3 Hierarchical Organization of a Reference System in newborn spontaneous Movements

Abstract

In this paper, we studied spontaneous newborn movements regarding the coordination of the four limbs, arms and legs, from a dynamic perspective. We used the method of Recurrence plots to analyze the kinematic data from audiovisual recordings of neonates. We identified temporal and spatial synchronization of the four limbs that resulted in high recurrence patterns of biomechanical reference configurations. Furthermore, we identified transitions between linear and nonlinear epochs in the movement behavior of newborns on different time scales by means of recurrence quantification analysis. Results are discussed in the context of the concept of a structural hierarchy, in which different time scales correspond to hierarchical levels of organization.

Introduction

Spontaneous motor activity is a ubiquitous feature of fetal and infant behavior. Spontaneous behavioral phenomena of organisms at all levels – from ion channel currents to the search patterns of animals to reaction times generated by subjects in experimental psychology – display the impression of irregularity and disorganization. Likewise, fetal and postnatal spontaneous behavior reflects the spontaneous irregular patterns of neural activity that underlie cognition and behavior [Anderson 2000, Robertson et al. 2001].

Motor development is at the center of early human development and both reflects and affects all its different aspects, including perception, planning and motivation [Thelen 2000, Hofsten 2004]. Although the motor behavior of neonates in general appears random, successive movements of individual limbs often cluster together or occur in bouts [Thelen & Fisher 1982]. Bouts of spontaneous activity, such as limb movements, exhibit self-similar bursting, which is reminiscent of the burst-within-burst characteristics of brain activity. Although the entire meaning of these findings is not yet clear, bout organization appears to enhance neural-motor synchronization during development [Robinson et al. 2000, Robertson et al. 2001, Khazipov et al. 2004].

There are many examples, in which actions of a neonate show some elements of coordination: various muscle groups work cooperatively rather than as independent elements. These include the newborn primitive reflexes such as the Moro, grasp, palmar, plantar and asymmetric tonic neck reflexes [e.g. Barnes et al. 1978, Capute et al. 1978, Meer et al. 1995, Bartlett [1997], functional actions such as rooting, sucking, and swallowing [e.g. Crook 1979, Rochat & Hespos 1997, Craig & Lee 1999], hand-mouth contact [e.g. Korner & Beason 1972, Takaya et al. 2003], eye-hand coordination [Hofsten 1982, Meer 1997], spontaneous arm movements and reaching [e.g. Hofsten 1982, Corbetta & Thelen 1996, Thelen & Spencer 1998, Zaal et al. 1999] and the coordination of leg movements in spontaneous kicking and adaptive dynamics of movement patterns [e.g. Thelen & Fisher 1982, 1983, Thelen et al. 1987a,c, Jensen et al. 1994, Angulo-Kinzler et al. 2002]. In contrast to reflexes, spontaneous newborn movements are not elicited by external stimuli, but instead, are pointing to intrinsic activity patterns of the nervous system. Therefore, the coordination of these spontaneous movements is likely to give insights into basic principles of organization of the intrinsic dynamics of the cognitive system and the interaction between body and mind.

In our study, we applied a dynamic systems approach to analyze the movement behavior of the four single limbs and their organization into overall movement patterns. The dynamic systems perspective regards the cognitive system as a dynamical system, whose processes unfold in the interaction of a changing environment, body (active and passive biomechanical apparatus) and nervous system. The nervous system is regarded as part of an embodied system, in which cognitive processes are continuously coevolving with all other aspects of the world [e.g. Port & Gelder 1995, Gelder 1998, Newell et al. 2001, Thelen 2000). The fundamental idea of dynamical systems theory consists in characterizing the state of a system at a certain time by a set of variables (e.g. in our case, we consider a set of 4 variables, namely, the positions of the 4 limbs). This set of variables forms a vector, which changes with time (the positions of the limbs depends on time). Hence, the evolution with time of the vector, characterizing the state of the system, describes a trajectory in a geometrical space, which is called phase or state space. If the system is dissipative, i.e. if the energy of the system is dissipated, e.g. in form of heat, the trajectory of the system is attracted to a certain region of the state space. This region of the state space is called attractor. Some examples of attractors are a fixed point (the state of the system stays fixed), a closed trajectory (the state of the system is periodic) and a strange attractor, i.e. a bounded region of state space with fractal dimension (usually the system would then be chaotic).

In a previous study, we also used symbolic dynamics to analyze the dynamics of newborn limb movements. There, we computed the cumulative time and the duration of staying in a certain configuration as well as the frequency and intervals of recurrence to a certain configuration, and suggested a system of reference configurations, in which the system can settle and start new movements [Aßmann et al. 2006]. Frames of reference in the dynamic behavior were given by limb/body positions which alternated with special movements, and seemed to be both the origin and the target of each movement. From this perspective, newborn movements appeared as a heterotype pattern series that displayed intermittency on different levels of observation and can be understood within the concept of a structural hierarchy. In turn, this concept has been successfully used for research on various kinds of behaviors and for the structure of spoken language as well [Todt 1986, 2004]. In a top-down direction, the latter can be subdivided, for example, into the following structural levels: (a) sequence of sentences, (b) a single sentence = a sequence of words, (c) a single word = a sequence of syllables. Each of these levels is distinguished by specific rules of unit combination [Hultsch et al. 1999]. Accordingly, we have subdivided the intermittent stream of newborn motor behavior into patterns of different structural complexity and examined whether and how far the behavioral accomplishments of newborns could be explained by a system of different hierarchy levels [Todt & Hultsch 1998, Hultsch et al. 1999]. Core questions for the investigation of pattern organization were, e.g. 'Which are the most basal patterns or units?', and 'How are these organized into patterns in order to form a hierarchically higher level?'.

To answer such questions, we first analyzed the movement behavior of the single limbs and then applied recurrence plots [Eckmann et al. 1987, Ott 1993, Marwan et al. 2007], and extended recurrence quantification analyses (RQA) [Marwan et al. 2002, 2007, Webber & Zbilut 1994, Zbilut & Webber 1992] to investigate the overall movement patterns. These methods are mathematical tools based on the dynamical systems approach and have been used to study a wide range of biological systems, e.g. neuronal spike trains [Kaluzny & Tarnecki 1993], breathing rhythms [Webber & Zbilut 1994], cardiology [Marwan et al. 2002], protein sequences [Manetti et al. 1999, Giuliani et al. 2000], electroencephalographic activity [Thomasson et al. 2001, Marwan & Meinke 2004, Acharya et al. 2005] and electromyographic data [Webber et al. 1995].

Taga et al., [1999] assessed the chaotic dynamics of general movements of young infants [Prechtl & Hopkins 1986] by the method of nonlinear prediction [Sugihara & May 1990] and found evidence that spontaneous movements of one to four month old infants were generated by chaotic dynamics [Taga et al. 1999, Taga 2000]. Our findings indicate that the spontaneous movements of neonates are characterized by intermittency and state changes between linear and nonlinear epochs that can be understood in terms of hierarchical organization. Describing the movement behavior of neonates in a dynamic terminology, used in a wide field of research including the neurosciences, provides a common language to identify similarities and differences in this case between biomechanics and brain dynamics.

Methods

Subjects

Subjects were six neonates, three boys and three girls. Two subjects, children 2 and 3, were dizygotic twins. They were all healthy, normal, full-term infants, with Apgar scores of 8 or more and without medical problems during their first days of life. Their gestagational ages ranged from 37 to 39 weeks and their birth weights from 2,040 to 3,360 grams. At the time of observation, the ages of the infants ranged from 1 to 10 days (mean age = 3.2 days).

Procedure

The design of these observations was a frame-by-frame movement microanalysis using videotape recording. Kinematic data collection used video recording with three synchronized cameras (50 Hz) that focussed into a space, which had been calibrated with a calibration frame. Infants were undressed and allowed to move spontaneously in the supine position for 20 minutes. There were no specific stimuli presented nor was the spontaneous posture of the infants controlled.

Videotape selection

For kinematic data analyses, we chose videotapes from each of the six infants between 5 and 20 minutes from 2-3 different days. Restrictions were that the movement episodes showed continuous motor activity without resting or crying intervals longer than 20 seconds, so that a total of 15 movement series was analyzed.

Kinematic data

Movement kinematics were analyzed with the *Ariel Performance Analysis System* (APAS). Every 12 frames, the 2- dimensional positions of movement relevant joints were tracked by a mouse click on the screen in three camera perspectives. The APAS software allows to compute a 3-dimensional picture by triangulation from multiple two-dimensional frames. Movement relevant joints were: shoulders, elbows, hands, hips, knees and feet. Joint angles for shoulders, elbows, hips and knees were calculated from the coordinate data. Since joint angle displacement of elbows and shoulders of one arm and those of hips and knees of the same leg displayed a correlation of 0.8 (data not shown), the movements of each limb were captured by the displacement of one angle. Arms were defined by elbow angles; legs by knee angles.

