Early emergence of temporal co-ordination of lower limb segments elevation angles in human locomotion

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Abstract

We analysed the co-ordination of the elevation angles of the thigh (α_t), shank (α_s) and foot (α_f) during walking in 19 adults and 21 children (aged 11–144 months), including the very first unsupported steps in four. Cross-correlation functions (CCF) maturation of pairs of elevation angles was quantified by a global error parameter $(Et_{(CCF)})$ reflecting the difference between particular CCF value of toddlers and mean adult value $(Ea_{(CCF)})$. During the very first step, $Et_{(CCF)}$ could be five times higher than $Ea_{(CCF)}$. With walking experience, $Et_{(CCF)}$ for both α_t-α_s and α_s-α_f pairs evolved following a biexponential profile, with a fast time constant below 6 months. Adult-like CCF parameters were reached earlier for α_s-α_f than α_t-α_s, indicating disto-proximal maturation of the temporal co-ordination of the lower limb segments in human locomotion. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Locomotion; Development; Temporal co-ordination; Lower limb

Studies in motor control have increasingly concentrated on the emergence of co-ordinative rules and integration of sensorimotor experiences into prewired neural networks [11]. In this context, the role of maturation in such a fundamental behaviour as locomotion appears critical but has received sparse attention until recently. Several parameters of postural and dynamical control have been studied with respect to early gait development, including head, trunk and hip stabilisation, intralimb co-ordination and centre of mass parameters [1,2,4,5,7,8,16].

In adults, a series of experimental studies of locomotion have demonstrated that the elevation angles of the lower limb segments provide a kinematic template revealing a motor organisation rule [3], which is related to minimisation of mechanical energy expenditure [14]. When the elevation angles of the thigh, shank and foot are plotted one versus the others, they describe a regular loop which lies close to a plane. Recently, we found that this planar covariation rule emerges early in toddler locomotion [7], suggesting a rapid

dynamical integration of forward propulsion and postural control into the motor command. Two important aspects of the co-ordination of angular evolution of the lower limb segments, namely excursion amplitudes and timing, are expected to influence the planar covariation. The temporal relationships between these angles evolution appear particularly crucial for locomotor co-ordination. Statistical approaches such as cross-correlation function (CCF) have proved to be adequate for deciphering consistent temporal relationships between kinematics signals during free-form movements [1,6]. In this study we introduce a global parameter based on CCF of lower limb segments elevation to quantify the gait kinematic maturation of children from the very first step through adolescence.

Twenty-one healthy children (13 girls and 8 boys, aged 11–144 months) and 19 healthy adults (9 females and 10 males, aged 25 ± 4 (mean ± SD) years) participated in this study. The procedures were approved by the local Ethics Committee of the University Children Hospital Queen Fabiola and conformed with the Declaration of Helsinki. Special attention was given to recording the very first steps of some toddlers. Daily recording sessions were programmed around the parents' expectation of the very

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first day of walking until unsupported locomotion was recorded. When we succeeded in recording this event, the same child was recorded again in order to follow the early maturation of walking. This was done for four children, who started to walk at 11, 11, 13 and 14 months, respectively. The other 17 children spanned the range of 3 weeks to 131 months of unsupported walking experience. The age of independent walking onset was reported by the parents.

For the recording of the very first steps, the toddlers were initially supported by a parent's hand. Then, when the parent moved forward, letting go of the child's hand, the child was encouraged to walk on the laboratory floor coated with a red band of linoleum (0.6 m wide and 8 m long). Toddlers were never supported during the actual recording of locomotion trials. For each subject, 10 to 15 trials were recorded in the same condition. Subjects were instructed to look straight forward and to walk as naturally as possible from one end of the ground band to the other end.

