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RESEARCH ARTICLE

Learning to tune the antero-posterior propulsive forces during walking: a necessary skill for mastering upright locomotion in toddlers

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Abstract This study examines the process of learning to walk from a functional perspective. To move forward, one must generate and control propulsive forces. To achieve this, it is necessary to create and tune a distance between the centre of mass (CoM) and the centre of pressure (CoP) along the antero-posterior axis. We hypothesize that learning to walk consists of learning how to calibrate these self-generated propulsive forces to control such distance. We investigated this question with six infants (three girls and three boys) who we followed up weekly for the first 8 weeks after the onset of walking and then biweekly until they reached 14–16 weeks of walking experience. The infants' walking patterns (kinematics and propelling forces) were captured via synched motion analysis and force plate. The results show that the distance between the CoM and the CoP along the antero-posterior axis increased rapidly during the first months of learning to walk and that this increase was correlated with an increase in velocity. The initial small values of (CoM–CoP) observed at walking onset, coupled with small velocity are interpreted as the solution infants adopted to satisfy a compromise between the need to generate propulsive forces to move forward while simultaneously controlling the disequilibrium resulting from creating a with distance between the CoM and CoP.

Keywords Walking · Learning · Propulsive forces · Centre of pressure · Centre of mass · Longitudinal study · Lower limb kinematics

Introduction

Walking may be defined as the forward displacement of the erected body through a succession of cycles comprised of a sequence of double-support and single-support phases, where single-support phases are alternated between feet. Yet, to move the body forward through this alternating sequence of movements, one must generate propulsive forces. In this paper, we hypothesize that the process of learning to walk may be viewed as the necessary acquisition of the capacity to produce—and modulate—these critical propulsive forces, particularly in the antero-posterior direction. In other words, our hypothesis is that what comes first in the process of walking acquisition is the aptitude to produce propulsive forces through a succession of double-support and single-support phases. Therefore, the development of the kinematic patterns that characterize gait is viewed as the consequence of such functional constraints on the musculo-skeletal system in the gravitational field.

To examine this view, we studied the development of this force production functional capacity using longitudinal data on the acquisition of walking in 6 toddlers followed up over a 4-month period beginning at the onset of upright locomotion. Again, we argue that in order to become a

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proficient walker, the child needs to learn and master how to control these propulsive forces.

Prior studies have shown that the force translations applied to the body during gait depend on the relative positions of the centre of mass (CoM) and centre of pressure (CoP) as defined in Eq. 1 (Brenière et al. 1987):

$$\begin{aligned} F_X &= (X_G - X_P)m^2/k_x \rightarrow k_x X_G'' = (X_G - X_P)m \\ F_y &= (Y_G - Y_P)m^2/k_y \rightarrow k_y Y_G'' = (Y_G - Y_P)m \end{aligned} \tag{1}$$

where F_x is the propulsive force along the antero-posterior axis, X_G'' is the antero-posterior acceleration, X_G is the vertical projection onto the ground of the CoM on the antero-posterior axis, X_P is the position of the CoP on the antero-posterior axis, m is the mass of the body, and k is a constant (see appendix pp. 74–75 in Brenière et al. 1987). F_y describes propulsive force along the medio-lateral axis. This means that the propulsive forces (F_x, F_y) are directly related to the difference between CoM and CoP. More precisely, we consider that the landmark of learning to walk rests on the child's capacity to produce and modulate one collective variable which can be summed as the distance between the CoM and CoP in both the antero-posterior and medio-lateral axes.

Such propulsive forces, however, can be generated using various combinations of limbs and body coordination (Kubo and Ulrich 2006; McCollum et al. 1995; Snapp-Childs and Corbetta 2009). Here, we argue that, whatever the mode of limbs coordination adopted by the child when beginning to walk, the fundamental process of learning to produce and regulate propulsive forces to move forward remains the same.

Having said that creating a distance between CoM and CoP automatically generates a situation of disequilibrium and unbalance which needs to be controlled to avoid a fall. During a step production, the CoM is first moving ahead of the CoP, which produces a forward acceleration (and forces), and then the CoM is moving backward following the heel strike, which produces a break in the phase. During the single-support phase, the body CoM is accelerated forward and sideways at the same time towards the swinging leg (see Hof 2008). Hence, the walker is in the dynamical situation of a forward movement and lateral fall on the opposite side of the stance foot. Furthermore, during the single-support phase, the vertical ground projection of the CoM is no longer aligned with the position of the supporting foot on the ground. Thus, the walker is clearly in disequilibrium. In normal gait, this situation does not lead to a loss of balance as postural adjustments stabilize the body in the upright position. In addition, smooth gait is generated by a very precise adjustment of the periodic reciprocal movement of the CoM and CoP while the body is shifting periodically from one foot to the other. As a result, during