Recurrence plot analyses

The method of recurrence plots (RPs) is a mathematical tool belonging to the dynamic systems approach. A dynamic system is a system, whose state changes in time. The state of the system at a certain time is given by a set of n variables $x_1, x_{2, \dots,} x_n$. To illustrate this idea, we might think of the "state" of a pendulum. Certainly, the position of the pendulum, i.e. the angle determines its state. (The position could be denoted by x_1). However, in this case, the angle alone is not enough, as can be seen, if we consider a photograph of the pendulum. We then know its position but we do not know in which direction it swings. Only if we also know its velocity, we can describe its state completely, in the sense that we can predict its position forever. (The velocity could be denoted by x_2). Hence, these two variables are sufficient to characterize the state of the pendulum and the set, which describes the state, contains $n = 2$ variables. These so-called state-variables can be measured in dependence on time and are, in general, real numbers. For convenience, this whole set can then be written in form of a vector $\mathbf{x}_i = (x_1(i), x_2(i), ..., x_n(i))^{\mathbf{T}}$. The dynamical behavior of the system is given by the change of $\mathbf{x}_i$ in time. Changes in the overall state of the system correspond to changes in this set of n variables, which uniquely describes the system. These n variables are the coordinates in a geometrical space - the entirety of overall states, the system can be in, and is called state space, commonly referred to as its phase space. (In the case of the pendulum, the state space is said to be 2-dimensional as two variables determine the state.) The part of the phase space, to which the trajectory of the dynamical system is typically attracted, is called attracting set or attractor. A fundamental property of dynamical systems is the recurrence of the trajectory to or near to former states of the system.

Recurrence plots (RP) are a method to visualize the time dependent behavior of a dynamical system, which is represented as a trajectory $\mathbf{x}_i \in \mathbf{R}^n$ $(i = 1, \dots, N)$ in an n-dimensional vector space [Eckmann et al. 1987, Marwan et al. 2007]. It represents the recurrence of the trajectory in phase space to a certain state, which is a fundamental property of dynamical systems [Ott, 1993; Argyris et al., 1994]. In mathematical terms, the main step of this visualization is the calculation of the NxN matrix,

$$\mathbf{R}_{i,j}: = \Theta\ (\varepsilon - \|\ x_i - x_j \|), \quad i,j = 1, 2\ ..., N,$$

where N is the number of measured points $\mathbf{x}_i$, ε is a cut off distance, $\|\cdot\|$ is the maximum norm, and $\Theta(\cdot)$ is the Heaviside function. The cut-off distance ε is fixed and defines a sphere that is centred at $\mathbf{x}_i$. If $\mathbf{x}_j$ falls within this sphere, the state is close to that of $\mathbf{x}_i$ and $\mathbf{R}_{i,j} = 1$. The binary values in $\mathbf{R}_{i,j}$ can be simply visualized by a matrix with the colours black (1) and white (0). In all RPs, there is a line along the diagonal, the line of identity (LOI), corresponding to $i = j$.

To capture the spontaneous movements of neonates, the configurational state of their body was defined by the four joint angles of the limbs ($n = 4$). Thus the phase space of the system was 4-dimensional. Four values of the angles belonged to each sample point of the time series, describing a time series of configurations. In mathematical terms, for a sample point i, the vector $\mathbf{x}_i = (a_1(i), a_2(i), a_3(i), a_4(i))^\mathbf{T}$ was generated, with $a_{1\text{-}4}(i)$ being the values of the four joint angles at the sample point i. The same procedure was applied for a sample point j: $\mathbf{x}_j = (a_1(j), a_2(j), a_3(j), a_4(j))^\mathbf{T}$. These two vectors depicted the configurational state of the system at the sample points i and j with four angles, respectively. In the RP, the horizontal and vertical axes represent the time. If the vectors at the sample points i and j are close to each other (equal or closer than the threshold epsilon), a black dot occurs in the RP, indicating that the state of the configuration at time j has recurred to the neighborhood of the state at time i. If the distance between the vectors is large (larger than epsilon), there is a white dot at the coordinates (i,j) of the RP, indicating that the states of the compared configurations were rather different.

Recurrence plots exhibit characteristic large-scale and small-scale patterns that are related to typical dynamical behavior [Eckmann et al. 1987, Webber & Zbilut 1994, Marwan et al. 2002, 2007]. Typical small scale structures are single dots, diagonal lines and horizontal or vertical black lines. The latter appear as rectangular clusters of black points. Single isolated black recurrence points indicate rare states, that do not persist for any length of time or that fluctuate heavily, e.g. white noise. Diagonals $\mathbf{R}_{i+k,j+k} = 1$ (for $k = 1\ldots l$, where l is the length of the diagonal line) indicate that a segment of the trajectory runs parallel to another segment in the same region of the phase space. For a periodic signal of recurrent movement patterns, e.g. locomotion, the plot looks like a series of stripes at 45 degrees. Vertical (horizontal) lines $\mathbf{R}_{i,j+k} = 1$ (for $k = 1\ldots v$, where v is the length of the vertical line) consist of sojourn points (see below) that appear as square-like collections or clusters in RPs and indicate time lengths, in which states do not change or change very slowly. States appear to be trapped for some time, which is a typical behavior of laminar states (intermittency) [Marwan et al. 2002, 2007].

Recurrence points can be classified as true recurrence points (also called recurrence points of the second type) and sojourn points [Gao 1999, Gao & Cai 2000]. If we choose arbitrarily a configurational state in the motor behavior corresponding to a point $\mathbf{x}_i$ of the trajectory, the recurrence points to this configuration are given by: $B\varepsilon(\mathbf{x}_i) = \{\mathbf{x}_k: \|\mathbf{x}_i - \mathbf{x}_k\| \leq \varepsilon\}$. Let us denote this set of points as $S_1 = \{x_{t1}, x_{t2}, \ldots ,x_{ti}\}$. S_1 consists of all data points that a neonate resided in the neighborhood of the configuration $\mathbf{x}_i$. From this set, we can define the Poincaré recurrence times by $T_1(i) = \{t_{i+1}- t_i, i=1,2 \ldots\}$, which correspond to the time spans between the occurrences of a configuration close to $\mathbf{x}_i$. If the time span was only one unit of sampling time, $T_1(i) = 1$, successive sample points $\mathbf{x}_{ti}, \mathbf{x}_{ti+1}, \ldots , \mathbf{x}_{ti+k}$ belong to S_1, and form a vertical line in the RP that corresponds to the "maintenance" of a configuration $\mathbf{x}_i$. The sequence $\mathbf{x}_{ti+1}, \ldots , \mathbf{x}_{ti+k,}$ (excluding $\mathbf{x}_{ti}$) is called sojourn points and is schematically shown in Figure 1. Collections of sojourn points usually give rise to square-like textures in RPs that correspond to staggering motions around the turning points of the trajectory [Gao & Cai 2000]. The size of a rectangle is proportional to the time that the trajectory is trapped close to a turning point. If the behavior of the system is quite uniform, rectangles display similar sizes, if the behavior is not uniform, rectangles display different sizes. If the sojourn points are removed from $S_{1,}$ the remaining points are denoted as $S_2 = \{x_{t'1}, x_{t'2}, \ldots ,x_{t'i}\}$, S_2 contains the true recurrence points, which correspond to the frequency of recurrence to a configuration x_i.

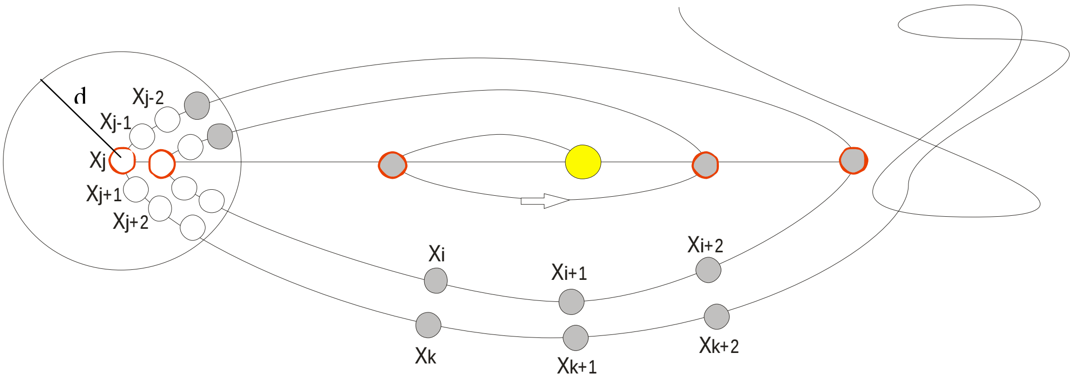


Figure 1. Schematic representation how a RP is composed. Direction of motion is assumed to be counter clockwise. Yellow: starting point, grey: true recurrence points, white: sojourn points, red margin: turning points, d: corresponds to epsilon ε. Diagonal lines are formed by two mechanisms: first, if points of the same orbit keep close together (x_i, x_{i+1} and x_{i+2}) and (x_k, x_{k+1} and x_{k+2}), which is termed tangential motion and second, if points of different orbits keep close together, such as pairs of (x_i, x_k), (x_{i+1}, x_{k+1}), and (x_{i+2}, x_{k+2}). Blocks are due to staggering motions around the turning points (x_{j-2}, x_{j1}, x_j, x_{j+1}, x_{j+2}).

