
5 General Discussion

Human newborns pass through a period of motor maturation, which lasts much longer than that of non-human primates. A detailed study of this period allows unique insights into the organization and dynamics of motor development. Nowadays, motor development is considered as a model or even the source of higher cognitive development. The first motor activity of newborn infants are spontaneous movements of their body and limbs, which can be taken as an expression of intrinsic activity patterns. The emergence of higher level organizational patterns from interacting lower level components is a characteristic of cognitive development. According to this work, organizational principles of this spontaneous motor activity concern (1) the temporal patterning of the movement flow by four limb coordination into static configurations leading to the serialization into movement phrases (bouts) and elements, (2) the spatial patterning of the movement behavior into transient reference configurations on different time scales and (3) the emergence of qualitatively different dynamical regimes. In the following, these organizational principles are considered in respect to (i) underlying mechanisms of spontaneous neural activity, (ii) reflex pathways in the spinal cord and (iii) biomechanical properties of the organism. I conclude that neonate movements not only reflect specific neuronal activities, but that their biomechanical properties also belong to the nascent cognitive system and take part in the patterning of developing cognitive functions.

Temporal Pattern Formation: Bout Organization and Serialization

Spontaneous motor behavior of neonates emerged as sequences, which alternated between states of elevated activity and periods of quiescence. Analysis of the velocity trajectories of hands and feet revealed bouts of activity - termed movement phrases - that were separated by silent intervals. In turn, movement phrases consisted of movement elements, which were movements of the single limbs that occurred separately (1) or simultaneously (2,3 or 4 limbs together) and revealed the sequential nature of the movement behavior (chapter 3).

Bout organization – movement phrases and interphrase intervals

Bout organization of newborn motor behavior showed irregular time spans of movement phrases (bouts) and interphrase intervals. This is in agreement with studies on spontaneous leg movements: Thelen & Fisher [1982, 1983] analyzed the kinematic structure

of kicking movements and reported that successive leg movements often clustered together or occurred in bouts. In this study, it was demonstrated, that bout organization of leg movements was not separated from arm motility. Instead, bout organization comprised the whole four effectors system of the limbs and is comparable to spontaneous episodic embryonic motility of vertebrates:

Spontaneous episodic limb movements have been widely observed in embryonic vertebrates [cat: Windle & Griffin 1931, sheep: Barcroft & Baron 1939, chick: Hamburger & Balaban 1963, rat: Narayanan et al. 1971]. The underlying neuronal mechanisms were first studied in the chick, proposing that embryonic motility has neurogenic rather than myogenic origin: Extracellular recorded burst discharges within the spinal cord correlated well with motor nerve discharge or body movements [Ripley & Provine 1972]. The study of spontaneous movements in the absence of sensory and supraspinal inputs indicated autonomous generation of motor activity already in the embryonic spinal cord [Bekoff et al. 1975, Oppenheim et al. 1975]. In humans, leg movements have been observed in anencephalic fetuses [Peiper 1963, Visser et al. 1985] and early movements of humans have also been assumed to be governed by spinal networks [Forsberg 1985].

The question of interest is, how far bout organization in neonate limb movements expressed spontaneous neural activity and to what extent reflexive and biomechanical aspects were involved.

Spontaneous episodic activity is a common feature of developing circuits in neural systems as for example the hippocampus, retina and spinal cord [O'Donovan 1999 for review]. Developing spinal networks have been extensively studied in the chick and rat. In the following, findings from human neonatal movements are discussed with regard to results from these studies on spinal cord preparations of chicks and rats. These kinds of invasive studies of in vitro spinal cord preparations are impossible in humans, and spinal cord organization of chicks and rats is similar to that of higher mammals [Eide et al. 1982, Velumian 1984, Okada & Oppenheim 1985, O'Donovan 1986].

A large body of studies considers spontaneous episodic activity in the chick and rat spinal cord to be network driven [e.g. Bracci et al. 1996, O'Donovan & Chub 1997, O'Donovan et al. 1998, Wenner & O'Donovan 2001, Rozzo et al. 2002]. Episodic discharge that recurs periodically in intervals of several (2-8) minutes can be recorded from the ventral roots, muscle nerves or individual spinal inter- and motoneurons that are activated synchronously [e.g. O'Donovan 1989, Sernagor & O'Donovan 1991, O'Donovan et al. 1994, Sernagor et al. 1995]:

The origin of this self-organization of developing neural networks into periodic episodic behavior is associated with two major network characteristics [Feller 1999, O'Donovan 1999, Ben-Ari 2001]: (i) a comparatively high and predominantly excitatory synaptic connectivity and (ii) the

presence of a transient activity-dependent negative feedback that depresses network excitability following an episode of synchronization.

The capacity for spontaneous episodic activity is distributed along the entire rostrocaudal axis of the spinal cord and can be expressed in a single segment. Motoneuron activity is synchronized over several segments by propriospinal pathways within the ventrolateral white matter tracts and synaptic interaction within the grey matter [Ho & O'Donovan 1993]. It appears reasonable to assume that this synchronization of bursts throughout the spinal cord accounts for the observed synchronization of limb movements into bouts as observed in this work. Within this hypothesis, the participation of each limb would depend on the state of excitability of the respective interneurons and motoneuron pools.

Concerning onset and termination of bursts of activity, the duration of bursts and interburst intervals have been studied in respect to the investigation of the mechanisms participating in network depression. High correlations between preceding pauses and burst durations have been found in rat spinal cord preparations [Staley et al. 1998, Tabak et al. 2001, Rozzo et al. 2002], in cultured spinal cord slices [Tschertter et al. 2001] and dissociated spinal neurons [Keefer et al. 2001, Streit et al. 2001]. This relationship between durations of bursts and preceding pauses has been assigned to synaptic depression (presynaptic transmitter depletion) [Lev-Tov & Pinco 1991, Streit 1993].

