excursions of the CP, during quiet standing, recorded from a force plate (Hayes et al. 1985; Odenrick and Sandstedt 1984). That is, the postural sway is greater for young children in the lateral and antero-posterior planes. The spectral composition of children's sway shows a relatively greater amount of sway at high frequencies (in the 0.8- to 2-Hz bandwidth) in young children (Hayes and Riach 1989) than in adults. This postural instability could make the anticipatory displacement of the CP difficult to control. Here, an electromyographic (EMG) analysis could have completed the understanding of the emergence of anticipatory behaviour. The absence of anticipation might be due to a different pattern of muscle activation than the one observed in adults (Brenière et al. 1981; Carlsöö 1966) or to an adult-like but inefficient pattern. In fact, children may have anticipation at the muscle level that has no effect at the global dynamic level because of the background postural instability. But still, it is the global dynamic consequence of muscle activation (displacement of the CP) that is effective for moving the body forwards.

The second kind of explanation about the emergence of anticipatory behaviour refers to cognitive or conceptual development (Mounoud 1993): the emergence of any new skill results from the involvement of new conceptualisations and new categorisations, that is, new knowledge. Bremner (1993) suggests that "in the realm of purposefully controlled action we need to invoke the notion of cognitive structures and representations that allow infants to solve the many new problems that they face as they gain control over action". According to this point of view, the emergence of anticipatory behaviour in gaint initiation might be interpreted as the ability for young children to have some sort of "representation" of their forthcoming velocity.

The second aspect of the results concerns the values of the parameters indexing anticipation: the spatial parameters show a significant increase with age. The disappearance of the significant effect when the absolute values were normalised suggests that the increase in the backward shift can in part be explained by the increase in feet length: a growth of foot length will permit a greater backward shift. In fact, the distance between the projection onto the ground of the CM and the position of the CP (x_G–x_P in Eq. 1) is constrained by the size of the base of support, which obviously depends on foot length. Consequently, a large base of support allows for a more important backward shift and thereafter a greater gait velocity than a smaller base. It is then possible to dissociate, at least in part the respective contributions of gait control development and morphological development in the observed trend of gait characteristics. The growth of foot length will permit a greater backward shift and then an improved efficacy leading to a greater velocity at the end of the first step.

The third aspect of the results concerns the relation between the parameters of anticipation (spatial and temporal) and the forthcoming gait velocity. While it has been shown that in adults the duration of the anticipatory phase is correlated with speed, that is, faster forthcoming velocity implies a longer anticipatory phase, this covariation slightly increases with age but fails to be significant even in the older age group. But, as we suggested above, temporal and spatial parameters could be independent until mature organisation of anticipation is achieved.

Contrary to the adult, the backward shift did not covary with steady-state gait in the youngest groups. However the correlation between the backward displacement and the forthcoming velocity progressively increased and became significant at 6 years, and still increased at 8 years. Differences in the initial posture could also account for this aspect of the results. As suggested by Lepers and Brenière (1995), the initial posture before the onset of dynamic phenomena is related to the forthcoming velocity. In adults, the distance between the ankle and the CP showed that the antero-posterior abscissa of the CP is more forward for the fast steps than for the slow or normal steps. The authors proposed that forward position of the CP, corresponding to a forward position of the CM, facilitates the action of gravity to create the destabilising forces. Although we did not compute the initial position of the CP relative to the ankle for the children, it might be that they do not have this preparatory fined-tuned control of the initial posture in anticipation to the forthcoming velocity. In addition, the proprioceptors of the sole of the foot may then be important in the control of the exact CP position under the feet (Dietrich et al. 1993; Lepers and Brenière 1995). It seems that it is between 4 and 6 years of age that children progressively expand their reliance on sensory cues to systems other than the visual system for the maintenance of balance (Woollacott et al. 1989). Although this was suggested from studies on unexpected balance perturbation, we may hypothesise that, in gait initiation, children under 4–6 years of age have difficulty in using the proprioceptive information from the sole in order to prepare their initial posture as efficiently as older children and adults. In effect, the important sway due to instability produces a great amount of information from the sole which would be of little use.