Recurrence Quantification Measures

The small scale patterns, diagonal and vertical (horizontal) lines, are the basis of a quantitative analysis of RPs. Zbilut & Webber have developed the recurrence quantification analysis (RQA) for the diagonal structures [Zbilut & Webber 1992, Webber & Zbilut 1994], which allows the detection of typical transitions (e.g. bifurcation points) in complex systems [Trulla et al. 1996]. The RQA measures, *recurrence rate, determinism, maximal length of diagonal structures, entropy* and *trend* are based on the recurrence point density and the diagonal structures in the RP. On the other hand, the recurrence time statistics are based on the vertical structures of the RP [Gao 1999, Gao & Cai 2000]. Several measures of complexity based on the distribution of the vertical lines length have been defined: the *laminarity*, the *trapping time* and the *maximal vertical length*, which are able to identify laminar states [Marwan et al. 2002]. The computation of these recurrence variables in sliding windows along the main diagonal of the RP allows the identification of transitions in the time series.

In the present study we computed the following measures for the quantification of the RPs of motor behavior within episodic windows consisting of 300 consecutive datapoints. Sequential windows were shifted by 20 datapoints (thus overlapping by 280 datapoints):

Recurrence rate (RR): the percentage of black points in the RP, i.e.

$$\mathbf{RR} = 1/N^2 \sum_{i,j=1}^{N} \mathbf{R}_{i,j}(\varepsilon).$$

Determinism (DET): the percentage of black points which are part of diagonal line segments of at least length l_{min},

$$\mathbf{DET} = \sum_{l=l_{min}}^{N} lP(l) \ / \ \sum_{l=1}^{N} lP(l),$$

where *P(l)* denotes the probability to find a diagonal line of length l in the RP.

Mean diagonal line (MDL): the average length of diagonal lines,

$$\mathbf{MDL} = \sum_{l=l_{min}}^{N} lP(l) \ / \ \sum_{l=l_{min}}^{N} P(l).$$

Entropy (ENTR): the Shannon entropy of the frequency distribution of diagonal lines in the plot,

$$\mathbf{ENTR} = \sum_{l=l_{min}}^{N} p(l) \ln p(l) \qquad \text{,where } p(l) = P(l) / \sum_{l=l_{min}}^{N} lP(l).$$

Laminarity (LAM): analogous to DET, the percentage of black points that are part of vertical lines of at least length v_{min}.

$$\mathbf{LAM} = \sum_{v=v_{min}}^{N} vP(v) \ / \ \sum_{v=1}^{N} vP(v),$$

where *P(v)* denotes the probability to find a vertical line of length l in the RP.

Trapping Time (TT): analogous to MDL, the average length of vertical lines is given by

$$\mathbf{TT} = \sum_{v=v_{min}}^{N} vP(v) \,/\, \sum_{v=v_{min}}^{N} P(v).$$

Surrogate time series

Iterated Amplitude Adjusted Fourier Transformed (IAAFT) surrogate time series were generated from the original time series by the program “surrogates” from the software package TISEAN, which is publicly available from http://www.mpipks-dresden.mpg.de/~tisean/ [Hegger et al. 1999, Schreiber & Schmitz 2000].

Results

Consideration of the velocity profiles of the motor activity of newborn infants in the supine position revealed intermittent movement behavior. According to the velocity trajectories of the hands and feet, motor activity was defined, if one of the limbs exceeded a velocity of 50 mm/s, or if the sum of the velocity of the four limbs exceeded 100 mm/s. By this definition, the stream of newborn motor behaviors turned out to consist of patterns of different structural complexity that could be assigned to hierarchically organized levels:

Movement phrases were defined by time delays between the end of one movement phrase and the beginning of the next exceeding 3 frames (750 ms). The distinction of phrases was due to the temporal synchronization of the activity patterns of the four limbs, whereby the activity levels of individual phrases could be characterized by their mean velocities. The time distributions of the durations of movement phrases and interphrases (pauses between the phrases) were exponential (figure 2 bottom), which is typical for organization on different time scales.

Movement elements were movements of single limbs that occurred separately (1) or simultaneously (2,3 or 4 limbs together). Elements were characterized by bell-shaped velocity trajectories that were separated by a decrease in velocity below 50% of their peak velocity between the movements. Decreases in velocity are associated with peaks in the curvature [Fetters & Todd 1987, Hofsten 1991] and therefore corresponded to turning points of the movement trajectories. Limbs were moving sequence-like from one position to the next one, with temporal synchronization of these turning points. This was indicated by parallel bell shaped velocity curves, when limbs moved simultaneously.

Concerning the core questions raised in the introduction, the most basal units in the motor activity were movement elements that occurred in a sequential manner. They were organized by temporal synchronization of active and inactive phases into movement phrases of a hierarchically higher level.

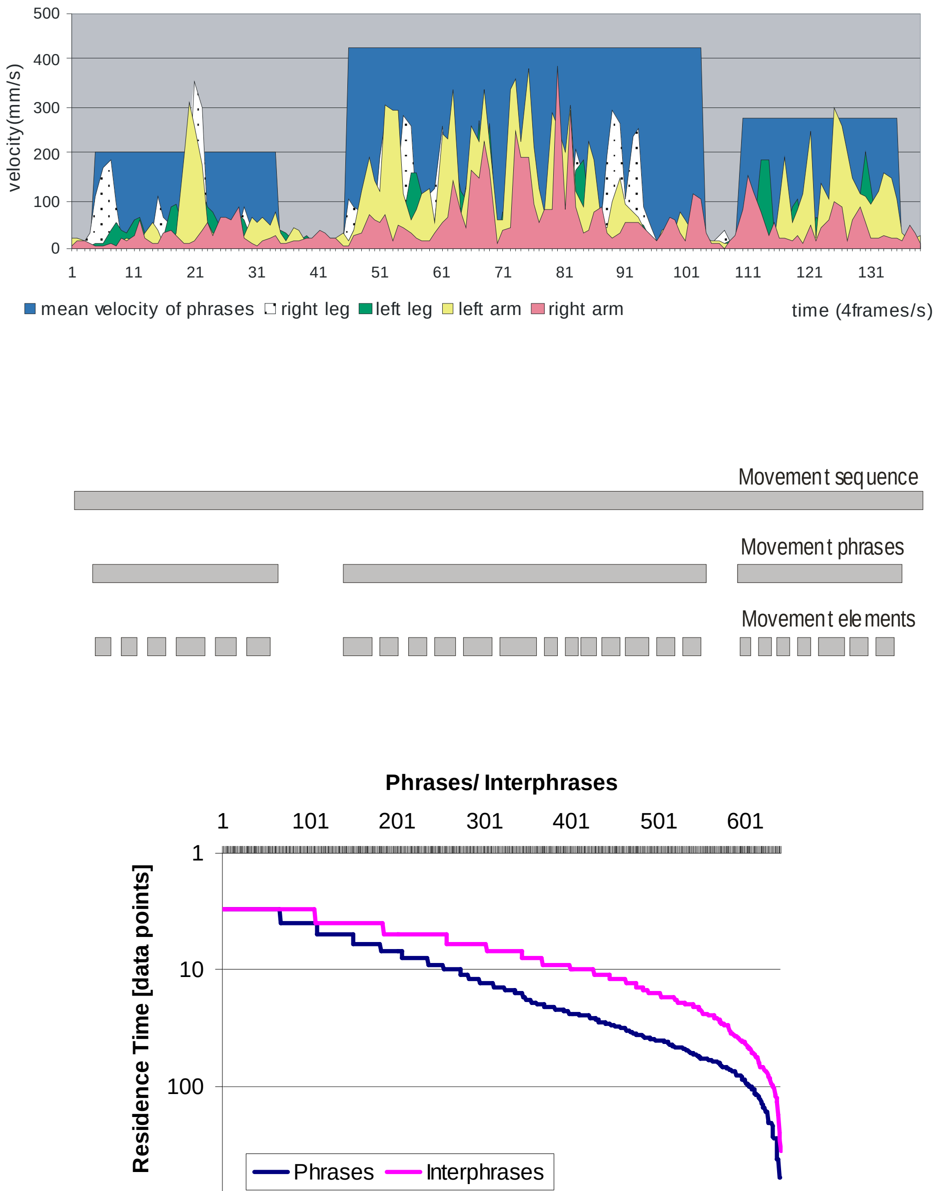


Figure 2. Top: Velocity profile of a movement sequence with three movement phrases. Middle: Scheme of a structural hierarchy. The bar on top refers to a sequence of movement that encompasses movement patterns called phrases and, on a lower level, movement elements that compose the movement phrases. Bottom: Residence time distribution of movement phrases and interphrases from 15 movement episodes of 6 infants.