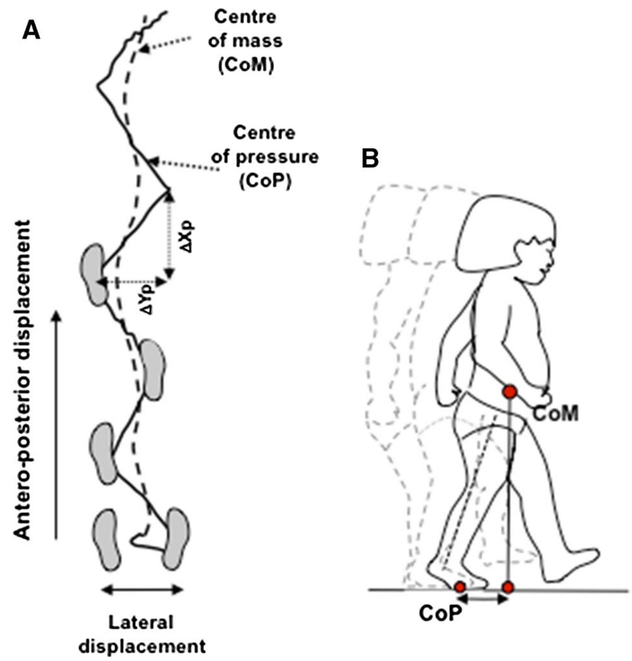

Fig. 1 **a** CoP and CoM oscillation during a sequence of six steps. *Solid line* gives the CoP displacement, and *dotted line* gives the CoM displacement. ΔYp = step width, ΔXp = step length. **b** Relative positions of CoM and CoP at the end of the single-support phase

walking, the trajectory of the CoM vertical projection onto the ground and the trajectory of the CoP are almost never superimposed. It is only during the double-support phase that the two intersect, and it is only during this double-support phase that the disequilibrium is minimal. Otherwise, the larger the distance between CoM and CoP, the greater the disequilibrium, this disequilibrium being maximal at the end of the single-support phase just prior to foot contact (FC) (Figs. 1, 2b).

Before toddlers initiate their first attempts to walk without support, they have never experienced a situation of unipodal stance requiring very subtle postural adjustments to avoid losing balance (Sutherland 1997; Sutherland et al. 1988). Consequently, the necessary disequilibrium that is inherent to gait appears as a major challenge for the new walker. We assume that at walking onset, the child needs to discover a compromise between these two opposite intrinsic demands of the gait movement (disequilibrium and control) in order to learn to walk. To do so, the child needs to figure out how to create a distance between CoM and CoP that is generating a necessary disequilibrium, while at the same time trying to minimize this disequilibrium. We anticipate that at walking onset, toddlers will control disequilibrium by maintaining a very small distance between CoM and CoP, which will lead, as a result, to the production of short steps.

The goal of this study was to examine the development of the maximal distance between the CoM and CoP that comes forth at the end of the single-support phase, just prior to foot contact in six toddlers followed up longitudinally from the onset of walking up to the fourth month of walking experience. This time span covers the first phase of learning to walk reported by previous studies (Bril and Brenière 1992; Brenière and Bril 1998; Clark and Phillips 1993; Cheron et al. 2001; Hallemans et al. 2006), which corresponds to the greatest changes in gait patterns.

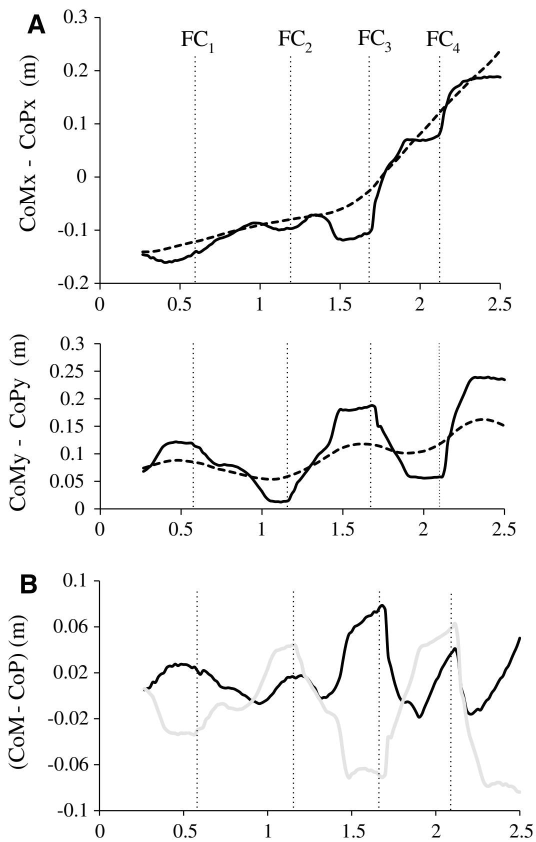

Fig. 2 **a** Time series of the trajectories of CoP (*solid line*) and CoM (*dotted line*) along the antero-posterior axis (*top graph*) and medio-lateral axis (*lower graph*). **b** Time series of the values of the distance between CoM and CoP along the antero-posterior axis (*black line*) and the medio-lateral axis (*grey line*)

