Human Motor Behavior

Prenatal Origin and Early Postnatal Development

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Abstract. The spontaneous movements of the newborn infant have a long prenatal history. From 8 weeks postmenstrual age onward the fetus moves in distinct motor patterns. There is no period of amorphic and random movements. The patterns are easily recognizable, as all of them can be seen after birth. The human neonate demonstrates a continuum of motor patterns from prenatal to early postnatal life. Around the 3rd month a major transformation of motor and sensory patterns occurs. This makes the infant more fit to meet the requirements of the extra-uterine environment. The developmental course of spontaneous movements during the first 20 weeks post-term age shows the emergence and disappearance of various movement patterns. The so-called *general movements* deserve special interest as they are in their altered quality a most reliable indicator of brain (dys)function with a specific prediction of later developing cerebral palsy.

Keywords: cerebral palsy, fetal movements, general movements, neurological assessment, spontaneous movements

The Motor Repertoire of the Fetus

Early studies on fetal movements were carried out on exteriorized fetuses. The survival was limited to a few minutes during which the fetus was stimulated with tactile stimuli (Hooker, 1952; Minkowski, 1928). These studies remained strictly in the tradition of reflexology and behaviorism, and it is not surprising that the endogenously generated spontaneous motor activity was totally overlooked or wrongly interpreted.

In the 1980s, the breakthrough in fetal movement studies came from the introduction of advanced ultrasound equipment. Heinz Prechtl and his group performed a series of longitudinal studies looking at the development of fetal movements from a developmental neurologist’s point of view. The following description is based on these findings (for reviews, see Prechtl, 1989a, 1997a, 2001).

The first movement to occur is sideward bending of the head. It is first seen at 7.5–8 weeks postmenstrual age (counted from the first day of the last menstruation before the amenorrhoea). At 9–10 weeks postmenstrual age, complex and generalized movements occur (de Vries, Visser, & Prechtl, 1982). These are the so-called *general movements* and the *startles*. Both include the whole body, but the general movements are slower and have a complex sequence of involved body parts, while the startle is a quick, phasic movement of all limbs, trunk, and neck. It should already be mentioned here that general movements became of extreme importance for the early diagnosis of brain dysfunction and the prediction of later neurological outcome (Einspieler, Prechtl, Bos, Ferrari, & Cioni, 2004).

Local and *isolated movements of one arm or leg* emerge only 1 week later, at 10–11 weeks, than the generalized movements (de Vries et al., 1982). It may be surmised that isolated movements are more difficult to produce by the very young nervous system than global motor activity. Traditionally, it is accepted that the early ontogenetic process goes from cranial to caudal. Although this was primarily based on the sensory system (stimulation experiments by Hooker, 1952), the motor system does not follow this rule. Isolated arm and isolated leg movements emerge at the same time, at 10 weeks. However, it is true that isolated arm movements occur more frequently than isolated leg movements, and this might have been overlooked in short-lasting recordings.

The next pattern to emerge around 10 weeks is the *hiccup*, caused by a mostly repetitive short contraction of the diaphragm. Such episodes of hiccups may last for several minutes. They can be so forceful that the whole fetus is passively moved in the amniotic cavity.

Around 11 weeks postmenstrual age the head of the fetus is becoming very mobile. *Head retroflexion*, even *head anteflexion*, and particularly *head rotations* are common events. Together with these head movements, arm movements may occur and produce *hand-face contacts* (de Vries et al., 1982). Most of the hand-face contacts are obviously accidental, and it is not at all likely that they are intentional.

Breathing movements emerge at 11–12 weeks and appear episodically. The rate of occurrence is related to the maternal glucose level (Mulder, Visser, Morssink, & de Vries, 1991). Hence, breathing movements are most easily observed after the mother had a meal. Breathing movements are an exception in this respect, while the occurrence of all other fetal movements is independent of the maternal glucose level.

A very interesting phenomenon in fetal motor develop-

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ment is the early emergence of *stretches* and *yawns* at 12 weeks. Both are complex movements and the most interesting aspect is their maintenance throughout the whole life without changing their form and pattern.

It is shortly after the 12th week that the fetus starts to drink amniotic fluid with rhythmical *sucking movements and swallowing*. At the end of pregnancy, the fetus drinks about 1 liter of fluid per 24 h.