Once we have defined movement phrases, we can describe the spontaneous motor behavior by a structural hierarchy (figure 2): A movement sequence could be segmented in movement phrases that are composed of movement elements. Movement phrases were variable in duration and displayed different activity levels represented by their mean velocity. According to dynamic systems theory increasing and decreasing activity levels in motor behavior create different dynamic patterns.

For investigation of organizational structures of the proposed hierarchical levels, we first focussed on motor behavior of single limbs and then examined, how this behavior assembled into overall movement patterns. Illustrations of recurrence plot analyses and recurrence quantification analyses are referring to a 20 minute movement episode of one child, presented results are referring to 15 movement episodes between 5 and 20 minutes of 6 infants.

Motor behavior of the single limbs

Figure 3a illustrates the histograms of the joint angles of a 20 minute movement episode, to which the illustration of the recurrence plot and the recurrence quantification analyses refer. The frequency distributions of the joint angles, in which the limbs resided, reveal peaks that refer to significant higher cumulative sojourn times in a flexed state, if the peak is in a low range, and to an extended state, if the peak is in a high range. The Kolmogorov-Smirnov-test against normal distribution was highly significant for all four limbs (all $N = 4700$, all $D_{max} > 0.170, p < 0.001$).

The phase space portraits of the joint angle positions and the velocities of the single limbs demonstrate that peaks in the histograms of the joint angle positions correlated with low velocity values. This means that pauses between movement phrases and velocity decreases between movement elements were associated with certain positions of the limbs (bent for the arms and bent or extended for the legs). Since velocity decreases are associated with curvature peaks [Fetters & Todd 1987, Hofsten 1991], the flexed and extended positions of the limbs seemed to correspond to turning points in the movement trajectory. This means that the limbs were attracted to either bent and/or extended positions, which acted as attractors in the limbs' phase space, but also repelled the limbs since these reference positions were also the origins of movement excursions. Points in the phase space that attract and repel the trajectory are often referred to as saddle points.

The frequency distributions of the joint angles of ten 5-minute movement episodes of five children on two different days respectively (figures 3b-k) show uni- or bimodal distributions for the arms and legs for all infants. In general, the frequency distributions of the arms show a unimodal shape with a major peak in the lower range between 20 and 60 degrees, and the legs show a bimodal shape with two peaks: one in the lower range between

Infant1

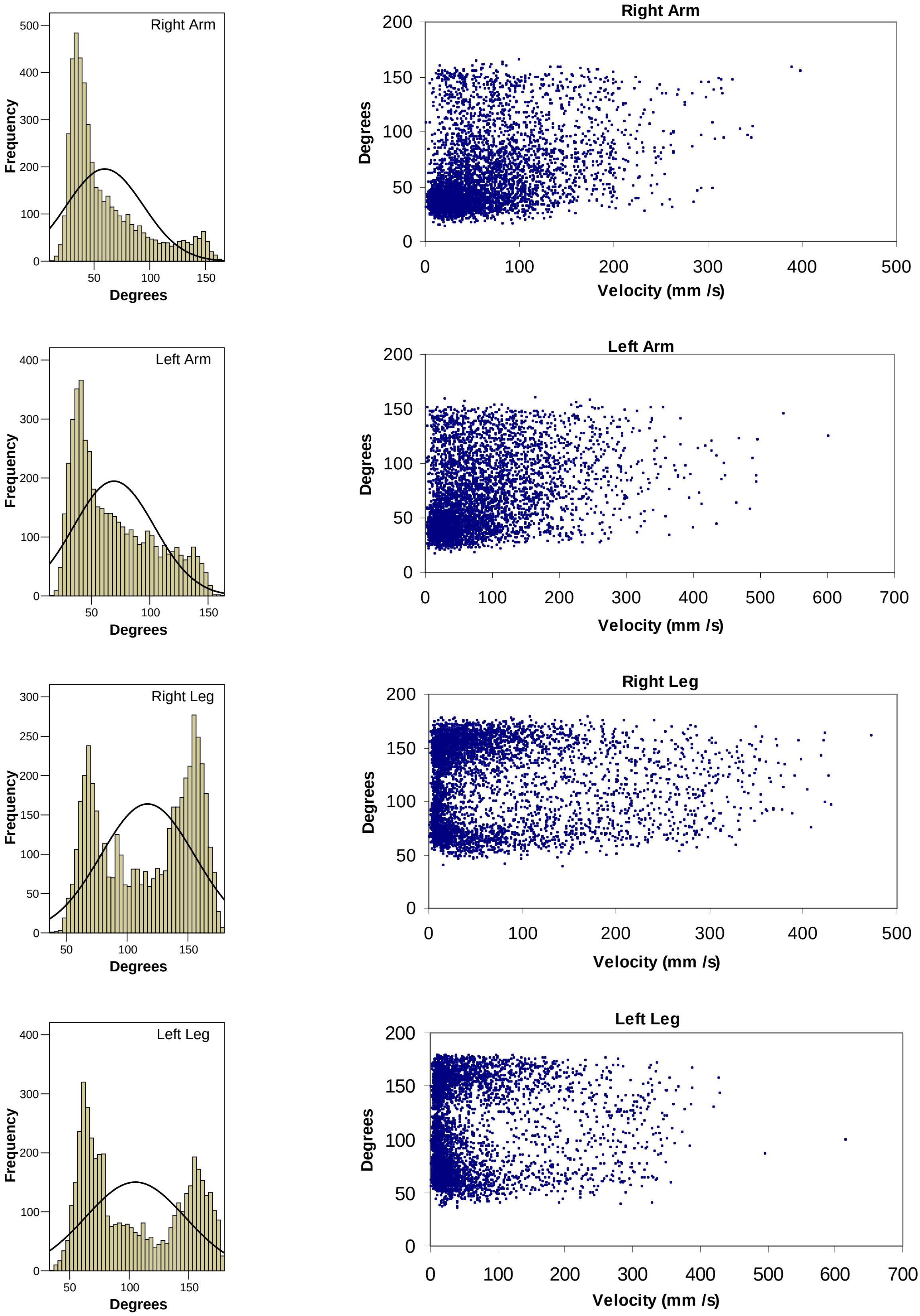
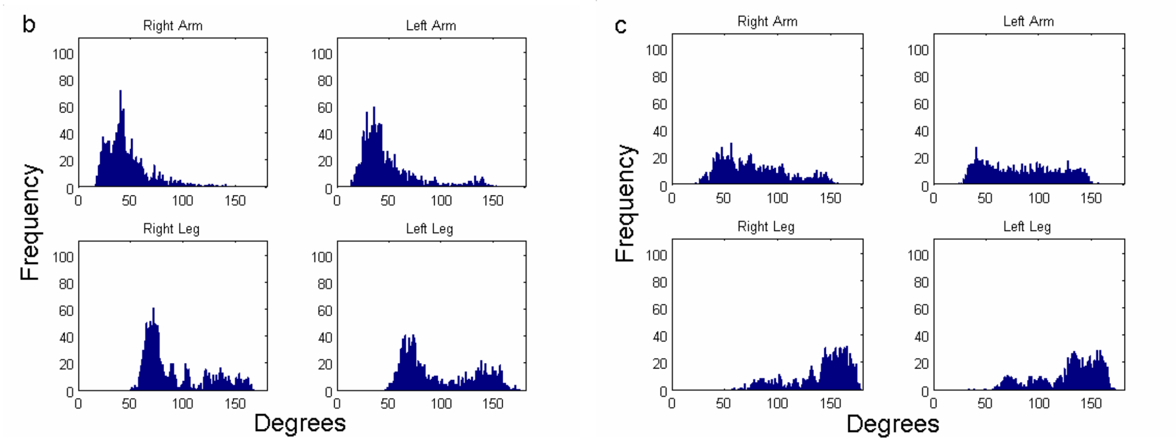
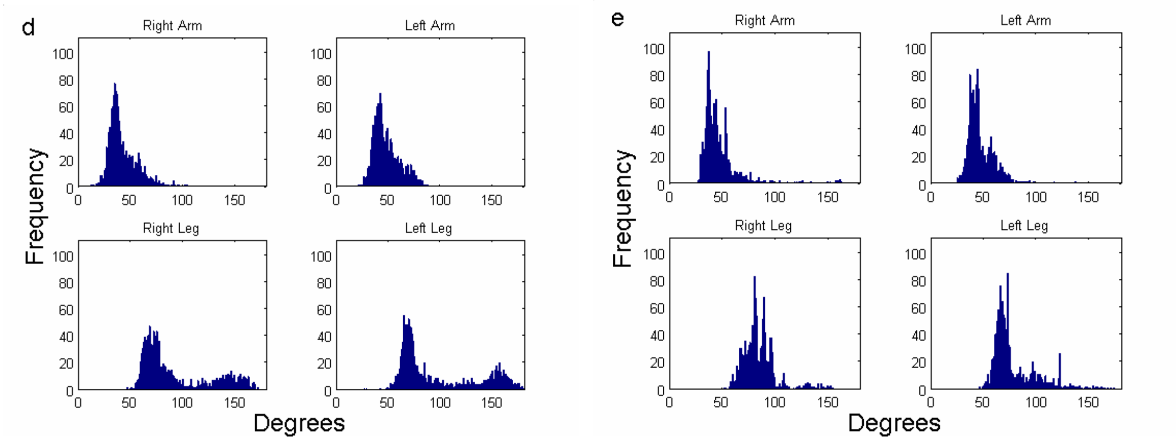