Materials and methods

Participants

Six toddlers (three girls and three boys) participated in this study. These toddlers were part of a larger longitudinal study that began when they were 7–8 months of age. This report only considers the data collected from the onset of walking. Toddlers' walking was recorded every week for the first 8 weeks after walking onset and then every other week until they had reached 14–16 weeks of walking experience. One of the six infants (SB) did not continue in the study after 8 weeks of walking experience because she became fussy. For this report, we even disregarded the data collected at the 7th week session of SB's independent walking as she was particularly fussy (Table 1).

The age of onset of walking was quite homogeneous among the sample of the six children, with an average of onset of walking at 12 months, varying from 10 months 2 weeks to 13 months 3 weeks. Walking onset was defined as the capacity to walk three steps unsupported.

Apparatus

The toddlers' gait was recorded using two devices. The movement kinematics were recorded using two Northern Digital OPTOTRAK sensors (sampling at 60 Hz). The motion sensors were placed on each side of a straight 2.5-m-long walking path. The sensors were located at a distance of 4 m from the walker providing a lateral view of each side of the body during the entire walking path. Before data collection, the OPTOTRAK sensors were calibrated with each other with a measurement error of less than .5 mm.

The OPTOTRAK was synchronized with a 40 cm by 60 cm AMTI force plate sampling at a rate of 240 Hz. The force plate was situated at a distance of 50 cm from the beginning of the walking path. These data were used to calculate the time series of the CoP. For one infant (MH), it has not been possible to record force plate data. This child would not walk in a straight line within the required

Table 1 Age of walking onset, body height and weight at onset of walking, number of sessions of walking recording, total of number of steps on the force plate used for analysis, total number of steps analysed from OPTOTRAK recordings used for analysis

Child	Walking onset (mo)	Height (cm) at walking onset	Weight (kg) at walking onset	No. of sessions	No. of steps on force-plate	No. of steps OPTOTRAK
LG	10.2	72.0	8.0	9	78	339
EH	13.03	75.5	10.2	9	118	472
MW	12.0	78.5	14.1	10	41	471
NE	11.2	74.0	10.5	11	91	552
SB	11.2	69.0	7.7	8	69	516
MH	12.1	77.0	11.2	9	0	453

path. In order to constrain him to follow the straight path to record kinematics, we built a 2.5-m-long walkway that was raised 18 cm above the floor.

A Sony Video Hi8 Handycam was also placed at a distance of 4 m on the right side of the walker allowing for a complete view of walking and an accurate interpretation of the patterns of movement produced.

Procedure

When the toddlers arrived at the laboratory, their clothing was removed and sixteen infrared-emitting diodes (IREDs) were placed bilaterally onto the fifth metatarsal, lateral malleolus, knee joint, greater trochanter, wrist, elbow and shoulder joints. To record head movement, two IREDs were also attached to an infant headband that was placed on the toddlers' heads such that the IREDs were positioned slightly above their ears. All toddlers did not always accept to wear this headband; thus, when not possible, only 14 IREDs were used for recording.

At each session, the toddlers had to walk through the straight path in between the motion sensors 10 times starting either behind or on the force plate. The child parents were standing at the end of the walking path and enticed their child to walk towards them either by calling them gently or by using an attractive toy for them to get. Typically, after two to three steps on the force plate, the toddlers generated another ten to twelve steps approximately towards the parents.

At the end of each session, anthropometric data were collected, including total height, leg length, foot length and head circumference.