A very important aspect of fetal movements is the change of fetal position *in utero*. Positional changes are frequent and may run up to 25 changes per hour during the first half of pregnancy (de Vries, Visser, & Prechtl, 1985). Later, these positional changes become rare but are still present. Several specific motor patterns are essential for these changes. Trunk rotations, general movements, and alternating leg movements, leading to a summersault if proper contact of the feet can be made with the uterine wall, all produce changes in the intrauterine position (Einspieler et al., 2004). These motor patterns are obviously an ontogenetic adaptation and have an effective function during prenatal life. The alternating leg movements outlive the duration of pregnancy and are known after birth as the newborn stepping (Prechtl, 2001).

Other movement patterns anticipate postnatal functions, such as breathing movements or eye movements. *Slow eye movements* emerge at 20 weeks and *rapid eye movements* at about 22 weeks (Birnholz, 1981; Bots, Nijhuis, Martin, & Prechtl 1981). These anticipating motor patterns are evidence for the primacy of the motor system. They develop early in ontogeny and are ready for their actual function after birth. In this line are also the *smiling movements*, which can be easily seen in the preterm infant and with ultrasound also *in utero* (Kurjak, Stanojevic, Azumendi, & Carrera, 2005). It may occur half-sided or bilateral. Despite this early onset, social smiling emerges around 6 weeks post-term age.

The majority of fetal movement patterns develop during the first half of pregnancy and continue not only until term (de Vries, Visser, & Prechtl, 1988; Roodenburg, Wladimiroff, van Es, & Prechtl, 1991), but also after birth (Prechtl, 1984).

The Continuity from Prenatal to Postnatal Life

There are hardly any changes in the form and pattern of the movements in the first weeks after birth, despite the profound changes in the environmental conditions (Prechtl, 1984). This is not unique to the human species (Forssberg, 1999). From studies of other vertebrates, we know that innate movement patterns are generated by central pattern generators (Grillner, 1999). Although hard to prove, it is likely that these innate fetal and infantile movements are generated by similar types of central pattern generators (Einspieler et al., 2004; Prechtl, 1997b).

After birth, a number of new functions are added. Prenatally, it was not possible to elicit vestibular responses in the fetus, when the mother had been adequately moved by the experimenter and the fetus simultaneously observed by ultrasound (Prechtl, 1997a). However, after birth vestibular responses such as vestibular-ocular response and the Moro response are clearly present.

The sensory trigger mechanism of otherwise spontaneous movement patterns becomes mandatory in the postnatal adaptation of the newborn infant (Prechtl, 2001). While the fetus drinks amniotic fluid whenever sucking movements occur, after birth sucking behavior needs to be triggered in the actual feeding situation. Hence, it is a matter of vital biological adaptation that sucking is elicited in the proper nursing situation initiated by the caregiver (Prechtl, 2001; Einspieler et al., 2004). Other examples are postnatal rooting (rhythmical head rotations in the fetus), breathing movements, and smiling movements.

New in the postnatal motor repertoire are functions depending on lung ventilation. Reflexes for protection of the airway such as sneezing and coughing, as well as the communication signal of crying, are only seen after birth, although a fetal homolog of crying has been described recently (Gingras, Mitchell, & Grattan, 2005).

By and large, there is an amazing continuation of the prenatal repertoire during the first 2 months post-term age (Prechtl, 1984). Needless to say, in the healthy preterm infant this continuation lasts until the same postmenstrual age as in infants born at term, that is, the corrected age for preterm birth.

Although psychologists often talk about the *competent newborn*, it is amazing how many neural functions are delayed in the human infant, compared to neonates of infrahuman primates, in particular with chimpanzees and other apes. There seems to be a very special delay in the ontogenetic developmental course in the human species.

The 3-Month Transformation of Neural Functions

Although there are vital adaptations occurring shortly after birth, there are few behavioral changes during the first 2 months post-term age. At about 8–10 weeks, however, many motor and sensory systems change their properties and make the infant more fit and adapted to the extrauterine environment (Prechtl, 1984, 1986).