Figure 3a. Left: Frequency distribution of the joint angles of the single limbs of a 20-minute movement episode of one neonate. The frequency on the y-axis is plotted against the values of the joint angles on the x-axis. Right: Correlation of the velocity and the joint angle position of the single limbs of the same time series (phase plane representations).

Infant 1



Infant 2



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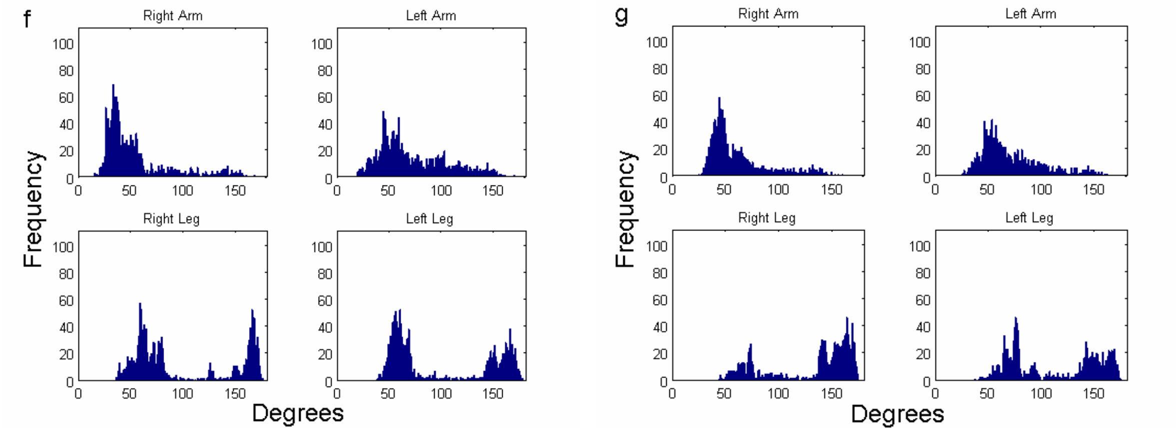
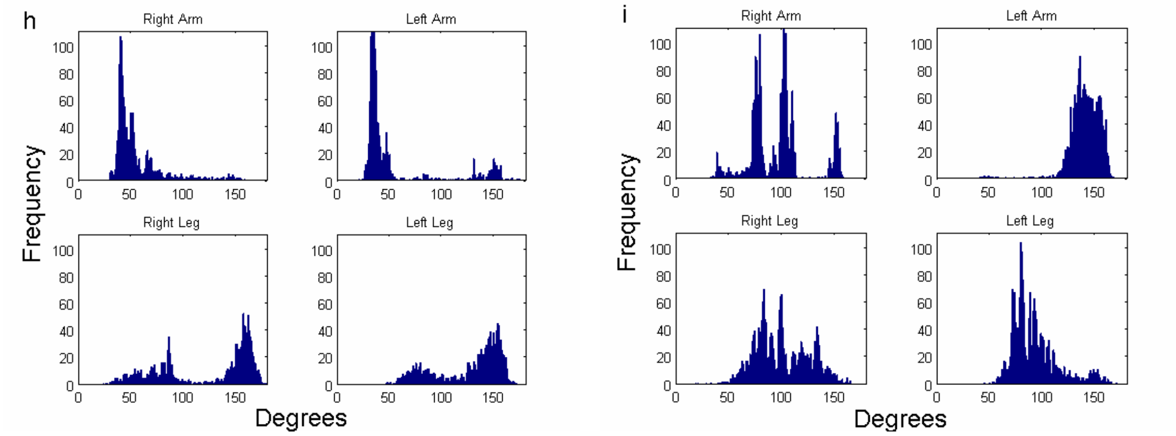


Infant 4



Infant 5

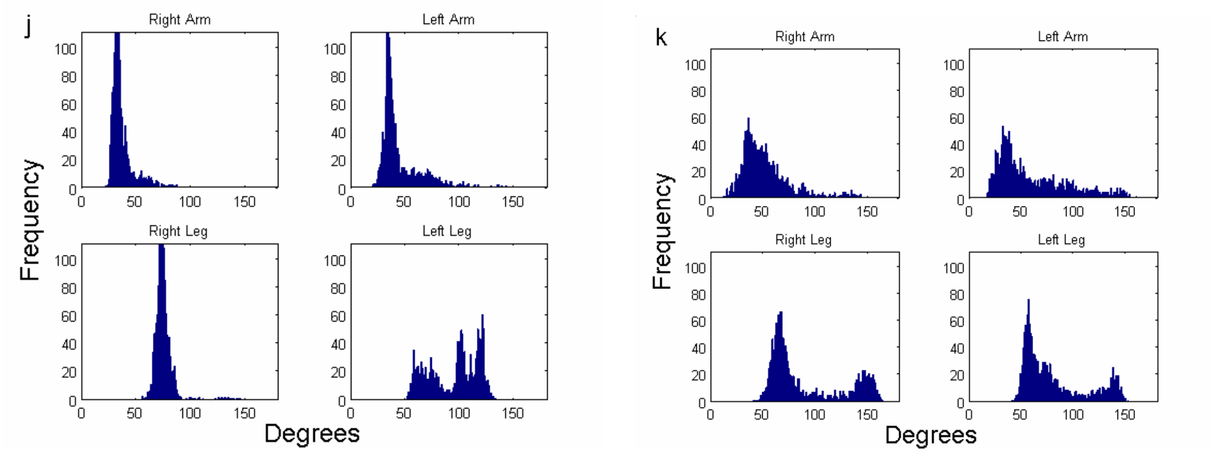


Figure 3b-k: Histograms of 5-minute movement episodes of 5 neonates, in which diagrams in horizontal order correspond to the same infant on two different days. a, b and c display diagrams of the same infant on three different days. The frequency on the y axis is plotted against the values of the joint angles on the x-axis.

50 and 90 degrees and/or one in the higher range between 130 and 170 degrees. However, there are exceptions, in which the arms show a peak in the extended position, or in which the legs show unimodal distributions in the flexed or extended position. The Kolmogorov-Smirnov-test against normal distribution was highly significant for all studied joint angle distributions (all $N = 1200$, $D_{max} > 0.068$, $p < 0.001$). Switches between reference positions indicate that they did not simply reflect static constraints of the physical properties of the body, but can be understood as temporary reference points in the movement behavior of the single limbs.

Concerning the questions about basal units of the motor activity and their organization on higher levels, basic units or movement elements consisted of flexions and extensions of the single limbs between the extended and/or flexed positions. Movement transitions or excursions between reference positions corresponded to the movement elements of the basic level in figure 2. Organization towards higher levels occurred by reference to the extended, flexed or both postures. The recurrence plot analysis visualizes, how successive flexions and extensions of the four limbs were related to each other and assembled into more complex movement patterns.