Data analysis

The data analyses began by merging the sequences of steps from the two source files (the kinematics and force plate data) using the "Motion Inspector" software (Biometrics France). Furthermore, prior to extracting dependent variables from the combined data files, we examined the videos to select only step sequences that were usable. A step was defined as the movement from one foot contact to the following contact of the contralateral foot. Foot contact (FC) was decided upon the vertical displacement profile of sensors 8 and 12 (lateral malleolus of the right and left foot, respectively). For the steps containing both force plate and kinematic data, a double check was done, based on the time series of the CoP displacement along the medio-lateral axis. Figure 2 clearly shows that at foot contact, the curve shows a sudden change in direction that corresponds to the onset of the displacement of the CoP from one foot to the contralateral foot. Usable step sequences were the ones where the child walked on the force plate at a steady state pace, and in a straight line. Once the step sequences were selected from the video, the corresponding kinematic data files were systematically checked, also for usability purposes. If there were missing data in the kinematics files, we interpolated missing gaps as long as the sum of all gaps in the file were not exceeding 10 % of the recorded data using quintic spline interpolation method. Then, the interpolated data were filtered with a fourth-order Butterworth filter (cut-off filtering at 10 Hz). If too many kinematics data were missing, the data files were eliminated. The force plate data were not filtered.

This data selection process resulted in 2803 steps being included in the analyses, of which 397 contained both force plate and kinematic data.

Centre of mass (CoM) computation

The method of calculation used to compute the position of the CoM during a sequence of steps was the classic "method of segmentation" which considers the body as a rigid body of homogeneous and solid cones. The mass proportion and centre-of-mass relative position of body segments have been calculated using regression equations from Jensen (1986).

Because sometimes data from the head were missing, we used two models to compute the position of the COM: (1) normal body (complete data), (2) body with no head (the weight of the head was added to the weight of the trunk.

Gait parameters

We have computed three categories of gait parameters.

The absolute distance between the CoM and the CoP was measured at the very end of each single-support phase for the 397 steps for which both force plate and kinematic data were available (Fig. 2). The time series of the displacement of the CoM were computed from the full-body model for all toddlers, except one, who systematically refused to wear the headband.

We also indexed the development of the angle of the support leg relative to the gravity vector (delineated by the greater trochanter marker and the lateral malleolus marker and the vertical ground projection at foot contact, Fig. 1) as another way to capture the increase in the distance between the CoM and CoP at foot contact along the anterior–posterior axis. This angle should increase as a function of walking experience and may also be viewed as an indication of the amount of disequilibrium experienced.

The amplitude of the leg angle was computed from the kinematics of the lower limbs for the 2803 steps included in the analysis.

Global gait parameters were computed from the kinematic data of each step. Step length and step width were

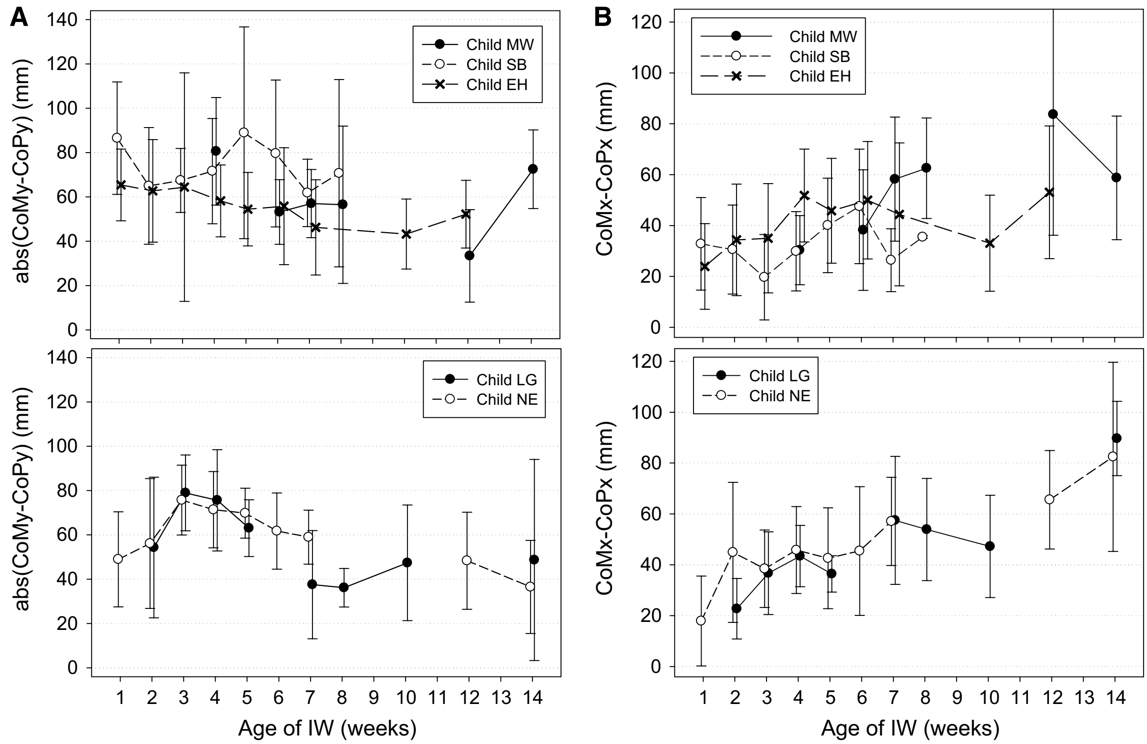

Fig. 3 Development of the distance between the CoM and the CoP just prior to FC of the contralateral foot depending on walking experience. **a** Along the antero-posterior axis. **b** Along the medio-lateral axis