At 3 months, the infant's muscle power increases and can more easily overcome the force of gravity, including proper head control. The body posture changes from body-oriented to a space-oriented control (Prechtl, 1989b). The sucking pattern changes from peristaltic tongue movements to a new pattern of sucking with open corners of the mouth (Iwayama & Eishima, 1997). The form of general movements lose gradually the writhing character and a new pattern of general movements emerge: the fidgety movements (Hopkins & Prechtl, 1984). Control of visual attention and binocular vision develop (Atkinson, 1984; Braddick & Atkinson, 1983). Social smiling and pleasure vocalization while looking toward the caregiver occur (van Wulfften-Palthe & Hopkins, 1984).

As far as it is known from studies on infrahuman primates, such a late adaptation to the extrauterine environment has not yet been reported. What could be the reason for this delay in the developmental course of so many neural functions in the human infant? The traditional idea of anthropologists was, first, the development of the upright body posture leading to an adaptation of the small pelvis, and, second, the later occurring increase in the brain size of the infant to be born. These all happened in the evolution of the hominids. If this concept is correct and the selective pressure had been concentrated on the small pelvis size and the enlarged brain, two things should have happened. In the first place, a clear sex-dimorphism of the pelvis size should have occurred; second, those infants with small brains would have been more successful in surviving. Both phenomena did not occur in the evolution of the hominids and, thus, can be refuted (Prechtl, 1986, 2001).

An alternative concept is based on allometric measurements of body size, brain size, basal metabolism, maternal-neonatal body weight relation, and longevity among primates. In this context, it became clear that the human pregnancy of 40 weeks is relatively short compared to other primates (Prechtl, 1986). This may not be too surprising as there are two factors specific for the human. The one is the relatively rapid brain growth of a differentiated brain, which puts a high demand on the energy metabolism of the maternal organism. The second point is the unique phenomenon among primates of subcutaneous white fat in the human. Obviously, as compensation for the loss of the fur during evolution, the thermoregulation became insured by this isolating white fat. It is in the order of 13% of the neonatal body weight and has to be produced by the maternal metabolism, but it is not existent in any of the infrahuman species. Similar to the human, neonate infrahuman primates have at birth 3% of the body weight brown fat for chemical thermoregulation. The production of the white subcutaneous fat is an additional burden on the energy metabolism of the human expectant mother. For this metabolic constraint, it can be conjectured that in the evolution of the hominids the duration of the gestation was not accordingly prolonged (Prechtl 1986, 2001; Einspieler et al., 2004).

Post-term Development of Spontaneous Movements

There exists a wealth of descriptions in the literature on reflex and response studies (e.g., Carmichael, 1946; Peiper, 1961). The first systematic description of the post-term development of the spontaneous movement repertoire was given by Hopkins & Prechtl (1984). The classification of the various movement patterns was as follows (Hopkins & Prechtl, 1984; Prechtl, 2001, Einspieler et al., 2004):

- *Wiggling-oscillating arm movements* (6–14 weeks post-term age): Irregular, oscillatory, waving-like movements; most noticeable in partially or fully extended arms, with a frequency of 2–3 Hz; small amplitude and moderate speed; should be clearly distinguished from tremulous movements, which are less smooth in appearance and have a more regular rhythm.
- *Swiping movements* (6–20 weeks post-term age): Ballistic-like movements with a sudden but fluid onset and smooth offset; can go in downward or upward direction; most noticeable in extended arms; but also in partially or fully extended legs; large amplitude and high speed.
- *Mutual manipulation of fingers* (emerging at 12 weeks post-term age): Both hands are brought together in the midline and the fingers of both hands repetitively touch, stroke or grasp each other.
- *Manipulation (fiddling) of clothing* (emerging at 12 weeks post-term age): The fingers of one or both hands repetitively touch, stroke or grasp some object or the clothing.
- *Reaching and touching* (emerging at 12 weeks post-term age): One or both arms extend to some object in the immediate environment. The fingers contact the surface of the object.
- *Legs lift* (emerging at 15 weeks post-term age): Both legs lift vertically upward; partial or full extension at the knees; hips are slightly tilted upward; one or both hands touch or grasp the knees; sometimes with anteflexion of the head.
- *Trunk rotation* (emerging at 12 weeks post-term age): As a result of the soles of the feet pushing down on the lying surface, one side of the hips is lifted and rotated.
- *Axial rolling* (emerging at 18 weeks post-term age): The whole body is turned from supine to prone lying in a movement started by the head. Sometimes the infant returns to prone lying.
- *General movements* (lasting until 20–25 weeks post-term age): At term age until about 6–9 weeks post-term age, they are called *writhing general movements*. Writhing movements are characterized by small to moderate amplitude and by slow to moderate speed. They may last from a few seconds to several minutes or longer. What is particular about them is the variable sequence of arm, leg, neck, and trunk movements. They wax and wane in intensity, force, and speed, and they have a gradual beginning and end. Rotations along the axis of the limbs and slight changes in the direction of movements make the movement fluent and elegant and create the impression of complexity and variability (Einspieler et al., 2004; Prechtl, 1990). At the time of the major transformation, a new type of general movements appears. They are called general movements of fidgety character. *Fidgety movements* are small movements of moderate speed, and variable acceleration of neck, trunk, and limbs in all