Recurrence plot analysis

From the combination of the joint angle positions of the four limbs at each sample point resulted a 4-dimensional trajectory that captured the movements of the four limbs simultaneously. The dynamics of the sequential distribution of these configurations can be visualized by a recurrence plot (RP). General characteristics of RPs and the coding used to capture the motor behavior of neonates are described in the methods.

In the RP (figure 4), black dots represent the recurrence of a configuration, meaning that the configuration of all the four single limbs returned to the neighborhood of a former configuration of the trajectory. The organization of black dots in vertical and horizontal lines that appear as square-like clusters on a time scale of 10 - 60 sample points (3 - 15 seconds) shows that a recurring configuration remained for a certain time interval. White areas between the black rectangles indicate movements of the limbs that generated different configurations. This illustrates that single limbs synchronized their turning points concerning the time pattern as well as the spatial pattern by synchronizing the returns to their reference positions (figure 2). Blocks of black points indicate laminar states that are usually due to staggering motions around turning points of the trajectory. The size of a rectangular cluster is proportional to the time that a trajectory stays close to a turning point [Gao & Cai 2000] and corresponded to time spans, in which the configuration of the four limbs did not change or changed very slowly. Therefore, black blocks in RPs visualize nonmovement interphrases and white interceptions reflect movement phrases (figure 2).

Regarding recurrence patterns of fixed configurations by following a vertical line, certain configurations showed a high number of black dots, indicating a high rate of recurrence. Other configurations displayed a low number of black dots, seen as a white line, indicating a low rate of recurrence. This means, that certain configurations were occupied with a higher preference compared to other configurations. A closer look at single configurations reveals that parts of the plot display high recurrence patterns with predominantly black dots and other areas display predominantly white sections. This means, that in parts of the time series newborns used certain configurations very frequently, and then within the same time series, switched to other configurations. This superior structure is demonstrated by changes in the texture of the RP, displaying a rectangular structure on a higher time scale of ca. 400 - 600 sample points (sp). These transitions arise from particular configurations that recurred with certain regularities in time windows of around 2 minutes. Configurations with high recurrence rates were termed reference configurations.

On a higher time scale, there are clear changes in the texture of the RP at 200, 2200 and 3500 sp. The rectangular structure on different time scales demonstrates the self-similar aspect of the dynamics of the motor behavior and hints towards dynamics in the movement patterns of this time series on three time scales: The first in the range of 1000 – 2000 sp, the second around 400 – 600 sp and the lowest between 10 – 60 sp. The phenomenon of multiple different time scales was apparent in all 15 computed RPs.

Concerning the questions about basal units of the movement activity and their organization into movement patterns on higher levels, the rectangular structure of the RPs demonstrates the organization of the movement behavior along static states (configurations). Basal units were movements from one configuration to the next one. The organization into higher levels is seen in pattern changes on higher time scales that result from changes from one (or more) individual recurring reference configurations to another one (or another set). The absence of diagonal structures on all time scales revealed that there were no recurring movement sequences or sequential recurring successions of static configurations.

Recurrence Quantification Analysis

In order to quantify the structures and pattern changes found in the RPs, we computed several RQA measures that are based on the recurrence point density and the diagonal and vertical line structures as introduced in the methods section. The computation of these measures in windows moving along the main diagonal yielded the time dependent behavior of these variables.

The quantification measures, RR, DET, MDL, ENTR, LAM, and TT were calculated for each of the 15 time series in sliding windows of length 300 sp (corresponding to time intervals of 78 seconds) along the main diagonal. Then 1000 iterated AAFT surrogate time series were computed for each time series and the RQA measures were computed for the surrogates also in sliding windows of length 300 sp along the main diagonal. These surrogates correspond to the null hypothesis that the underlying process of the original data was a linear stochastic process that has undergone a static nonlinear transformation. This would mean that the underlying process of the motor behavior of neonates could be described by a linear stochastic process. The comparison of the recurrence quantification analysis of the original data with the one of the surrogates revealed that the measured data differed significantly from the surrogates in some time intervals and in others, they did not. This analysis shows that the motor behavior of neonates exhibited transitions between phases, in which the dynamics of the motor behavior can be described by a stochastic process and other movement sections, in which the movement behavior appeared nonlinear and more complex than such a process. Quantification of the linear and nonlinear time intervals over 15 RPs of movement episodes of six infants revealed an exponential distribution of residence times for both states (figure 5).

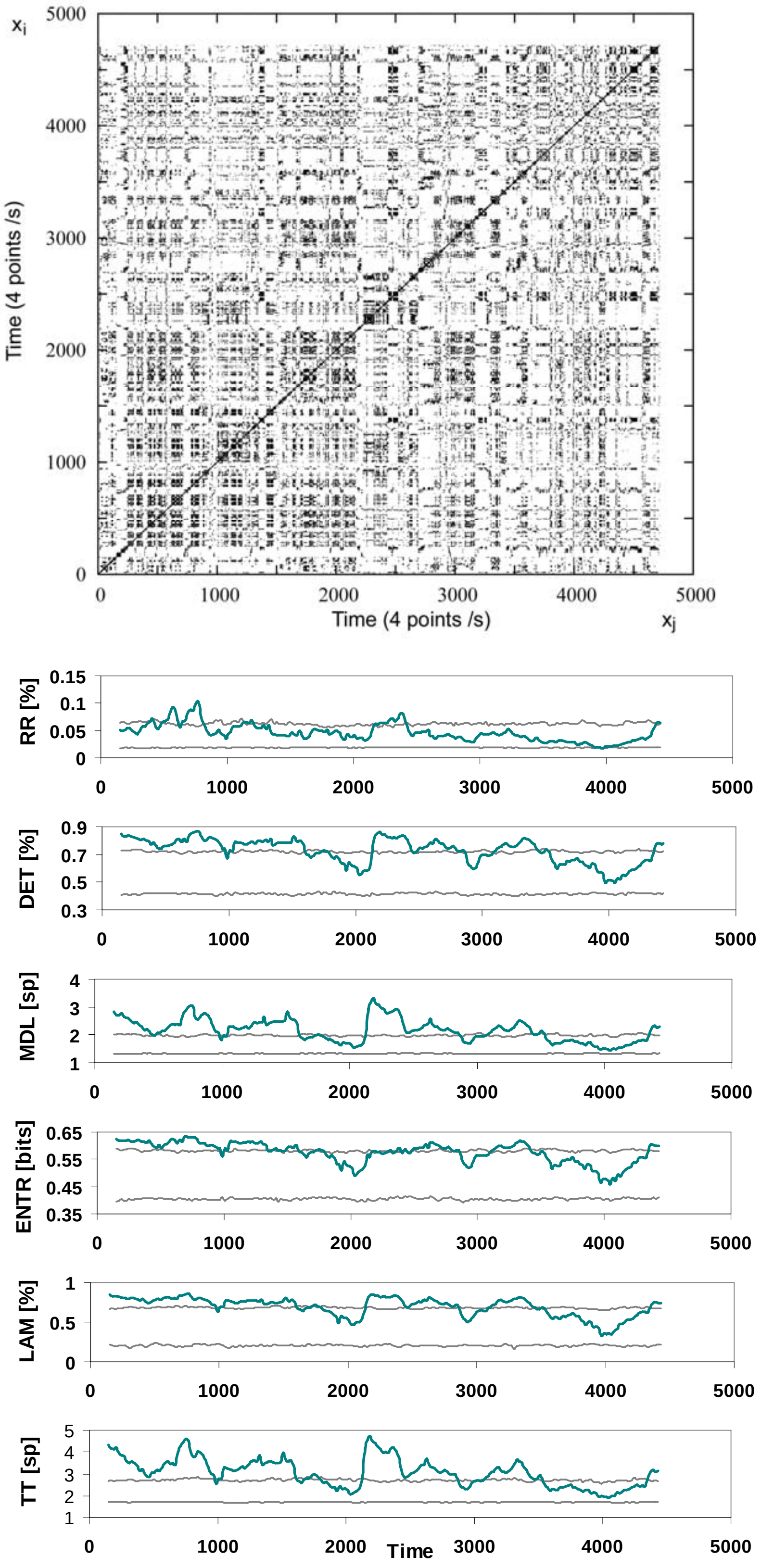


Figure 4. Top: Recurrence-plot of the integrated joint angle displacement time series with dimension m = 4 and ε = 30.0 of the same 20-minute movement series as in figure 3a. The horizontal and vertical axis display the time series x_i and x_j, respectively. Below: RQA measures RR, DET, MDL, ENTR, LAM and TT. ENTR is measured in Shannon bits of information (Webber & Zbilut, 1994). Values are computed from a 300-point window moving along the main diagonal. Adjacent windows are shifted by 20 points. Blue: RQA measures computed from the original time series, Grey: 0.01 and 0.99 confidence intervals of 1000 IAAFT surrogate time series.