computed as the distance between the position of the marker placed on the malleolus at foot contact of one foot and the position of the same marker of the contralateral malleolus at the following foot contact. Velocity was computed for each step as the distance covered by the swinging leg from lift off to heel strike of the same foot and divided by the duration elapsed during these two same moments (step length/step duration).

Statistical analyses

The data from each child were analysed separately. To assess changes with walking experience of the above variables, we performed repeated measures ANOVA for each child and every parameter.

Results

Changes in the absolute distance between the CoM and the CoP

Along the antero-posterior axis, the values of the distance between the CoM and CoP rose from 20 to 40 mm at onset of IW to more than 80 mm. Increase in the distance between the CoM and CoP at foot contact of the contralateral foot was significant for four children (LG, EH, MW and NE). It was not significant for SB, and there were no force plate data for MH. Along the medio-lateral axis, the decrease in the distance between the CoM and CoP at foot contact of the contralateral foot was significant for three children: LG, MW and NE, but not significant for EH and SB. Again, there were no force plate data for MH. For reason of fussiness, SB participated in the experiment for the first 2 months only. This could explain at least in part the lack of significant change in the distance CoM–CoP observed for this particular toddler (Fig. 3).

Changes in the value of the leg angle from the vertical ground projection at foot contact of the contralateral foot

The increase in the distance between the CoM and CoP in the sagittal plane is anatomically commensurate to an increase in the magnitude of the leg angle α, defined as the angle formed by the hip great trochanter–foot lateral malleolus in the sagittal plane from the vertical direction at time of foot contact of the contralateral foot. The value of the leg angle α increased significantly with walking experience for all children (see Table 2; Fig. 4). Not exceeding 5°–10° at onset of independent walking, this value more than doubled

Table 2 Developmental changes with walking experience in the parameters studied for each child

	LG	EH	MW	NE	SB	MH
CoMx–CoPx	$F(6, 69) = 5.80$, $p < .000$	$F(8,110) = 1.774$, $p = .089$	$F(5, 36) = 4.96$, $p = .0015$	$F(9, 82) = 5.024$, $p < .000$	$F(6, 58) = 1.85$, $p = .105$	No data
abs (CoMy–CoPy)	$F(6, 68) = 4.72$, $p = .004$	$F(8, 110) = 1.299$, $p = .251$	$F(5, 36) = 3.31$, $p = .0156$	$F(9, 82) = 3.178$, $p < .002$	$F(6, 58) = 1.180$, $p = .333$	No data
Velocity	$F(8, 327) = 38.51$, $p < .000$	$F(8, 466) = 20.22$, $p < .000$	$F(9, 462) = 41.23$, $p < .000$	$F(10, 542) = 59.87$, $p < .000$	$F(6, 471) = 20.36$, $p < .000$	$F(9, 435) = 21.49$, $p < .000$
Step length	$F(8, 327) = 34.51$, $p < .000$	$F(8, 466) = 12.64$, $p < .000$	$F(9, 462) = 34.99$, $p < .000$	$F(10, 542) = 16.17$, $p < .000$	$F(6, 471) = 16.17$, $p < .000$	$F(9, 435) = 19.21$, $p < .000$
Step width	$F(8,327) = 21.45$, $p < .000$	$F(8, 466) = 22.66$, $p < .000$	$F(9, 462) = 28.08$, $p < .000$	$F(10, 542) = 34.36$, $p < .000$	$F(6, 471) = 37.41$, $p < .000$	$F(9, 435) = 18.04$, $p < .000$
Leg angle α at FC	$F(8, 327) = 16,73$, $p < .000$	$F(8, 466) = 11.00$, $p < .000$	$F(9, 462) = 62.87$, $p < .000$	$F(10, 542) = 73.85$, $p < .000$	$F(6, 471) = 27.34$, $p < .000$	$F(9, 435) = 22.80$, $p < .000$