Regarding onset and termination of limb movement activity of neonates in the present work, analysis of durations of movement phrases (bursts) and interphrase (interburst) intervals both revealed exponential distributions. This indicates irregular episodic activity that can not be due solely to an underlying mechanism of neuronal periodic activity as described for chick and rat spinal cord preparations. It rather speaks in favour of interplay between several individual mechanisms that are active on different time scales. Supraspinal influences are conceivable as well as biomechanical and reflexive mechanisms that are triggered via afferent muscle neurons and alter periodic neural burst activity. This idea is supported by findings from chick spinal cord activity that was less variable if recorded from the isolated cord than the activity occurring in ovo [Landmesser & O'Donovan 1984]: Burst episodes observed in ovo were generally irregular and variable. Thus, irregular and variable movement episodes in neonatal infants might result from spinal mechanisms that are in principle similar to those recorded in the embryonic chick or rat. These preparations indeed include muscle afferents, but obviously in such a way that they do not any more correspond to the physical properties of the intact body.

Traditionally, it has been presumed that motility is governed by central pattern generators (CPGs) and that afferent systems are not important for shaping movement patterns in fetal chicks

[Hamburger 1963, Oppenheim 1972, Narayanan & Malloy 1974]. More recently, it has been shown that proprioceptive input due to environmental variables can alter limb motility in the chick [Orosz et al. 1994, Bradley 1997] and limb coordination in fetal and neonatal animals [Bekoff & Trainer 1979, Stehouwer & Farel 1984, Fentress 1992]. Erratic elements in spontaneous movements are attributed to self-perturbing forces that are not compensated by reaction forces to stabilize posture [chick: Chambers et al., 1995].

‘Self-perturbing forces’ are an emergent property of biomechanics. The human body is a linked mechanical system consisting of a trunk and multisegmented limbs. Forces that are generated at any one segment by muscle contractions produce passive forces, which are not controlled by the nervous system. These inertial forces are transmitted from one segment to another. In skilled movements, linked segments are stabilized by muscle contraction against these motion dependent passive forces. For instance, if a muscle contraction at the shoulder is not counteracted at forearm and hand segments, uncontrolled reactions are created at these segments [Hollerbach & Flash 1982].

In unskilled movements, as with the spontaneous unsolicited movements of neonates studied in this work, passive forces generated from movements of one segment are incorporated and expressed in ongoing movements of other segments [Thelen & Spencer 1998]. These passive forces might account for deviations from neuronal periodic bursting in the spinal cord. Furthermore, reflex pathways and the transmission of passive forces by afferent fibers might contribute to the irregular aperiodic properties of the observed burst-interburst structure in neonatal movements of human infants.

Further clarification concerning similar mechanisms underlying intermittent burst activity of animal spinal cord preparations and human neonatal limb movements can be gained from the analyses of correlation relations between successive burst and interburst durations of the kinematic data of spontaneous movement activity of human neonates.

Serialization – movement elements

In the spontaneous motor behavior of neonates studied here, movement phrases consisted of movement elements, which comprised movements of single limbs that occurred separately (1) or simultaneously (2, 3 or 4 limbs together). The patterning of the movement behavior into movement elements showed that four single behavioral channels (arms and legs) were coordinated into one channel of behavior: a sequence of configurations (chapter 3).

Sequential behavior of newborn limb movements has been proposed for single limb behavior in separate studies on upper and lower extremities. Thelen & Fisher [1982, 1983] characterized newborn leg movements by kick cycles consisting of four phases: (1) a flexion phase, during which the leg was moved towards the trunk, (2) an intrakick pause in the flexed

position, (3) an extension movement, in which the leg moves away from the trunk and (4) an interkick interval in the extended position [Thelen & Fisher 1983]. For arm movements, movement units have also been proposed. On the basis of a correlation between velocity peaks and curvature valleys, arm movements have been segmented into movement units [Fetters & Todd 1987, Hofsten 1991]. In the present work it was shown that not only single limb behavior can be segmented in units, but also that arms and legs showed synchronous coordination of 'their individual units' into movement elements. The question of interest is, to what extent neuronal or biomechanical factors are involved in the synchronous coordination of the four extremities.

Electromyographic studies on kicking movements revealed antagonist co-activation to initiate the flexion phase and almost no muscle intervention during the initiation of the extension phase [Thelen & Fisher 1982, 1983, Okamoto et al. 2001]. Antagonist coactivation is a characteristic quality of immature and unskilled motor behavior [e.g. Mortier & Prechtel 1971, Gatev 1972, Schloon et al. 1976]. It is attributed to the predominance of excitatory activity from primary afferent fibers causing reciprocal excitation [Myklebust 1986, 1990, Myklebust et al. 1986, Lee et al. 1988, Leonard et al. 1988, O'Sullivan et al. 1991], which is in contrast to later reciprocal inhibition in the adult organism. Reciprocal excitation of antagonist motoneurons from muscle afferents in neonates is assumed to be segmental in origin and to be generated by reflex irradiation [Myklebust 1990, O'Sullivan et al. 1991, Myklebust & Gottlieb 1993]. Reflex irradiation is the phenomenon, if excitation from muscle spindle afferent neurons spreads to other muscles including antagonists (reciprocal excitation).