directions. They are continual in the awake infant, except during fussing and crying. They may be concurrent with other movements. Fidgety movements may be seen as early as 6 weeks but usually occur around 9 weeks and are present until 20–25 weeks, at which time intentional and antigravity movements occur and start to dominate (Prechtl et al., 1997).

General Movements Are a Window into the Brain

Studies on the relationship between documented brain pathology and changes in general movements have shown that the quantity of occurrence of general movements, and also of other spontaneous movements, is not altered (Bos et al., 1997; Ferrari, Cioni, & Prechtl, 1990; Prechtl & Nolte, 1984). However, infants with brain lesion move differently compared to infants without brain lesion. This view was supported by previous studies on impaired fetuses (e.g., Bekedam, Visser, de Vries, & Prechtl, 1985; Kainer, Prechtl, Engele, & Einspieler, 1997; Prechtl & Einspieler, 1997), and particularly by a study on anencephalic fetuses (Visser, Laurini, de Vries, & Prechtl, 1985). It became clear that malformations of the forebrain and the diencephalon change dramatically the expression of general movements into a kind of chaotic movement pattern. This was later confirmed on various forms of brain malformations after birth (Ferrari et al., 1997). From all these studies, it can be concluded that an intact brain is a prerequisite for the normal quality of general movements. Hence, general movements are a window into the brain integrity (for a review, see Einspieler & Prechtl, 2005).

What is particular about this finding is the fact that, with the qualitative assessment of general movements, a specific prediction of later development of cerebral palsy is possible (Einspieler, 2008; Prechtl et al., 1997). There are two patterns which reliably predict the later neurological outcome of cerebral palsy: first, a persistent pattern of cramped-synchronized general movements. These are abnormal general movements which appear rigid and lack the normal smooth and fluent character. All limb and trunk muscles contract and relax almost simultaneously (Einspieler, Prechtl, Ferrari, Cioni, & Bos, 1997; Ferrari et al., 1990). If this pattern exists over several weeks during preterm and term age, a cerebral palsy will develop at later age (Ferrari et al., 2002). The second predictor concerning the quality of general movements is the absence of fidgety movements (Prechtl et al., 1997). This has a sensitivity of 95% and a specificity of 96%, which has been recently confirmed in a study on more than 900 preterm infants (Romeo et al., 2007). Interestingly, infants with subsequent unilateral spastic cerebral palsy have bilaterally no fidgety movements (Cioni et al., 2000; Guzzetta et al., 2003). The first asymmetric sign, independent of the head position, is isolated finger or toe movements, so-called *segmental movements*, which are reduced or absent contra-lateral to the side of the lesion. This asymmetry occurs in preterm born infants from the 3rd month post-term age onward (Cioni et al., 2000). In term born infants with neonatal infarction, the asymmetry of segmental movements is already present during the 2nd month (Guzzetta et al., 2003). Also, infants who later develop dyskinetic cerebral palsy do not have fidgety movements. They display abnormal *arm movements in circles* with finger spreading. The abnormal unilateral or bilateral arm movements are monotonous, slow forward rotations from the shoulder (Einspieler et al., 2002). From 3 months onward, a lack of movements toward the midline, particularly foot-foot contact, is an additional specific sign of later dyskinetic cerebral palsy (Einspieler et al., 2002).