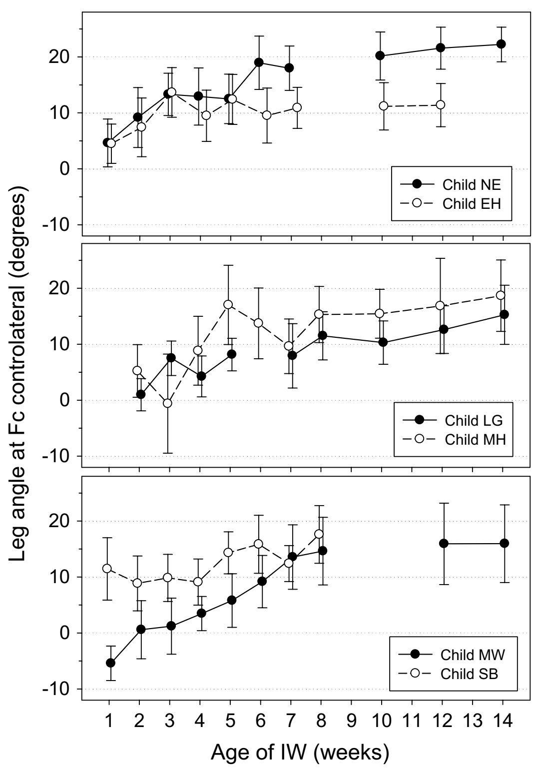

Fig. 4 Development of the angle α (leg position towards vertical) at foot contact for each child

within the first 16 weeks following the onset of independent walking.

The correlation coefficient between the absolute value of the CoM–CoP distance and the angle α at foot contact along the antero-posterior axis was significant [corrected for multiple samples from the same participants ($r^2 = 1974$; $r = .444$, $p < .001$)].

If we consider a simple trigonometric model of the limb, an increase in the angle α from 5° to 20° for an infant whose lower limbs measure about 280 mm, the distance between the CoM and CoP will increase from 24 mm to 95 mm (280 mm × sin(5°) to 280 mm × sin(20°)). Such a simple computation gives results in the same range as the experimental values obtained.

Changes in "global gait parameters"

Table 2 gives the development of step length and step width and velocity for each of the children. Step length and velocity increased significantly for every child, and the decrease in step width was significant for every child (Table 2), hence replicating prior data reported in the literature (Bril and Brenière 1992; Sutherland et al. 1988 among many others).

Discussion

The point of view that we offered here was that producing a distance between CoM and CoP represents the basic requirement to produce propulsive forces in locomotion. Yet, this distance does create instability that must be controlled to stabilize the system (Bottaro et al. 2005). Note that the relative position of X_G and X_P can be interpreted in two ways. On the one hand, this parameter could be defined as a way to produce propulsive forces (see Eq. 1). On the other hand, many studies have put forward that this distance qualifies balance and consequently provides a description about stability/instability in gait (Jian et al. 1993; Winter 1995). Along the same lines, the $X_G - X_p$ pendulum model (Masani et al. 2007; Hof 2008) suggests that this relative position could be used to investigate walking stability.

The discussion that follows will address how these two adverse features of gait (generating propulsive forces and monitoring stability) are mastered by the young walkers.

Learning to produce propulsive forces

It is widely recognized that walking experience acts as a "functional trigger for maturation of the innate kinematic pattern" to use Ivanenko et al. terms (2005: 761; see also Ivanenko et al. 2004; Hallemans et al. 2006). According to this approach, the maturation of the CNS is viewed as the primary responsible factor for the changes observed (Cheron et al. 2001; Dierick et al. 2004; Forssberg 1985; Ivanenko et al. 2005) although the CNS must incorporate limbs and body parameters (Dominici et al. 2011; Lacquaniti et al. 2012a). Cheron et al. (2001), for example, speculated that the developmental changes of joint angles covariation of the lower limb observed during the first months of IW, can reflect the developmental changes of cerebellar control of posture and gait (p. 465). The CNS would control joint angles and their correlation, as well as their angular velocity. These authors hypothesized the existence of an "isomorphism between the internal model of the body scheme and the actual limb and body movement" (p. 463). More recently, Ivanenko et al. (2011) and Lacquaniti et al. (2012a,b) proposed that the control and the coordination of the multi-segment movement could be simplified by using biomechanical constrains and muscle activity as accounted for by a combination of few basic patterns. They argued that the coordination of locomotor activities emerges from the interaction of neural oscillators (locomotor patterns) and limb mechanical oscillators using passive mechanical properties (Holt et al. 2006). According to Lacquaniti et al. (2012a), the learning process could consist in discovering through experience the optimal tuning between these two components. This assumption could explain the kinematics of gait. However, if the question is to explain the locomotor action, i.e. moving the body from point A to point B, through a succession of movements, we need to consider a more "global" variable. From a functional point of view, the physical variables that cause the displacement of the body are forces (Brenière and Bril 1998; Ledebt and Benière 1994). Here, we offer the point of view that forces represent one central functional parameter of the locomotor task. The relative position of the CoM and CoP fully explains how such propulsive forces are produced (see Eq. 1) and therefore represents the actual physical parameter generated by the walker. The functional approach to action we posit (Bril et al. 2010, 2012; Parry et al. 2014) stresses that any given goal can be defined by a particular set of physical principles and that achieving the goal depends upon the capacity of satisfying the task constraints stemming from these physical principles. Our hypothesis is that it is indeed the mechanics of the task (functional constrains) that impose the characteristics of the action (functional parameters) and, therefore, of the movement. Here, we have defined walking as a task that requires the production of antero-posterior (fore-aft) forces to move the body forward. Lateral forces enable the body to load and unload body weight from one foot to the other (Winter 1995). Thus, the development of walking entails the acquisition of the capacity to produce these specific forces. We speculate that, to a large extent, much of the characteristics of early walking may be explained as reflecting a solution discovered by the young walker to solve these complex mechanical constraints.