Kinematics of the locomotor movements was recorded and analysed using the opto-electronic ELITE system. This system consists of two CCD-cameras detecting retro-reflective markers using a sampling rate of 100 Hz. The cameras were placed on a line parallel to and 4-m away from the progression line of the subjects, 1 m above the floor, 3 m apart. After calibration, two-dimensional data were corrected for optical distortion and converted to 3D co-ordinates [10]. The position in space of 10 passive reflective markers (1.5 cm in diameter), defining 9 links, was recorded (Fig. 1A). The markers were fastened over the nose at the horizontal extent of the lower border of the orbit, ear meatus, acromial process, lateral condyle of the elbow, styloid process of the wrist, tubercle of the antero-superior iliac crest, greater trochanter, lateral condyle of the knee, lateral malleolus and 5th metatarsal.
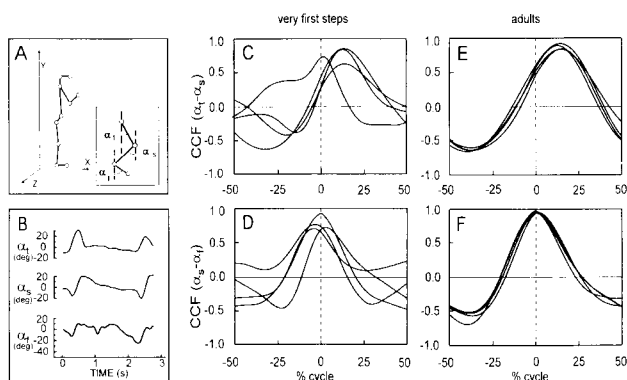
After reconstruction of the stick diagrams representing successful locomotion, we focused our analysis on the orientation of the trunk and the lower limb segments with respect to the vertical. The following segments were analysed: trunk (defined by the line connecting the acromion and the iliac spine markers), thigh (trochanter-knee), shank (knee-lateral malleolus) and foot (lateral malleolous – 5th metatarsal). The elevation angles of the thigh, shank and foot in the sagittal plane are noted α_t, α_s and α_f, respectively (Fig. 1A).

In order to test the temporal co-ordination between α_t, α_s and α_f, CCF between each set of two variables were calculated. The span of time lags or leads was analysed for a time window (T) corresponding to one gait cycle defined as the time interval between two successive maxima in the time series of α_t. The CCF between two functions, e.g. α_t and α_s, was defined as:

$$CCF_{\alpha_t, \alpha_s}(\tau) = \frac{1}{T} \int_T \alpha_t(t)\alpha_s(t - \tau)dt$$

where τ is the lag between the two functions, expressed as percentage of the cycle duration. When the signals $\alpha_t(t)$ and $\alpha_s(t)$ are statistically correlated, their CCF displays a peak (a significant CCF maximum (CCF_{max})) or a trough (a significant CCF minimum) at the abscissa τ^*. Positive values of τ^* denote a time lead of α_t (t) relative to α_s (t), whereas negative values denote a time lag. A significant CCF peak means that the two elevation angles vary in the same direction (forward or backward). Conversely, a significant CCF trough means that both angles vary in opposite direction (see Ref. [6] for more details).

In order to evaluate the maturation of the CCF of a pair of elevation angles we compared CCF shapes in the toddlers with the mean mature CCF shape of the adult. This was quantified by means of the following equation:

$$Et_{(CCF)} = \int_T |CCF(\tau)_{toddler} - \overline{CCF(\tau)_{adults}}|d\tau$$

where $Et_{(CCF)}$ is considered as a global error parameter of a toddler's CCF with respect to the mean adults' CCF.

In order to define a lower reference bound of $Et_{(CCF)}$ value, we have calculated $Ea_{(CCF)}$ (the global error of an adult's CCF with respect to the mean adults' CCF) by means of the following equation:

$$Ea_{(CCF)} = \int_T |CCF(\tau)_{adult} - \overline{CCF(\tau)_{adults}}|d\tau$$

We have thus considered that a mature temporal co-ordination between two elevation angles is reached when $Et_{(CCF)}$ is comprised between mean $Ea_{(CCF)}$ ±2 standard deviations.