Neonatal arm and leg movement dynamics have been described to result from coactive phasic bursts that yield cyclical movements partly coupled to the lateral-symmetrical limb [Thelen et al. 1993, Jensen et al. 1994]. Unitary structuring across the legs was demonstrated in a study on bilateral coordination of leg movements, in which weights were added to one leg. The perturbation sensed in one leg showed systematic effects on the time-space behavior of both legs [Thelen et al. 1987c]. In the present work it is shown that movements of the limbs were also coupled to limbs of different anatomical positions (arms and legs). In a study on postural control during reaching it was found, that trunk and extending arm are dependently controlled [Thelen & Spencer, 1998]. This indicates, that limbs and trunk are not functioning independent of each other and might explain the observed coupling between ipsilateral and contralateral arm and leg pairs. The capacity to detect the dynamic state of the moving segments and to adapt the neuronal activation level has been shown to be inherent in the neuromuscular system in kicking studies [Thelen et al. 1987c]. To my knowledge, there are no studies on the influence of perturbations of the lower extremities on the behavior of the upper extremities or vice versa. The above findings of synchronous coordination of the four

extremities suggest that these principles also work in the four limb system of the human body. Coordination of the limbs might be due - at least partly - to reciprocal excitation and reflex irradiation not only between lateral-symmetrical but also between upper and lower limbs.

The impact of gravitational and biomechanical demands on motor behavior has been shown in a variety of studies including the striking demonstration of the 'reappearance of the stepping reflex' after stepping has disappeared, when legs were submerged in water [Thelen & Fisher, 1983]. Thelen et al. [1983] demonstrated alternating and synchronous interlimb coordination as well as single leg movements naturally falling out of the intrinsic dynamics of the body. Likewise, concerning arm movements, Thelen et al. [1993] have shown that synchronous interlimb coordination as well as single arm trajectories fall out of the intrinsic natural dynamics of the body.

What are intrinsic dynamics? Movement coordination demands heterogeneously assembling individual parts – bones, joints, muscle fibers, neurons, metabolic processes – with almost infinite combinatorial possibilities, into efficient effector movements. As a matter of fact, anatomical and dynamic properties of the body and the nature of the physical environment already set first constraints on the degrees of freedom: Limbs have mechanical and elastic properties and can function e.g. as mass spring systems [Kugler & Turvey 1987], in which kinetic and elastic energy alternate. In turn, muscles are intrinsically elastic, and afferent fibers are in place to detect and respond to muscle stretch [Schneider et al. 1990]. Afferent feedback detecting changes in skin and joints are also functional as well as neural networks in the spinal cord and brain. Metabolic processes limit energy supplies to move the limbs. All these characteristics constitute the body's intrinsic dynamics. From a dynamic perspective, movement coordination means that these dynamic properties are softly assembled. A softly assembled system occupies self-organizing qualities and behavioral patterns can emanate from the dynamics themselves.

Neonatal limb movement trajectories have been described to resemble dynamic characteristics generated by oscillating springs or pendulums. In dynamic terms, newborn bilateral and unilateral flapping of arms and leg kicking looked like limit cycle attractors [Thelen et al. 1993, Jensen et al. 1994]. Therefore, if both arms and legs are conceptualized as oscillating springs, synchronous coordination in movement elements, as observed in this work, becomes reasonable. The four springs, arms and legs, are biodynamically - biomechanically and neuronal via afferences - linked systems. However, this concept does not answer the question, to which extent spontaneous periodic neuronal activity is involved.

Getting back to spontaneous neural spinal cord activity, as outlined in the previous section, recurring burst episodes consist of periodic cycles of activity (1-2 seconds). Cyclicity can be recorded from motoneurons and interneurons but is not evident from muscle discharge [O'Donovan & Chub 1997]. Likewise the synchronization of bursting, axons running in the ventral and lateral

tracts are primarily mediating the synchronization of the cyclic activity within bursts between distinct motor pools of the lumbosacral cord.

In the present work, we detected temporal synchronization of the four limbs in movement elements that did not show regular rhythmicity comparable to rhythmic discharge observed in chick and rat spinal cord preparations. Recurrence plots showed transient rhythmical activity between recurring configurations, but these patterns were not stable and changed within movement episodes of several minutes.

Thelen & Fisher [1983] reported highly rhythmical leg movements evidenced by non-random periodicity of short movement sequences of 10 seconds. These authors suggested that these coordinative qualities arise from the low-dimensional properties of the moving system: equivalent to a spring that is stretched, stores energy and is released, kicking trajectories result from active flexor contraction that creates inertial torque, a change of sign and a (passive) extension [Thelen et al. 1987b].

From this perspective, transient rhythmical activity between recurring configurations was probably due to periods of rhythmical single limb behavior when the other limbs were at rest. Variable durations of movement elements showed that rhythmicity of a single limb was obviously not always synchronized with the rest of the system. Instead, irregular durations of movement elements support the idea that individual movement units of arms and legs were subject to mutual interaction via the biomechanical apparatus and reflex irradiation. Therefore, I conclude that synchronous coordination of the four limbs into movement elements was not an expression of the synchronization of rhythmical neuronal within burst activity in the spinal cord. Instead, I assume that the synchronous coordination of the entire four limb system revealed that passive forces are also acting between upper and lower limbs. This coordination can be understood as an intermittent dynamic or more flexible kind of coordination, termed by von Holst [1939/73] as relative coordination. Likewise, transient rhythmical patterns might be due to 'stable durations' of extensions and flexions of the legs [Thelen & Fisher 1982, 1983] - because of biomechanical constraints - and mutual reciprocal excitation.

These issues might be further investigated by the quantification of the durations of movement elements of the four limb system in comparison to the durations of movement units of the single limbs, respectively. Furthermore, electromyographic investigations over the entire four limb system as well as over longer time periods than previous studies might give new insights.