Instability caused by the CoM–CoP decoupling

Toddlers starting to walk need to learn how to generate these propulsive forces through an alternate leg pattern. Knowing that generating propulsive forces necessitates the decoupling of the CoM and CoP, an act that by definition causes instability, toddlers face the challenge of potentially falling or loosing balance when lifting one foot. To our knowledge, no developmental study has framed the problem of learning to walk in toddlers as mastering the inherent disequilibrium generated by the decoupling between the projection of the CoM and the CoP during stepping—a necessary condition to induce a displacement of the body forwards. This disequilibrium has been viewed by others as a lack of control that requires active postural corrections to prevent a loss of balance (Hsue et al. 2009). Hsue and collaborators, in particular, considered that the relation between the CoM and CoP provides a comprehensive description of postural stability and of a lack of balance in early gait development. Contrary to this notion, we consider that producing such differential between the CoM and CoP is a necessary condition for walking and as such expresses an index of the toddler's capacity to create the dynamics of gait movement.

Many studies on early walking stress a deficit in postural control, which in turn is considered as the reason for the large base of support (or wide steps) and short steps observed in novice walkers. Along those lines, Bril and Brenière (1992) earlier studies on gait development suggested that the first few months after walking onset were devoted to the adjustment and integration of postural synergies of the bipedal and unipodal dynamic stance to insure a secure balance. A second phase follows that is characterized by a more precise adjustment of the gait parameters. This second phase was considered a tuning phase. The present study allows for a better understanding of the first integration phase, which consists in the progressive shift of a movement performed along the medio-lateral axis to a movement performed along the antero-posterior axis.

Why would walking development undergo such a developmental process? To describe this process, we need to examine the "walking posture" in terms of kinematic chains (see Fig. 5) and resultant constraints contrasting the double-support phase and the single-support phase. The kinematic chain is formed by the two lower limbs with six joints, ankles, knees and hips. Due to mechanical and

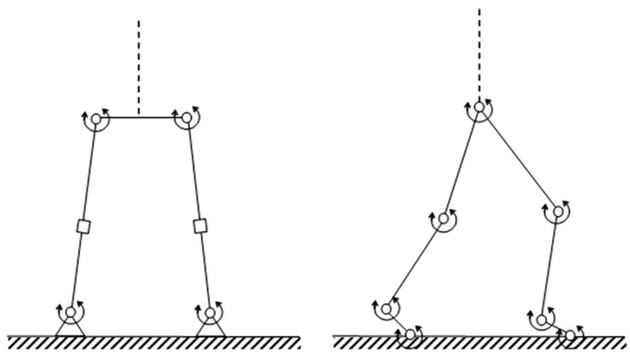

Fig. 5 Schema of walking postures presented in terms of kinetic chains view along medio-lateral axis and the antero-posterior axis

anatomical constraints, these six joints do not imply the same number of degrees of freedom (dof) for each plane (medio-lateral and sagittal). During the double-support phase, in relation to the medio-lateral plane, we consider the four-segment closed chain formed by the two legs, the pelvis and the ground, the ground being considered as the fourth link. Furthermore, this closed chain is mechanically coupled due to its geometrical configuration. Following Zatsiorsky (1998: 106), a closed chain in a planar system (medio-lateral plane) is characterized by a number of dof equals to the number of joints multiplied by the number of dof per joint minus 3, ending here in one dof only as illustrated in Fig. 5 (left panel). A variation in any of the four joints ends up in a single possibility of a variation of the three others. If we consider the same closed chain in the sagittal plane, however, the number of joints is 7 (see right panel of Fig. 5, the chain is formed by the pelvis, the two legs, the feet, related with the following joints: hip, knees, ankles, toes). Here again, for a planar system, the mobility is equal to the number of joints minus 3, ending in 4 dof. Consequently, during the double-support phase the mechanical chain is more constrained in the medio-lateral plane, making the system more rigid, consequently reducing the mobility and making the system easier to control (Bernstein 1967; Vereijken et al. 1992).