Statistical analysis was performed using Statistica Software (StatSoft, Inc.).

The profile of CCFs calculated for the very first steps of four toddlers (Fig. 1C,D) shows great inter-individual variability as compared with the well reproducible CCF profile in adults (Fig. 1E,F). In adults, CCF_{max} between α_t and α_s

Fig. 1. Schematic illustration of the placement of reflexive markers and definition of elevation angle of the thigh (α_t), shank (α_s) and foot (α_f) (A). Temporal evolution of α_t, α_s and α_f recorded during the very first two steps of an 11-month-old toddler (B). Superimposed CCF profiles of the thigh-shank (C) and shank-foot elevation angles (D) calculated for the very first steps of four toddlers are shown for comparison with the corresponding CCF recorded in four adult subjects (E,F). Lag values are expressed as percentages of the gait cycle duration.

(Figs. 1E and 2B) and between α_s and α_f (Figs. 1F and 2C) reached a mean value of 0.91 ± 0.02 and 0.96 ± 0.01, respectively. Whereas the thigh consistently led the shank by $13.58 \pm 1.88\%$ of the gait cycle (Figs. 1E and 2A), shank and foot elevations were perfectly synchronised (0.00%) (Figs. 1F and 2A). Fig. 2A shows that the evolution of α_s-α_f lag converges much more rapidly towards adult values than α_t-α_s lag. For the very first steps, CCF_{max} between α_t and α_s (Fig. 2B) and between α_s and α_f (Fig. 2C) reached a mean value of 0.69 ± 0.12 and 0.71 ± 0.15, respectively. Both parameters rapidly converge towards adults values (time constants of 4.9 and 1.3 months, respectively) (Fig. 2B,C).

Fig. 3 shows the superimposition of the CCFs (dark grey) of one representative toddler and the mean CCF profile of the adult subjects (light grey). Although significant CCF_{max} were present for each pair of angles since the very first steps, CCF profiles could be different from the mean profile of the adults' CCF. However, the main trend of the adults' CCF was already present at an early stage in the illustrated toddler. For example, forward α_t leads α_s (Fig. 3A) and the CCF_{max} for α_s-α_f rapidly reaches almost perfect