Spatial Pattern Formation – Reference Positions and Configurations

Pattern formation in newborn limb movements has been studied on the basis of single limb behavior (intralimb coordination) and of the assembly into four dimensional movement patterns (interlimb coordination). In this section, these findings are discussed in respect to earlier studies on human neonatal limb coordination and to pattern formation in network activity of animal spinal cord preparations, in which intralimb coordination has been studied by analysis of flexor and extensor activity and interlimb coordination by investigation of left/right coordination patterns.

Intralimb Coordination – Reference Positions

Concerning the spatial pattern formation of intralimb coordination, single limbs displayed preferred positions in correspondence to their biomechanical properties in the flexed state and the extended state. Both positions could act as reference (goal/target) or turning point positions (chapter 3). In general, limbs showed one preferred position for the upper extremities and two for the lower extremities. The function of the positions – if reference or turning position – switched between and within individual movement sequences.

Thus, on a lower time scale of individual movement elements, the upper extremities performed ‘cyclic’ movements starting at a reference position, moving in any one direction up to a turning point and then returning to the reference position. Lower extremities performed both cyclic movements from the flexed or extended position, and ‘half cycle’ movements between the flexed and extended state, that both acted as transient reference positions in the majority of cases.

Considering the lower extremities, these findings are somehow different to the analysis on kicking movements by Thelen & Fisher [1982, 1983]. Their analyses showed relatively stable durations of flexion and extension phases, short intrakick pauses and variable interkick intervals with the interkick intervals displaying a 10 times higher mean duration than the intrakick pauses [Thelen & Fisher 1982]. Since intrakick pauses correspond to the flexed position and interkick intervals to the extended one, these results implicate a ten times higher residence time of the legs in the extended position than in the flexed position. This is different to our results, according to which legs are with an at least comparable and often higher preference hold in the flexed position. The most likely explanation for this difference is the age of the studied infants that were two weeks old in the Thelen & Fisher studies and in average 3 days old in the present work. The relative higher magnitude of the flexed position is reasonable from the mechanical pressure of the limitations of intrauterine space that facilitates the flexed posture during the first days [Maekawa & Ochiai 1975]. Nevertheless, there is

disagreement, whether this flexor dominance is due to active or passive mechanisms [Schulte et al. 1968, Maekawa & Ochiai 1975, Schloon 1976].

From their results, Thelen & Fisher [1982, 1983] assumed kicking movements to consist of kick cycles originating in the extended position, having a short intrakick pause in the flexed position and returning to the extended position for an interkick interval. Our findings, however, suggest both the extended and flexed position to have the capability of acting as origin and target position for 'kick cycles'. That means, that two types of kick cycles were performed: originating from the flexed position and turning at the extended position, as well as originating in the extended position and turning in the flexed position - with reference positions being stable over certain time intervals on different time scales. Furthermore, simple flexions and extensions could act as self-contained movements from a start (flexed) to a goal (extended) position and vice versa. The question of interest here is, to what extent and how neuronal and biomechanical mechanisms are responsible for the function of the positions - origin/target or turning position - and switches between these functions. Looking at spinal mechanisms studied in the developing chick embryo, multiple pathways within the spinal network - guided by distinct transmitters - are in place:

Spontaneous motoneuron patterns change in a systematic way from an early totally coactive pattern of flexors and extensors to a later pattern of initial coactive bursts with a second burst that is delayed in flexor motoneurons as described above [O'Donovan & Landmesser 1987, O'Donovan & Chub 1997, Milner & Landmesser 1999]. These changes go along with changes in the responsible transmitter driving the bursting frequency of episodes from acetylcholin to glutamate. If cholinerg (in the early) or glutamatergic (in the later) transmission is blocked, the network exhibits considerable plasticity by recovering spontaneous bursting now driven by GABA in both cases [Chub & O'Donovan 1998, Milner & Landmesser 1999]. Similar principles have been found in rat spinal cord studies [Bracci et al. 1996, Rozzo et al. 2002].

Extrapolating these outcomes from animal studies to findings from movement behavior of neonates, different functions of preferred positions - goal/target position or turning point position - might be due to a variety of pathways within the spinal network, each guided by distinct transmitters. This assumption is supported by the identification of polyneuronal innervation as well as mono- and polysynaptic reflex pathways in human neonates [Myklebust & Gottlieb 1993, 1997]. Long-term changes between the function of reference positions - goal/target position or turning point position - might be due to activity dependent local network depression [Tabak et al. 2001] or activity dependent transmitter expression [Borodinsky et al. 2004] that favour individual pathways. Short-term changes might be due to mechanisms involved in changes of spinal reflex pathways [Myklebust & Gottlieb 1993, 1997]. The question is now, what mechanisms initiated the changes between the function of reference positions.

The outlined neuronal mechanisms work in concert with the biomechanical conditions of the body that both act on the physical apparatus and are transcribed into the spinal network via afferent muscle fibers. The movement outcome results from the composition of patterned EMG output and passive forces. The latter are produced by the length and resting conditions of the muscles, mechanical linkages between muscles and joint ligaments, the mass effects of the individual segments on each other and gravitational forces. These passive forces might not only exert influence within limbs but also, even though to a much lower extent, between limbs. Furthermore, they form a considerable portion of afferent feedback to the neuronal system. Thus, dynamics due to biomechanical properties of the body are incorporated into activity-dependent neuronal processes. Therefore, position, elasticity and inertia of the limbs exert mutual influence on each other both via biomechanical linkages of the physical system and activity-dependent neuronal mechanisms within the spinal network. I suggest, that the definition of reference positions and switches between them occurs in consequence of these biodynamical interactions of the limbs – including (to some extent biomechanically induced) activity dependent network depression and changes in transmitter expression that govern distinct pathways.