The absence of fidgety movements in all forms of cerebral palsy caused by different brain lesions indicates that intact cortico-spinal fibers, as well as the output from the basal ganglia and cerebellum, are necessary to generate normal fidgety movements (Einspieler et al., 2002, 2004). Interestingly, an absence of fidgety movements can also be observed in infants with genetic disorders, such as Rett's syndrome (Einspieler, Kerr, & Prechtl, 2005a). Those infants with the most severe phenotype had no fidgety movements at 3–4 months of life, when otherwise their development was considered to be more or less normal (Einspieler, Kerr, & Prechtl, 2005b).

There are some abnormal patterns of general movements, which are less predictive for the neurological development (Nakajima, Einspieler, Marschik, Bos, & Prechtl, 2006; Prechtl et al., 1997). Among them are abnormal fidgety movements, which are exaggerated in their amplitude and speed and appear jerky and monotonous (Prechtl et al., 1997). These abnormal fidgety movements have been discussed in the context of the development of minor neurological deficits, attention deficit hyperactivity disorder, and boisterous, disobedient behavior (Bos et al., 1999; Einspieler et al., 2007; Hadders-Algra & Groothuis, 1999). Also, infants with chronic hypoxic events have abnormal fidgety movements (Einspieler, 1994) and have an increased risk for complex minor neurological dysfunctions (Milioti & Einspieler, 2005). The latter have been discussed in children with a delayed language development (Marschik, Einspieler, Garzarolli, & Prechtl, 2007) and nonoptimal fidgety movements.

After Prechtl had discovered the existence of fidgety movements as an age-specific, distinct form of general movements, he speculated about the potential biological function of this transient movement pattern (Hopkins & Prechtl, 1984; Prechtl, 1997b). It might be conjectured that one of the ontogenetic adaptive functions of these small movements is optimal calibration of the proprioceptive system. This is supported by the fact that fidgety movements emerge at the 3-month transformation of neural functions (Prechtl, 1984), and precede visual hand regard, the onset of intentional reaching, and visually controlled manipulation of objects (Prechtl, 1997b). As many aspects of the adaptation to the extrauterine condition are not achieved before the 3rd month post-term age, the proprioceptive system is still tuned to the intrauterine condition. A recalibration of this sensory system is required in order to achieve proper control of subsequent fine motor activity (Einspieler et al., 2007; Prechtl, 1997***[a or b?]***). Similar observations were made in blind infants. Their fidgety movements are exaggerated in amplitude and jerky in character, and their presence lasts longer than in infants with vision. In fact, abnormal fidgety movements were observed until the post-term age of 8–10 months (Prechtl, Cioni, Einspieler, Bos, & Ferrari, 2001). In the latter study, the authors speculated that exaggerated fidgety movements might be indicative of an attempt to compensate poor integration of proprioception and vision.

The qualitative assessment of general movements is based on pattern recognition. The interobserver agreement is 89–93%, with an average κ of 0.88 (for a review, see Einspieler et al. 2004). These values were already achieved after 3–4 days extensive training (Valentin, Uhl, & Einspieler, 2005). In addition, it is of utmost importance that the intraindividual consistency is high. A recent study revealed κ values between 0.90 and 0.96 for intraindividual consistency (Mutlu, Einspieler, Marschik, & Livanelioglu, 2007).

The methodological breakthrough of the assessment of general movements lies in the fact that it predicts the development of neurological deficits, in particular of cerebral palsy, at a much earlier age than was previously possible. In addition, the qualitative assessment of general movements is totally nonintrusive, easily learned, and cost-effective. The great advantage of being able to detect the risk of later development of cerebral palsy so early is the possibility to install interventions long before pathological features of cerebral palsy develop. It is most unlikely that these interventions will prevent the development of cerebral palsy, but they can help to lessen the handicap and to prevent secondary defects such as contractures and other forms of immobility. The psychological support for parents and the maximal functional deployment and early adaptation of the impaired child are of crucial importance. In addition, it is of similar significance to select those infants with normal general movements despite being at-risk due to their history, but will have a normal neurological outcome.

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