Fig. 3. Evolution with age of the cross-correlation function of the lower limb segments elevation angles. The CCF of the data of one toddler (dark grey area) of each couple of lower limb segments are plotted superimposed on the mean profile of the adult corresponding CCF (light grey area). CCF of the elevation angle of the thigh-shank and shank-foot pairs are plotted in the left and right column, respectively. Four maturation stages are plotted: the very first steps (A,B); 3 weeks (C,D); 6 weeks (E,F); 18 months after the onset of walking (G,H). Lag values are expressed as percentages of the gait cycle duration.
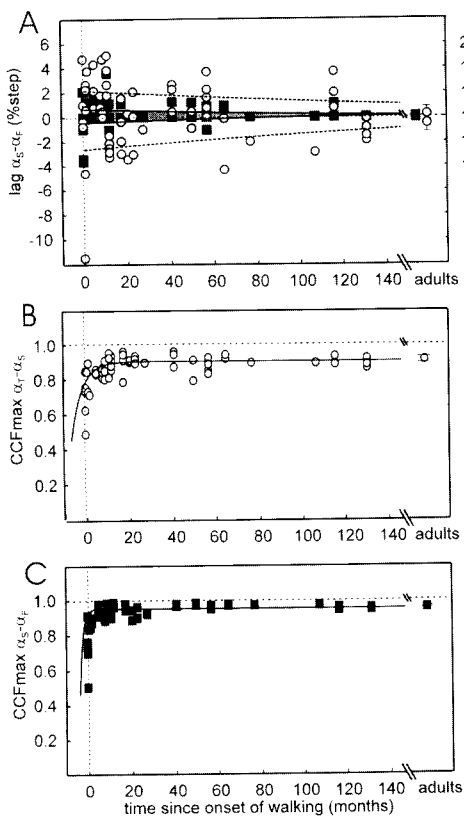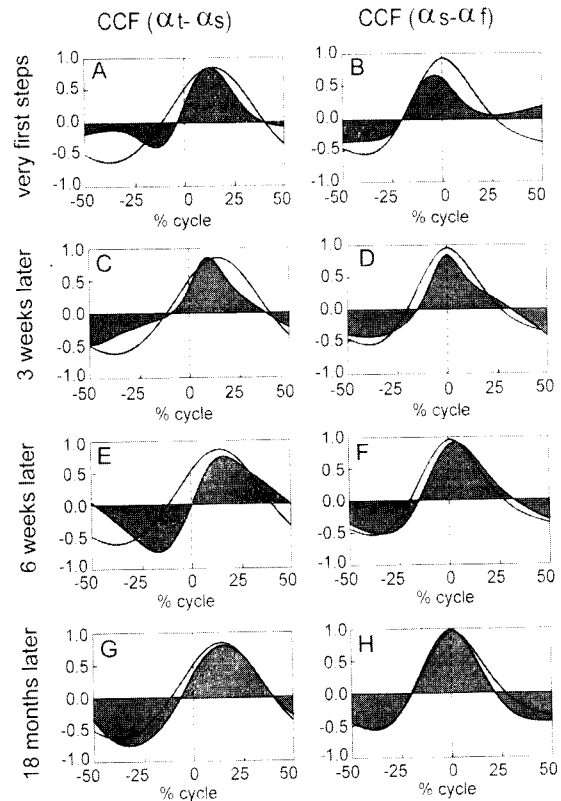

Fig. 2. Evolution of lags (A) and maximal values of the cross-correlation function (CCF_{max}) for the thigh-shank (α_t-α_s) (B) and shank-foot (α_s-α_f) (C). Lag values for α_t-α_s (open circles) and α_s-α_f (filled squares) are plotted together (A) by superimposing the two respective adult mean values (0% for α_s-α_f left ordinate and 14% for α_s-α_f right ordinate). Adult values are represented by their pooled mean and standard deviation.

synchronisation (lag value close to zero) by 3 weeks of walking experience (Fig. 3D).

The maturation with age was analysed by using the global error parameter $Et_{(CCF)}$ which is defined as the area under the curve obtained by subtracting the mean absolute value of CCF of the adults from the absolute value of CFF of a toddler at a particular stage of maturation. Fig. 4 shows the temporal evolution of $Et_{(CCF)}$ for α_t-α_s and α_s-α_f. The overall time course of changes with age can be described by a biexponential function:

$$y = a^{-x/t_1} + b^{-x/t_2}$$

(where x is the time since onset of unsupported walking, t_1 is the fast time constant and t_2 is the slow one). The function fitted reasonably well $Et_{(CCF)}$ values ($r = 0.74$ and 0.82 for α_t-α_s and α_s-α_f, respectively). The first time constants were fast ($t_1 = 3.18$ and 6.12 months after the onset of unsupported locomotion for α_s-α_f and α_t-α_s, respectively) and $Et_{(CCF)}$ rapidly converged toward the adult values (repre-
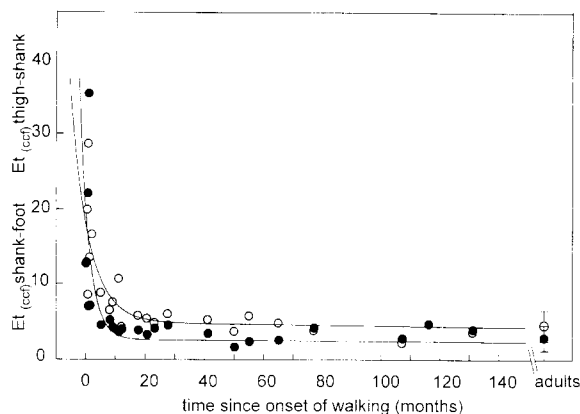
Fig. 4. Evolution of the global error parameter. The temporal evolutions of the $Et_{(CCF)}$ values (expressed in arbitrary unit) of the thigh-shank (open circles) and shank-foot (filled circles) elevation angles are represented by biexponential function. The mean and standard deviation of the adult values ($Ea_{(CCF)}$) are represented for each pair of angles.