Interlimb coordination – Emergence of reference configurations

The analysis of interlimb coordination of the four limbs, arms and legs, revealed the sequential organization into movement elements along static configurations. The formation of configurations resulted from ‘relative synchronization’ of moving, turning and resting phases of individual limb movements. Configurations that displayed high recurrence rates and high occurrence time spans emerging in transient and variable time windows, were termed reference configurations (chapter 4).

Interlimb coordination has been studied in neonates concerning nonreaching movements of the arms [Goldfield & Michel 1986a,b, Corbetta & Thelen 1996] and infant leg patterns [Touwen 1976, Thelen & Fisher 1982, 1983, Thelen et al. 1983]. In these studies, shifting epochs of patterns of coordination have been reported:

For upper extremities, Corbetta & Thelen [1996] found fluctuating periods of predominantly uni- and bimanual coordination tendencies within the first year. The time course of periods of spontaneously uni- or bimanual coordination was different for individual infants. Furthermore, fluctuating periods with lateral biases in spontaneous arm movements were reported [Corbetta & Thelen 1998]. For lower extremities Thelen et al. [1983] found a relative high proportion of alternating leg movements in the newborn period, a shift to single leg kicking after the first month and a returning shift to predominantly symmetrical movements at 3 month. Therefore, in upper and lower extremities, limb specific coordination tendencies were apparent: Arm movements displayed fluctuations between symmetrical (bimanual) and asymmetrical (unimanual) movements, whereas

leg movements displayed periods of alternating, symmetrical and asymmetrical movements with predominance of alternating periods in the first month.

In regard to these findings of various transient coupling mechanisms between lateral-symmetrical limbs, reference configurations in neonatal limb movements composed of upper and lower limbs suggest that upper and lower extremities not only show coordination among themselves, i.e. lateral-symmetrical limbs, but also between arms and legs. Switches between emergent reference configurations might reflect switches in the coupling tendencies of arms and legs among themselves. Furthermore synchronization tendencies between upper and lower extremities suggest also coupling tendencies between limbs of anatomical distinct positions that might be of a similar nature to those observed in arms and legs separately. Coupling mechanisms between individual limbs (regardless of lateral-symmetrical extremities or other) might also be reflected in transient rhythmical activity between certain configurations as indicated from the recurrence plots. Precise investigation of these assumptions requires further studies that might be accomplished by e.g. pointwise transinformation (PTI) or related techniques.

The analysis of the relative distributions of reference configurations did not indicate evidence for predominant couplings of lateral-symmetrical limbs neither for synchronous nor alternating patterns. The only configurations that displayed a higher (but not significant) tendency of occurrence and recurrence were the completely symmetrical configurations 0000 (all four limbs proximal) and 1111 (all four limbs distant from the trunk).

Considering neuronal mechanisms, interlimb movement synchrony has been reported for all limb combinations in the rat fetus and has been assumed to be mediated spinally [Kleven et al. 2004]. Furthermore, Ho & O'Donovan [1993] reported that rostrocaudal synchronization of motoneuron activity is mediated by a propriospinal fiber system travelling in the ventrolateral white matter and synaptic interactions within the grey matter. Moreover, the rostral part generates more cycles than the caudal part and transection reduces the frequency in the caudal part from 8-9 to 2-3 cycles, indicating considerable interaction between the rostral and caudal parts of the spinal cord [Ho & O'Donovan 1993]. These findings provide a neuronal basis for the hypothesis that coordination of limb movements in human neonates comprises the whole four limb system. However, this neuronal interaction seems to be one-directional from rostral to caudal and implies that leg movements align with arm movements and not the other way round.

In search for underlying neuronal mechanisms of interlimb coordination a variety of studies on animals has been accomplished. In various animals, spontaneous interlimb coordination before

the onset of functional locomotion has long been shown. For example, bilateral coordinated wing movements in pre- and postnatal chicks [Provine 1980, 1981], alternation between lateral-symmetrical and ipsilateral pairs of legs in cat fetuses [Windle & Griffin, 1931] and ‘walking-like’ interlimb coordination in postnatal rat pups submerged in water [Bekoff & Trainer, 1979] have been reported. For the mechanisms that are responsible for the generation of rhythmic motoneural activity patterns, Grillner et al. [1991] proposed a single network for lower vertebrates that generates both rhythmic activity and alternation between left and right segmental pools by nesting excitation and reciprocal inhibition. Alternatively, Ho & O’Donovan [1993] suggested for the chick spinal cord separate neural mechanisms for rhythmogenesis and alternation.

The results obtained in this study on movement organization of neonates support the model by Ho & O’Donovan [1993], in which synchronous and alternating patterns potentially coexist and are obviously mediated by distinct transmitters. From this view, activity dependent transmitter expression can be responsible for switches between coupling modes and associated emerging reference configurations in this work. The hypothesis that afferent input is able to influence coupling modes is supported by a study in the rat fetus. Robinson [2005] showed, that kinaesthetic experience can alter coupling tendencies. Limb coordination was altered by the experience of physical linkages between two limbs with an interlimb yoke [Robinson 2005]. Interestingly, the present work demonstrated no preferences for configurations that are symmetrical toward lateral-symmetrical limbs as would be expected from natural linkages via bones, muscles, ligaments and so on. This means, that in neonates there is no functional dissociation between upper and lower extremities yet, and interlimb coordination comprises the whole four effector system equally. From a biomechanical perspective it is reasonable that postural stability is a prominent demand in the supine position and constitutes the driving force for an equally distributed four limb coordination.