These results confirmed the visual impression, yielded by the RPs, that the movement dynamics displayed transitions or – in dynamical terms bifurcations - between distinct dynamical regimes of behavior on various time scales.

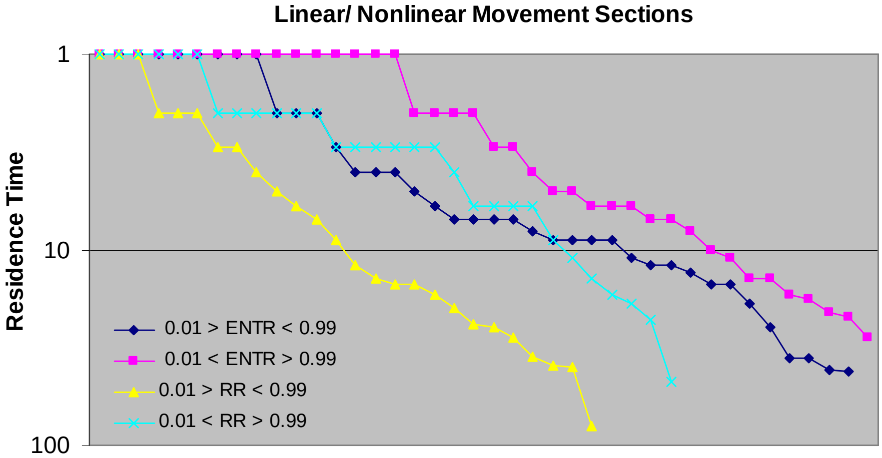


Figure 5. Residence time distribution of linear and nonlinear movement sections from 15 movement episodes of 6 infants according to RR and ENTR.

In more detail, the analysis of the quantification measures can be used to identify the pattern changes seen in the RP quantitatively. The simplest measure is the RR, which is a measure of the density of recurrence points in the RP and corresponds to the definition of the correlation sum (excluding LOI). RR represents the percentage of recurrences and is the probability of the recurrence of a configurational state in the movement behavior. In figure 4, the RR was low at the beginning of the RP and increased when the window moving along the diagonal entered a part with more black dots. It decreased, when the window entered into a white section with a low number of recurrences.

The measures DET, MDL and ENTR are based on the histogram of diagonal lines of a minimal length l_{min}. Uncorrelated or weakly correlated stochastic behavior causes no or very short diagonal lines, whereby deterministic processes cause longer diagonal lines and less isolated recurrence points. DET is the ratio of recurrence points that forms diagonal lines (of at least length l_{min}) to all recurrence points and represents the probability that a segment of the trajectory (a segment of the movement sequence) is close (similar) to another segment of the trajectory (movement sequence) at a different time. DET is a measure of predictability. MDL is the mean length of the diagonal structures and contains information about the average time that the two segments of the trajectory are close to each other, which means, how long two sequences of configurations were similar. ENTR refers to the Shannon entropy of the histogram of diagonal line length and reflects the complexity of the system. If there are diagonal structures with varying length, the entropy is high; if the diagonal lines have similar length, the entropy is small.

The measures LAM and TT are analogous to DET and MDL but based on the histogram of vertical lines of a minimal length v_{min} and give information about laminar behavior and intermittency. Analogous to DET, the ratio of the recurrence points forming vertical lines are computed by LAM which decreases, if the RP contains more single recurrence points than vertical lines and represents the probability of the occurrence of laminar states. Laminar states correspond to configurations in the movement behavior that do not change or change very slowly. TT is analogous to MDL the averaged length of vertical structures and gives information about the mean time that the system abides in a specific state corresponding to how long neonates were trapped in a specific configuration. TT is high if the system contains mainly trapped states, and low for a system without laminar states.

In most of the studied RPs, the evolution of DET and LAM as well as those of MDL and TT was very similar, indicating that the measured diagonal lines corresponded to the rectangular clusters of recurrence points created by the vertical and horizontal lines. This means that all four measures referred mainly to the occurrence of turning points in the movement behavior that corresponded to square-like clusters. But it should be noted that in some RPs, single RQA measures displayed unique curve progressions that were not parallel to the other measures, e.g. the initial phase of RR in figure 4.

In general, the six quantification measures showed maximal and minimal values in correspondence with the visually detectable pattern changes in the RP. If the RP exhibited changes from black to white areas, the quantification measures decreased and showed minimal values when the shifting window entered again into black sections. When moving into a black cluster, or an area of black clusters, the quantification measures increased and exhibited maximal values when leaving a black area and entering into a white one. In general, the six computed variables RR, DET, MDL, ENTR, LAM and TT yielded congruent results and indicated bifurcations corresponding to the pattern changes in all 15 studied RPs.

In figure 4, the RQA measures mark off transitions at 1000, 1500, 2200, 3000, 3500 and 4400 sp either from linear to nonlinear (2200, 4400), from nonlinear to linear (1500, 3500) or between nonlinear regimes (1000, 3000). Changes occurred gradually or abruptly, e.g. regarding DET, there was a gradual decrease from the maximum at 1500 to the minimum at 2100 and then an abrupt increase to the 2200 maximum following the 2100 minimum. Some RQA measures were more sensitive to bifurcations than others and their changes were not always simultaneous. Concerning the question about the organization of basal units into movement patterns of higher levels, the RQA shows switches between sequence generation in a linear stochastic and a more complex nonlinear way.

Discussion

Our analyses of newborn motor behavior revealed that these movements can be understood on a basic level as sequential behavior of extensions and flexions of both arms and legs that show a tendency to synchronize into sequences of configurations. These basic movement elements can be referred to the notion of motor primitives. Motor primitives are assumed as basic units in most of the motor learning models that can be combined into chunks of coordinated motor patterns [Mussa-Ivaldi et al. 1994, Mussa-Ivaldi & Bizzi 2000, Thoroughman & Shadmehr 2000, Konczak 2005, Kuniyoshi & Sangawa 2006]. Thelen & Fisher [1982, 1983] already characterized newborn leg movements as flexions and extensions [Thelen & Fisher 1983]. However, their results implicated a ten times higher cumulative time of the legs staying in the extended position than in the flexed position, which is different from our results. According to our findings, legs are held for an at least comparable, and often higher, cumulative time in the flexed position. One reason might be the age of the studied infants, which might be proven by a longitudinal study from the first days up to four weeks of age.

The analysis of single limb motor behavior uncovered that preferred spatial positions were at the natural biomechanical turning points of the limbs, which resulted from their spring-like properties [Kelso et al. 1981, Saltzman & Kelso 1987, Thelen et al. 1987b]. This means that pauses between movement phrases and stops between movement elements occurred at positions that were turning points and marked switches between different movement directions. Preferred positions were not fixed, but changed between different movement episodes from the bent to the extended, or to both states. This implies that biomechanics did not constrain the movement to certain positions, but the biomechanical apparatus of the body appeared to be temporarily attracted to certain turning point positions.

Preferred positions of single limbs have been proposed as reference points that serve as origin- and goal-positions for movement excursions of these limbs [Aßmann et al. 2006]. In a dynamical framework, goal-positions refer to attractors of the movement trajectory and origin positions to repellors. Thelen et al. [1987b] presented phase plane trajectories of short ~10 second segments of single leg kicking movements suggestive of nonlinear limit cycle oscillators [Kelso et al. 1981, Thelen et al. 1983, Goldfield & Wolff 2003). Such short single limb movement segments have also been observed in our data in the range of seconds (data not shown). In the range of minutes, however, attractors of the movement trajectories of the single limbs appeared to be the turning points. These findings suggest that the high dimensional motor behavior of single limbs displayed periods of different kinds of low dimensional behavior on different time scales: e.g. transient attraction to a limit cycle on a lower time scale and organization towards a point attractor on a higher time scale.

According to the analysis of the velocity profiles of the four limbs together, a movement sequence was segmented in movement phrases and movement elements. Sequences, phrases and elements formed different time scales and corresponded, seen in a structural hierarchy, to different hierarchical levels. Movement segments (phrases and elements) were separated by nonmovement segments, in which the velocity was decreased. Velocity decreases in movement trajectories are associated with peaks in their curvature [Fetters & Todd 1987, Hofsten 1991] and, therefore, corresponded to turning points in the movement trajectories. The velocity profiles revealed that the four limbs were synchronizing their turning points. This resulted in a sequence-like movement behavior from one turning point to the next one, with pauses between phrases and punctual stops between movement elements at the turning points.