These results, together with those of Brenière et al. (1989), establish that internal anticipatory behaviour in gaint initiation is not innate, as suggested in Hayes and Riach (1989). In addition, once present, it must still undergo development to be systematic and functional. However, it is necessary to question the meaning of this development of backward shift, which progressively becomes correlated with the forthcoming steady-state velocity. Anticipatory postural adjustments are generally viewed as a feedforward control of a predictable disturbance of the body's overall equilibrium (Massion 1992). An obvious function of postural adjustment viewed in this light is to reduce disequilibrium and consequently minimise the energy expenditure required for maintaining equilibrium during gait. In gait initiation, however, anticipatory behaviour has another purpose as well: to create the conditions that enable steady-state velocity to be achieved efficiently. This means that the human locomotor system first has to predict disequilibrium, due to the shift of bipedal to unipedal stance and to forward motion, and, second, to create the conditions for the first step as well. The complexity of this dual function could be one reason why the development of anticipatory behaviour takes so long.

While the above-mentioned biomechanical model stipulates that the establishment of a gap between the position of the CP and the projection onto the ground of the CM is a necessary condition that creates the dynamics of the first step, it has a corollary of importance for the young walker: it simultaneously creates a situation of disequilibrium. Early walking is in fact characterised by poor postural control (Sutherland et al. 1988), so the child is confronted with two competing necessities: minimising disequilibrium as well as creating this disequilibrium. Bril and Brenière (1993) suggested that learning to walk could be viewed as learning dynamic postural control, that, is learning to master, but also to produce, situations of disequilibrium. The present data show that it is only around 4 years of age that all children, even if not consistently, are able to create and to master the disequilibrium necessary to set up steady-state velocity at the end of the first step. However, the fact that the backward shift is not proportional to the forthcoming velocity in the youngest groups suggests that creating this gap between CP and CM appears as an initial step towards anticipatory control. It is only later that the child is cap able of the more accurate tuning required. Poorer quality of postural control of the overall postural adjustments in the youngest children could account for the immature anticipatory behaviour. If we compare the development of anticipatory behaviour in gait initiation with the development of propulsion strategies in steady-state gait, it is interesting to note the same trend. It is only from 4 years of that children are able to produce a positive vertical acceleration at foot contact (Brenière and Bril 1994). This result was interpreted as the child's capacity for self-control of movement with respect to gravity during unipedal stance. It is, then, from this period that the child is able to produce an adult-like push-off during single-stance phase. We may then speculate that a fine tuning of anticipatory behaviour necessitates a good mastery of the various components of gait.

Conclusion

The development of anticipatory behaviour in gait initiation is a good example of how the acquisition of the mastery of gait results from the development of different components of action (Thelen 1986). Anticipatory behaviour is not necessary for walking but it is necessary for efficient walking, as von Hofsten (1993) put if from studies on the development of prehension: "An important aspect of sensorimotor development is the acquisition of prospective control over movements in order to make them more continuous and smooth".

Anthropomorphic compoents, such as foot length, as well as postural control of balance, may influence greatly the characteristics of anticipation. It is important to understand how the development of various components of action constrains the observable behaviour. The development of independent walking is often viewed as depending on a maturational process (Forssberg 1985; Hirschfeld and Forssberg 1992). If instead we consider that the behavioural aspects of gait, at any age, are the expression of the working assembly of available competencies, one need no longer interpret the discrepancies between early- and mature-gait anticipatory behaviour as a consequence of immature neural functioning. Even if neural maturation is an obviously important part of early motor development, the development of anticipatory behaviour in gait, and probably in other motor skills, may depend more on the experience one has of that skill than on neural maturation per se. An important aspect of learning to walk, and of motor learning in general, is probably to understand how one constructs an action depending on the available competencies. The analysis of the development of anticipation may be a good path for understanding what level of expertise in a skill is necessary to allow a feedforward control of action.

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