Transitions between qualitatively distinct dynamical regimes

Recurrence plots of the movement behavior of neonates revealed dynamically distinct regimes that were indicated by pattern changes on different time scales (chapter 3). Changes in the texture of the RP were related to 1) the relative percentage of black and white recurrence points, 2) the presence or absence and size of black rectangles and 3) the presence or absence of repetitive characteristics of black block sizes or white distances between black clusters. Switches between some of these parameters could be determined statistically by recurrence quantification analyses and comparison to surrogate data. This procedure revealed switches between regimes that could be described by a linear stochastic process underlying the movement dynamics and by regimes characterized by nonlinear more complex behavior. However, transitions were not always strictly synchronous concerning individual parameters.

A similar phenomenon appeared by evaluation of the occurrence and recurrence of individual configurations - obtained by symbolic dynamics – along recorded movement time series and their relation to surrogate time series (chapter 4). Particular configurations showed transient sections of significantly higher or lower scores concerning occurrence or recurrence on different time scales compared to surrogate data. This indicated switches between regimes defined by individual or sets of reference configurations and regimes defined by the absence of any reference configuration both between and within recorded movement sequences. Again, alternation between the emergence and disappearance of reference configurations, did not always completely conform in respect to the parameters of occurrence and recurrence.

Transitions between observed distinct dynamical regimes indicate switches between different coordination patterns. This can be explained by separate interacting mechanisms that are responsible for the generation of spontaneous movement expression. Considering the neuronal basis, interacting processes have been described. The two main mechanisms are spontaneous spinal network driven activity and afferent feedback mechanisms from muscle activity states. The latter incorporate biomechanical properties of the body including passive intersegmental forces and environmental forces like gravity. Spontaneous network activity includes features like neuronal growth and synapse formation, coupling via gap junctions and transmitter mediated interaction, activity dependent changes in network connectivity and conductances and supraspinal modulation, yielding tremendous plasticity.

Transitions between linear and nonlinear regimes revealed by recurrence plots

For switches between linear and nonlinear regimes I suggest the following hypothesis: For linear epochs, predominance of reflexive signals, including mediation of biomechanical properties, is conceivable. For nonlinear segments, prevalence of spontaneous network activity generating the motor activity can be assumed.

Generally, limb kinematics as well as interactions among neurons and neuromuscular interaction are characterized by nonlinearities. However, biomechanics can be described to a large extent by linear proportionalities. This speaks in favour of a relatively large scope of involvement of biomechanical interactions in linear sections. Linear principles have indeed been found in the motor system of lower vertebrates and humans [Mussa-Ivaldi et al. 1994, Gottlieb et al. 1996, Zaal et al. 1999].

Linear vector summation has been suggested as a property of muscle activation by the spinal cord in the context of findings of linear combinations of motor primitives in the frog [Mussa-Ivaldi et al. 1994]. In humans, a linear relation between elbow muscle torque and shoulder muscle torque has been reported for adults in natural pointing movements in the sagittal plane [Gottlieb et al.

1996] and for infants learning to reach [Zaal et al. 1999]. In adults, the linearity principle was lost when people were asked to use a different hand path than the natural comfortable one. Straight reaching paths are not naturally chosen [Atkeson & Hollerbach 1985] and were not associated with linear joint torques [Gottlieb et al. 1996]. Zaal et al. [1999] proposed the principle of linear synergy as a ‘fundamental property of the human neuromotor system from early in life’ (p. 257). The synergy is maintained across the transition from prereaching to reaching – in spite of the recruitment of different sets of muscles - and is suggested as a natural principle for controlling degrees of freedom [Spencer & Thelen 1996].

In this view, it is conceivable that newborn unsolicited movements obey to some extent the natural comfort principle and that this linearity principle is expressed in the kinematic pattern formation. Therefore, observed linear sections in neonatal limb movements might be attributable to predominantly reflexive signal transduction pathways that relay biomechanical dynamics of the body and passive forces within the physical apparatus. By continuously re-exciting the ‘recovering’ network excitability that is depressed from the preceding burst, afferent excitation of motoneurons might balance extreme burst and interburst activity. This hypothesis, however, requires certain points of interaction, e.g. mutual excitability between the two mechanisms. More clarity on this issue might be gained by analysis of further kinematic parameters or by direct investigation on a myographical or neurophysiological level.

Nonlinear sections in newborn spontaneous movements appeared both above the 0.09 quantil and below the 0.01 quantil of the surrogate time series. RQA parameters were mainly sensitive to occurrence, recurrence and the sizes of block clusters that correspond to periods of quiescence or time spans of maintenance in a configuration. This indicates, that these parameters detected the presence (above 0.09 quantil) or absence (below 0.01 quantil) of significant durations of interburst/ interphrase intervals in a configuration.

Nonlinear segments due to the presence of block clusters can be plausibly attributed to prevalent intrinsic network activity, in which periods of quiescence reflect activity dependent refractoriness of network excitability and correspond to the presence of significant long interburst durations in repetitive configurations.

Nonlinear sections by reason of the absence of black clusters indicate that interburst intervals are short and occur in varying configurations (in contrast to repetitive), which implies a low degree of pattern formation. This might be due to a coequal interaction between the two neuronal processes of endogenous activity and activity due to reflex pathways and biodynamical passive forces. This suggestion, however, postulates different signal transduction for the two neural processes in terms of independent refractory mechanisms as

well as the ability for interaction between intrinsic and reactive mechanisms. This hypothesis is supported by studies of embryonic rat motoneuron activity indicating that distinct transmitters mediate spontaneous burst activity and developing spinal reflexes (Nishimaru et al., 1996).