If we consider now the single-support phase, in both the medio-lateral and sagittal planes the number of dof will be greater as the chain formed by the lower limbs is an open chain with less constraints, characterized by 2 and 7 dof, respectively.[1] Considering that mobility depends on the number of dof, a small number of dof reduces mobility. The double-support phase appears to induce less mobility, hence more stability than the single-support phase. Therefore, in both cases, in double-support and single-support phases, the number of dof is smaller in the medio-lateral plane.

Due to the feet geometrical position, disequilibrium in the medio-lateral plane will reduce the possibility of a fall as the projection of CoM falls necessarily within the base of support. In the sagittal plane, however, due to the 4 dof of the lower limbs and the small antero-posterior length of the base of support (foot length), a shift of CoP from one foot to the contralateral foot will induce a greater disequilibrium that will necessitate a greater level of control in order to overcome unbalance. The increase in the distance between CoM and CoP along the antero-posterior axis and the decrease along the medio-lateral axis that characterize the first weeks after onset of walking can be interpreted as a progressive shift of manoeuvrability from the medio-lateral plane to the sagittal plane, thereby decreasing the stiffness of the gait movement and increasing its smoothness. We speculate that the new walker learns to exploit the stable dynamics offered by the mechanical properties of stability of the body in the frontal plane (Winter et al. 1996), as relying on stability in the frontal plane allows the new walker to develop a better coupling between lateral and sagittal balance.

Early walking entails discovering synergies that respond to functional gait constraints that, in turn, affect muscular and bone morphological development as well as brain connectivities.

Based on a functional perspective of walking development that gives primacy to the mastery production of propulsive forces, we question the idea that maturation of the CNS may fundamentally explain the remarkable changes in walking parameters during early months of IW. The problem we face here is the following: How could the development of the nervous system generate changes such as those observed in the coordination of lowers limbs, and more broadly of the entire body, that involve a large number of degrees of freedom? This is even more so as young walkers adopt various forms of motor strategies involving different whole body coordination (McCollum et al. 1995; Snapp-Childs and Corbetta 2009) and eventually can be achieved with many different spatiotemporal patterns of muscle activation (Chiel et al. 2009). This is consistent with the principle of “abundance” of degrees of freedom that assumes that “the central nervous system does not search for a unique solution, but rather facilitates families of solutions that are equally able to solve the task” (Latash 2010: 643).

In agreement with Bernstein (1967), we see gait movements in young walkers to be “less dependent on these

[1] See Zatsiorsky (1998) Kinematics of human motion, section 2.2.1. Degrees of freedom. Mobility of kinematic chains (p. 106). When the kinematic (open) chain is described using the planar system, the number of dof is equal to $3(N - k) + \Sigma f_i$, where N is the number of links, k is the number of joints, and f is the number of dof in the ith joint; for a closed chain in the planar system, the number of dof is equal to $\Sigma f_i, -3$.

central impulses than on the external force field" (p. 21) and that "an unequivocal relationship between impulses and movements does not and cannot exist" (p. 20). We speculate that the gait movements observed in young walkers express an emergent coordination fitting the strategy developed by the young walker to produce a functional solution to satisfy the task constraints, that is the production of propulsive forces. With practice, the young walker explores and discovers task requirements, i.e. producing propulsive forces, by progressively taking advantage of the passive dynamics of their pendulum-like system at both the level of the entire body, i.e. the inverted pendulum model (Brenière et al. 1989; Ivanenko et al. 2004; Hallemans et al. 2006; Kuo 2007; Smith et al. 2007), and at the level of the lower limbs, i.e. the pendulum model of the swing legs (Kuo and Donelan, 2010; Looper et al. 2006). This mastery of passive mechanisms allows for more efficient and less energy-consuming movement.

Conclusion

To conclude, the scenario proposed here considers walking experience as driven by the search of an optimal solution to the primary necessity to produce propulsive forces that result in the shaping not only of muscular and kinematic patterns but also in the modelling or remodelling of morphological characters of the skeleton (Tardieu 1999; Tardieu et al. 2013) and bone structure (Ryan and Krovitz 2006). Along the same line, as well as the muscular patterns or the skeleton respond to gait practice, the neural system must develop connectivities that are sensitive to experience (Chiel et al. 2009; Holt et al. 2006; Teulier et al. 2012).

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