Recurrence plot analyses revealed that the four limbs synchronized the spatial positions of the nonmovement segments, to which they returned. This pattern follows logically from the results of the analysis of the velocity trajectories and the frequency distribution of the positions of the single limbs: If the single limbs synchronized their turning points temporally and turning points corresponded to peaks in the distribution of spatial positions, the phase-space trajectory of the four dimensional movement behavior logically exhibited turning points that were visible in the recurrence plot by square-like clusters. Square-like textures are typical features of RPs generated from biological data, e.g. neuronal spike trains [Kaluzny & Tarnecki 1993], EEG recordings [Pijn et al. 1997] and rhythmic eye movements [Shelhamer 1998], but are also found in dynamical systems [Casdagli 1997, Zbilut et al. 1998] and are associated with laminar phases, in which states do not change or change very slowly. In the case of newborn motor behavior, square-like blocks corresponded to staggering motion around the turning points of the trajectory. Laminar phases in the movement dynamics occurred at these turning points. Again, here, on the level of configurations, turning points represented goal and target configurations and acted as attractors and repellors of the system's dynamics.

The repeating square-like pattern of the RPs on different time-scales suggests the existence of principles of organization that could be important at different hierarchical levels

[Anderson, 2000]. From a spatial perspective concerning the amount of components involved, a lower level was defined by reference points, to which single limbs returned (level of movement elements). On a higher level, if the behavior of the four components was taken together, the organization of configurations seemed to be related to a reference system that was organized on different time scales: The rectangular RP structure on a time scale in the range of seconds was related to the level of movement phrases. Within the concept of a structural hierarchy, changes in the system between linear and nonlinear epochs on a higher level of minutes indicated an additional level between the level of phrases and the level of sequences (figure 6). Generally, specific patterns of timing are thought to reflect the organization, in which motor sequences are represented and are related to the concept of chunking.

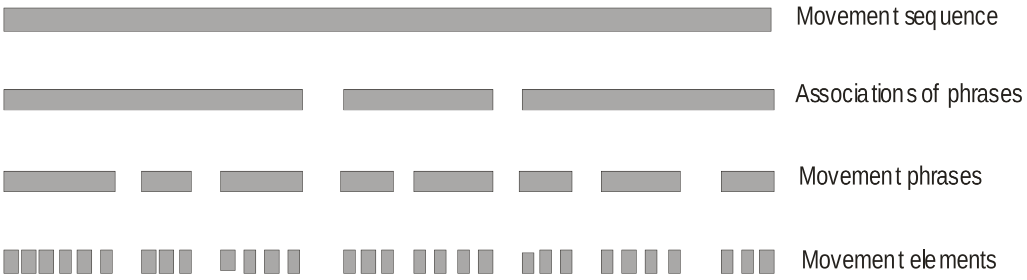


Figure 6. Scheme of a structural hierarchy with two intermediate levels. The bar on top refers to a movement sequence that encompasses movement patterns called phrases that are organized in association groups of movement phrases and consist of movement elements that define the basic level.

Several studies suggest a chunk representation for motor sequences that are hierarchically organized with chunks of subsequences in: explicit learning of visuomotor sequences [e.g. Povel & Collard 1982], implicit learning of visuomotor sequences [e.g. Keele & Jennings 1992, Koch & Hoffmann 2000] and speech production [Gordon & Meyer 1984]. In these studies, chunking occurred corresponding to spatial and temporal cues such as changes in the pattern of movements (repetition, inversion and transposition) [Koch & Hoffmann 2000], transitions between movements [Cohen et al. 1990] or temporal delays in response intervals [Stadler 1993]. These findings point towards external specification of chunk patterns according to physical parameters that determine the sequence structure. In turn, Sakai et al. [2003] found the spontaneous emergence of chunk patterns independent of physical parameters speaking in favor of hierarchical sequence organization at a representational level.

Considering the structure of the intermittent movement behavior of neonates, movement phrases as well as movement sections of linear and nonlinear dynamics can be regarded in a similar way to the hierarchical chunking of subsequences of motor behavior.

Hierarchical organization can be observed from physiology - as e.g. in muscles from gross anatomical, stepwise down to molecular units - to cognitive accomplishments as explained in language. The detection of hierarchical principles frequently brings up questions about their biological significance [Anderson 1983, Greenfield 1991, Nelson 1990, Pepperberg 1994, Todt 1986, 2004] and the nature of their underlying or functionally correlated mechanisms. Concerning the biological significance, hierarchical organization and chunking are very effective mechanisms to reduce the degrees of freedom in information processing [Todt & Hultsch 1998]. Therefore, it is plausible to appear in exploratory behavior of neonates in the process of gathering information about the biodynamical properties of their bodies.

Concerning the underlying or linked mechanisms, both, the constraint of degrees of freedom is essential for learning about the physical qualities of the body, and flexibility and plasticity are important for the exploration and emergence of new forms of behavior. The latter were indicated by new reference positions of single limbs and new reference configurations of the whole body that emerged and disappeared and can be referred to as freezing and freeing of degrees of freedom. This interplay revealed, how the biomechanical system appeared as a multi-level system, in which a variety of temporary levels emerged and disappeared. The variety of transient levels manifested in the exponential distributions of the residence times of linear and nonlinear behavior sections as well as movement phrases and nonmovement interphrases. The variety of transient levels as well as the variability of activity levels in movement phrases asks for further investigation of the underlying mechanism from which hierarchical levels emerge by e.g. analyzing coupling mechanisms between the limbs. Changing modes of interlimb coordination have been documented separately for arm movements [Corbetta & Thelen 1996] and leg kicking [Thelen et al. 1983].

Recently, Kuniyoshi & Sangawa (2006) proposed a baby model consisting of chaotic oscillators coupled through embodiment that exhibits the development of motor primitives. Coupled chaotic oscillator systems display rich dynamical properties [Kaneko 1989,1990, Kaneko & Tsuda 2001] including chaotic itinerancy [Tsuda 1991], where the system wanders between quasi attractors. This might provide a model for the underlying mechanisms of the nascent motor system exploring various quasi-stable dynamics that might be similar to our findings of different sets of reference configurations or in different types of interlimb coordination.

The assumption of start and goal configurations involves the ability to return to specific configurations, which implies some kind of memory system that captures the spatial relationships of the limbs as a reference frame to return into this configuration. Current evidence suggests that information about the three-dimensional shape and mechanical properties of the body must be laid down by some adaptive mechanism in the synaptic connectivity of sensorimotor systems (Petersson, 2003). The use of ideothetic information has been studied in the path integration system, which allows orientation and navigation by updating position and direction solely on the basis of ideothetic information [for details see: Biegler & Morris 1996, Etienne et al. 1996, Wehner et al. 2006]. This process has been extensively studied in insects and mammals and several connectionist models have been proposed [e.g. Wilson & McNaughton 1994, Wittmann & Schwegler 1995, McNaughton et al. 1996] but there is no consensus yet. The study of processes of gathering ideothetic information in the course of exploratory motor behavior might inspire research on the later utilization of this information. Reference configurations emerged by temporal and spatial synchronization of the turning points of the movements of the single limbs via the biomechanical connections between the limbs. Marking origin and target positions, the system of configurations might provide reference frames, in which other parameters of the three dimensional mechanical properties of the body can be explored and integrated. Such presumption can be proven by further investigations into the dynamics of parameters like distance, path length and curvature of coordinated trajectories.

Discussing reference positions of single limbs and configurations in the spontaneous movements as origin and target positions on multiple organizational levels leads towards an action perspective on motor development. Growing evidence from many research fields indicates that human movements are organized as actions that are defined by a goal, which is already represented when actions are planned [Johnston 2000, Hommel et al. 2001, Hofsten 2004]. Converging evidence from neuroscience shows that the brain provides representations of movements in terms of actions. A specific set of neurons, ‘mirror neurons’ are specific to the goal of actions and not to the mechanics of executing them [Gallese et al. 1996, Rizzolatti & Luppino 2001, Umilta et al. 2001]. The idea of goal representations is also supported by investigations in non-human primates [Graziano et al. 2002a, Niemitz 1989, 2002] suggesting postural coding as a general method of movement control [Fowler et al. 1980, Rosenbaum et al. 1995]. The concept of postural coding assumes a set of stored postures that is used for the direction of movements. From the perspective of postural coding, the formation of reference configurations in the motor behavior of newborns - that appeared as emerging attractors in the phase space - can be considered as part of a process, by which posture representations are established. Attractors in the phase space of neonate movements are attracting recurrent experiences of action and perception of certain configurations. Thus recurrence to reference configurations is the phenomenon of an attractor of action and perception, by which goal representations might be developed. We propose that neonates experience goal directedness as the matching of action and perception through the biodynamical organization of their body towards single final postures. From this point of view, the phenomenon of goal directedness can become apparent on a bodily level already in the coordination of exploratory movements of neonates.