The assumption of a dynamic interplay between spontaneous and reflexive neuronal signals is also in agreement with slight disparities in the indication of transitions between linear and nonlinear epochs of individual RQA parameters, also. Individual parameters are probably sensitive to different aspects of the dynamics. The diversities again might reflect intersecting transmitter mediated pathways conducting parallel signals originating from various sources – reflexive and spontaneous - via identical neurons, but communicated by different transmitters. Completely separate pathways for reflexive and spontaneous signal transduction would expect synchronous transitions between linear and nonlinear regimes of all parameters and disagree with the detected discrepancies.

Transitions between the presence and absence of reference configurations

Transformation of the kinematic time series into symbolic strings of 16 configurations revealed switches between regimes defined by individual reference configurations, sets of reference configurations or the absence of any reference configuration, both between and within recorded movement sequences (chapter 4). If switches between reference configurations are explained by transient coupling mechanisms between the limbs, as hypothesized above, the absence of reference configurations should be due to the absence of coupling mechanisms or the interaction of several coexistent coordination tendencies. The existence of coupling mechanisms can be inferred from findings of transient modes of interlimb coordination between lateral-symmetrical extremities in spontaneous human neonatal arm- and leg movements [arms: Corbetta & Thelen 1996, legs: Thelen et al. 1983]. From our findings, there is no evidence, that interlimb coordination tendencies are restricted to or prevalent within lateral-symmetrical limbs, since no reference configuration revealed significant deviations from a uniform distribution. This means that in spite of clear differences in the activity profiles obtained from single limb behavior between arms and legs, the distribution of resulting configurations is quite uniform. However, it might be that asymmetrically distributed coupling mechanisms transform asymmetrical limb dynamics of arms and legs into an even distribution of configurations. In the mature cognitive system, interlimb coordination appears to be represented effector-independent:

Kelso & Jeka [1992] studied the dynamics of relative phasing patterns of four limb coordination patterns and found relative phase as an order parameter. Jeka et al. [1993] investigated

and modelled switching behavior between 8 four-limb coordination patterns and found four attracting circles, if lateral-symmetrical limbs are coupled sufficiently stronger than arms and legs. Based on investigations of reaction time measures of multilimb coordination, Swinnen et al. [1995] suggested that fundamental different processes are responsible for the control of upper and lower extremities. Different mechanisms for single limb control do not preclude abstract representations of coordination patterns that are effector independent [Bernstein 1967]. Kelso & Zanone [2002] found evidence for spontaneous transfer of attractive states of interlimb coordination from arms to legs and vice versa.

In reference to these findings and the question what is represented, it might be interesting to quantify transitions between configurations and phase relations between the movements of the single limbs in respect to coordination tendencies between lateral-symmetrical limbs and between upper and lower extremities. Furthermore, qualitative change between different coordination patterns can be used for the identification of the order parameters (for four-limb patterns, e.g. a set of three relative phases) that represent the system's coordinative state.

Changes between periods defined by distinct reference configurations or the absence of reference configurations indicates switches between distinct coordinations patterns of the limbs and also of biomechanical and neuronal mechanisms. Regarding the mechanistic origin of periods characterized by the presence or absence of reference configurations, I hypothesize the following: The absence of reference configurations indicates a prevalence of reflexive activity and the presence of reference configurations indicates the predominance of biomechanical properties. I do not assume that the effects of spontaneous neural activity are observable from this analysis because of the method of symbolic dynamics: during the transformation into symbolic strings details of the trajectories, i.e. higher oscillations due to spontaneous neural activity, are lost. A second reason is the assumption that reference configurations arose from repetitive behavior of single limbs and/or coupling mechanisms between (two) single limbs. This idea precludes spontaneous neural activity that generally spreads over the entire spinal cord involving all four limbs [Ho & O'Donovan, 1993].

The presence of a reference configuration implies a configuration that repeatedly attracts the system. Such a configuration must have some kind of positive effect on the organism. Movement of a limb in the supine position demands balancing the body with passive forces within the body and with gravity. To maintain balance, the forces of the movement of one limb might be compensated by the movement of another limb. If this coordination induces a stable situation for the organism in the gravitational field it is likely to act as an attractor of the system. This attractor becomes apparent as a reference configuration

and also informative to the neural network via afferent fibers. Within the neuronal pathways this might lead to activity-dependent molecular (synaptic or transmitter) changes that in turn affect efferent output that either enhances the recurrence to a reference configuration or counteracts it. The latter induces a qualitative change to another reference configuration or the absence of a reference configuration.

The absence of reference configurations indicates periods, in which there are no recurrences to certain configurations and implies more independent movement behavior of the four single limbs. Short-term coordination of single movements of certain limbs that is not attracted by a certain configuration, can be attributed to reflexive mechanisms, antagonist coactivation and reflex irradiation, as outlined above.

Discussion of these mechanisms requires further research into the dynamics of hypothesized coupling between limb movements. This might be accomplished, for example, by the analysis of phase relations between maxima and minima of distance trajectories of the four limbs. Furthermore, the precise evaluation of the behavior of different parameters both of the recurrence plots (RR, DET, MDL, ENTR, LAM, TT) and those of the symbolic dynamics (occurrence, recurrence) might further elucidate interactions between biomechanical and neuronal properties and processes in the early human cognitive system.

Conclusions

The question of interest here is what the functional relevance of limb movement activity is in the neonatal period for the organism.