sented by the respective means and standard deviations of $Ea_{(CCF)}$ for both angle pairs.

Because the maturation of infants' motor cortex is relatively slow, as reflected by thresholds of transcranial magnetic stimulation [10,17] and myelination of the corticospinal tract, the rapid maturation of the temporal co-ordination of lower limb segments suggests that the control of these kinematic variables could be mainly assumed by lower neural structures situated in the brainstem and/or spinal cord, such as locomotion central pattern generators (CPG) [11]. A common locomotor CPG for the multidirectional control of stepping has been recently supported by the study of infants aged 2–11 months [15] and could be a good candidate for performing the earlier co-ordinative function of the elevation angles during unsupported locomotion. However, the phase coupling between the CPG units driving different limb segments may change during development, as the result of maturation of supra-segmental control. Mechanical factors likely contribute to synchronise α_s and α_f more than α_t and α_s because ground contact intermittently closes a kinematic chain during walking at the level of the foot while the knee retains more biomechanical freedom. However, the facts that (1) effective locomotion can be achieved with a positive or negative α_s-α_f lag and (2) the evolution towards perfect synchronisation is more rapid than morphological changes [7] suggest that neural control mechanisms are implicated. The difference in time evolution between α_s-α_f and α_t-α_s lags is in agreement with the study of Assaiante and Amblard [1] suggesting an ascending organisation of locomotor balance control from foot to head. Although this mode of organisation is not related to an unexpected perturbation, it is also reminiscent of the known prevalence of the ankle strategy [13]. This observation is further reinforced by the similarly rapid evolution of distal intersegmental temporal co-ordination and trunk stabilisation during locomotion [16,7].

Furthermore, the present results corroborate a previous study [7] where we showed that it is possible to follow the maturation of human locomotion by using the planar covariation analysis. This latter study has permitted to show an early emergence of an adult-like orientation of the covariation plane which also paralleled the maturation of the trunk stability with respect to vertical [7]. As it can be argued that the planar covariation represents a specific pattern of neural co-ordination of intersegmental kinematics [14], its comparison with the present CCF results may shed a new light on the temporal aspect of this co-ordination. Indeed, in adults the CCF of each pair of elevation angle provide a highly reproducible temporal template which can be used as a mature reference for the co-ordination of timing. The CCF analysis of kinematic descriptors therefore reinforce the idea of a priming influence of the timing control in locomotion. Like the present evolution of $Et_{(CCF)}$, the orientation of the covariation plane and trunk stability are well represented by biexponential functions. We found significant linear correlations between $Et_{(CCF)}$ and the orientation of the covariation plane ($r = 0.75$ and 0.74 for α_f-α_s and α_s-α_f, respectively). We also found significant linear correlations between $Et_{(CCF)}$ and trunk stability, both stability in the sagittal plane ($r = 0.64$ and $r = 0.69$) and in the frontal plane ($r = 0.67$ and $r = 0.72$). However, the fast time constants of these correlations were slower than that of the covariation plane orientation with trunk stability (analysed in Ref. [7]). Whereas the planar covariation analysis of locomotion presents the advantage to follow the evolution of co-ordination of at least three body segments by only one parameter in normal [3] or pathological situations [9,12], the CCF analysis can decipher subtle differences in disto-proximal maturation of temporal co-ordination.

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