Spontaneous motoneuron activity is well known to be involved in path finding decisions of motoneurons [Hanson & Landmesser 2004, 2006], in initial synaptogenesis and intramuscular motoneuron branching [Ding et al. 1983, Dahm & Landmesser 1991, Milner & Landmesser 1999], in the later refinement of synaptic connections [O'Brien et al. 1978, Thompson 1985, Greensmith & Vrbova 1991], in the survival of motoneurons [Pittman & Oppenheim 1978] and in the development of muscles, bones and joints [Toutant et al. 1979, Persson 1983, Hall & Herring 1990, Jarvis et al 1996].

The frequency and pattern of neuronal spike trains can have considerable influence on the development of muscles [Calvo et al. 1996, Jarvis et al. 1996] and neurons [Fields & Itoh 1996, Li et al. 1996]. It has been shown that distinct spike patterns encode distinct neuronal processes ranging from neurite extension to transmitter expression [Gu & Spitzer 1997, Moody & Bosma 2005]. From this view, afferent spike patterns of muscle nerves that result from the biomechanical coherences of the body shape the neuromuscular system. Therefore, bodily dynamics are laid down via spatiotemporally patterned afferent spike trains in the

synaptic connectivity of the spinal cord. Together with information on bodily dimensions, organizational principles of the body parts are also communicated from the physical apparatus to the nervous system. One principle that is transferred is the synchronization of activity patterns from parallel channels (arms and legs) that yielded a serialization into one higher dimensional channel (configurations). The second principle is the temporal segmentation into nested units (movement phrases consisting of movement elements). The third principle is the emergence of transient attractors (reference configurations). The fourth principle is the bistability between qualitatively different dynamic regimes: (a) between active and silent, (b) between linear and nonlinear and (c) between the presence and absence of attractors (reference configurations).

Mechanisms plausible for the encoding of physical dynamics and resulting organizational principles in afferent signals might involve Hebbian or spike-timing-dependent competitive interactions between proprioceptive afferents as known from visual afferents in the visual system [Hebb 1949, Zhang et al. 1998, Ruthazer & Cline 2004, Hanson & Landmesser 2006]. This afferent activity possibly interacts with ongoing spontaneous network activity in the spinal cord. Resulting interferences might be communicated via early spinocortical connections [Eyre et al. 2000] to higher brain centres. In support of this hypothesis are findings of similar organizational principles in motor based cognitive functions, e.g. hierarchical organization in human speech [Todt 2004] and home base behavior in rats [Eilam & Golani 1989].

Traditionally, the function of spontaneous limb movements of embryonic and neonatal animals and humans has been discussed as precursors to adult motor patterns like locomotion [Bekoff & Trainer 1979, Bekoff & Lau 1980, Thelen et al. 1981, Thelen & Fisher 1982, Thelen 1986] or reaching [Corbetta & Thelen 1996]. The results in this work do not show evidence that predominant neural pattern generating circuitries are already established in the neonatal stage as proposed in the idea of central pattern generators (CPGs) [Grillner 1991]. The structuring of the movement flow along configurations that are defined by flexed and extended positions can be explained to a large extent by the biomechanical properties of the limbs. Furthermore, the uniform distribution of reference configurations does not indicate any preferences of interlimb coordination that can be ascribed to pre-wired neuronal pathways. The results in this study support the argumentation that movement of the limbs are “as much a product of the mass, stiffness, and inertial properties of the limbs as of central neural processes” [Thelen et al. 1984, p.479, Kelso et al. 1980, Kugler et al. 1980, Lestienne 1979]. The central neural processes appear to be highly flexible and switches between

reference configurations might be attributed to – biomechanically induced - activity-dependent transmitter changes. The latter have been described in various studies [e.g. Bell et al. 1997, Magee & Johnston 1997, Markram et al. 1997, Borodinsky et al. 2004, Dan & Poo 2004]. Rather, spontaneous limb movements of neonates might function in channelling neural pattern generating circuits that are appropriate for later aim-specific movements like locomotion and reaching by informing the nervous system about physical and dynamical coherences and interplays of the individual body parts. Reference configurations and switches between them reflect ‘CPG-islands’ that emerge in the process of exploration and provide afferent activity patterns involved in synaptic refinement.

With a dynamical perspective on the results of this work, organizational principles emerging in the physical parts of the motor system are part of the cognitive system that encompasses the nervous system the physical apparatus and the environment [Gelder 1995, 1998]. Bernstein [1967] already understood the motor system as a dynamical system:

The term dynamical refers to the most abstract and simplest descriptions of the formation of movement generated by a system. A dynamical perspective is low-dimensional and aims by abstraction of the form of motion at the discovery of regularities intrinsic to the system. A central hypothesis in this context is that joints and muscles never function in isolation. Instead, the entire system responds as a whole to changes in each single component [Bernstein, 1967]. Furthermore, Bernstein realized that the final movement is the ensemble result of muscular and nonmuscular forces, comprising inertial and reactive forces from the dynamically linked moving body parts.

From a dynamic perspective of the cognitive system, self organization of the physical apparatus is regarded as a process that is continuous with higher mental processes [Thelen 2000]. The description of principles of organization of neonatal limb kinematics in a dynamic terminology in this work reveals principles that show continuity with higher cognitive functions: (1) multiple stable regions in phase space allow for optimal adaptability, (2) the freeing and freezing of degrees of freedom facilitate learning and (3) the recurrence of the same principles in different contextual frames allows for abstraction. Therefore, I would like to offer the results of this study to serve as a contribution to the idea of an embodied cognitive system that is perfectly centralized by developmental psychologist Esther Thelen:

“To say that cognition is embodied means that it arises from bodily interactions with the world. From this point of view, cognition depends on the kinds of experiences that come from having a body with particular perceptual and motor capacities that are inseparably linked and that together form the matrix within which memory, emotion, language, and all other aspects of life are meshed.” [Thelen et al. 2001, p.1].