4 On the Generation of Goal-Representations

Abstract

In recent theories in cognitive psychology human movements are considered in terms of goal-directed actions that are represented in the brain as goal states in a shared neural representation of action and perception. Converging evidence from developmental psychology regards the human newborn as “active problem solver”: Movements of neonates are not just reflexes but goal-directed actions. In the present study, application of symbolic dynamics of kinematic data from neonatal limb movements demonstrated self-organization towards transient reference configurations that have been postulated as start and target positions for movement sequences. By using symbolic dynamics we found transitions between qualitatively different dynamical regimes that were defined by the presence or absence of reference configurations. The transient emergence and disappearance of reference configurations provides a mechanism that might contribute to the generation of goal representations. We suggest that reference configurations provide perceptual goals as transient invariants in the otherwise highly variable exploratory process.

Introduction

Converging evidence from a wide range of research areas suggests that human movements are goal-directed actions rather than reactions [Hommel et al. 2001, Hofsten 2004]. This means that the goal or the target is represented as a goal state, namely as a successfully completed action pattern. The production of a goal-directed movement demands the nervous system to generate a complex muscle activation pattern that accomplishes the goals of the movement. The movement of the hand to a target position, for instance, can be executed by an infinite number of different muscle activation patterns, but is considered as the same action, if the goal remains the same. A goal state representation of actions integrates motivation, perception and planning [Johnston 2000, Hofsten 2004]. A common coding between perception and action is advocated in both motor control and development literature [e.g. Hofsten & Fazel-Zandy 1984**,** Hofsten & Rönnquist 1993, Knoblich & Flach 2001, Mechsner et al. 2001, Prinz & Hommel 2002, Claxton 2003].

Recent neuroscientific findings speaking in favor of an innate link between perception and action, suggest a shared neural representation of the action and perception of movements in terms of action end-states. A specific class of premotor neurons, designated as “mirror neurons”, discharge when executing as well as when observing an action [Gallese et al. 1996, Rizzolatti et al. 1996, Rizzolatti et al. 2002, Gallese 2003]. The discharge correlates with the goal of actions and not with parameters that form the movement [Umilta et al., 2001]. The mirror system embodies exactly the kind of action-perception matching that the idea of common coding requires. Meltzoff & Decety [2003] assume an innate connection between perceiving and performing of human actions on the basis of studies of human newborn imitation of facial gestures. In the present study, we addressed the question, where goal representations come from or how they develop or self-organize by looking at the organization of spontaneous limb movements of neonates.

Traditionally, the movements of neonates have been considered as reflexes, which are stereotyped, elicited and automatic. Although they serve fundamental functions for the subject, they are not regarded as goal-directed or volitional. However, a growing body of evidence suggests that neonatal behaviors are prospective and flexible goal-directed actions: Re- investigation of the classical primitive reflexes often revealed that they are goal-directed. For neonatal sucking, for example, Craig & Lee [1999] have shown that it relies on prospective monitoring of the flow of milk and that it is altered with respect to their mother's voice [Caspar & Fifer 1980]. Rooting, which is the movement of the mouth towards a cutaneous stimulus in the lower part of the face, is not automatic. It does not occur if the child touches him or herself or if it is not hungry [Rochat & Hespos 1997].

The Asymmetric Tonic Neck Reflex (ATNR) was re-examined by Meer et al. [1995]. Newborn infants in the supine position with their head turned to one side tend to extend the arm on the side where the head is turned and flex the contralateral arm. It was shown, that infants are in control of the arm movements in the ATNR by gently pulling downwards both arms: the ipsilateral arm resisted this pulling force in accordance with the ATNR. However, occluding both arms, neither arm resisted the pull. Presenting the view of the contralateral arm on a videomonitor initiated resistance to the pull in the contralateral arm. Another experiment revealed the ability of neonates to control position, velocity and deceleration of their arms in order to keep their hand within a presented narrow beam of light in front of the infant in otherwise dark surrounding [Meer et al. 1997]. Closing the visual-manual loop is suggested to allow exploration of the relation between action and perception and between visual and proprioceptive input in order to explore possibilities and constraints of the visuo-motor system.

Re-investigation of the stepping reflex of neonates by Zelazo et al. [1972] and by Thelen and colleages [Thelen & Fisher 1982, Thelen et al. 1984] challenged the traditionally view that cortical inhibition is responsible for the disappearance of this primitive reflex.

Zelazo et al. [1972] suggested that stepping disappears due to disuse and that practice preserves the movement patterns and even supports the conversion of the reflex into the instrumental activity of walking. Thelen and colleages [Thelen & Fisher 1982, Thelen et al. 1984] proposed that the disappearance of stepping could be explained by simple physical growth, in which muscle strength is limited rather than by cortical inhibition or learning. Their main argument is that stepping and supine kicking display identical kinematic and electromyographic characteristics and that kicking does not disappear with age. Furthermore, stepping 'reappeared' when infant's legs were submerged in water [Thelen & Fisher 1982, Thelen et al. 1984].

Spontaneous limb movements of neonates have been extensively studied in the framework of dynamic systems theory and in the context of motor development [e.g. Thelen & Fisher 1982,1983; Thelen 1985, Thelen et al. 1987b, Corbetta & Thelen 1996]. These studies have documented a substantial quantity of coordinative features in both arm and leg movements. In former studies, we investigated the coordination of the motor activity of the limbs as a four effector system by applying recurrence plot analyses to joint angle displacement trajectories and discovered recurrent patterns of temporal and spatial synchronized positions of the limbs into reference configurations [Aßmann et al. 2006, 2007]. In this study, we further investigated the postulated reference system in regard to a potential mechanism that underlies the generation of goal representations. For this purpose, we applied symbolic dynamics [Engbert et al. 1997a,b, Graben & Kurths 2003] to distance trajectories of endeffectors to transform the kinematic data into a suitable form of notation.

Symbolic dynamics belongs to the mathematical theory of dynamical systems for studying discrete-time dynamical systems with continuous state space. The fundamental idea of dynamic systems theory is to conceptualize systems geometrically in a state space. This is a graphical means to display all the states a system can reach in terms of positions, distances, trajectories and regions. States of the system are defined by sets of interdependent variables that can be in different states at different times. Attractors are regions in the state space that attract trajectories and where the system comes to rest. They can be a point, cycle or area of state space.

The basic idea of symbolic dynamics is to describe states and trajectories by symbolic sequences obtained from a partitioning of the system's state space into a finite number of regions, each of which is labelled with some symbol [Engbert et al. 1997a,b, Graben & Kurths 2003]. It has been successfully applied to physiological data, for example cardiorespiratory time series [Kurths et al. 1995, Schiek et al. 1998], movement control

[Engbert et al. 1997a,b, Scheffczyk et al. 1997, Tass et al. 1996], bone structure [Saparin et al. 1998] and neuronal spike trains [Rapp et al. 1994]. The approach of symbolic dynamics is based on a coarse graining of the system's dynamics by loosing some information about the details of the trajectory in phase space while leaving robust properties of the studied dynamical systems invariant. This simple but informative notation system of motor behavior, permits to address movements through symbolic language [Golani 1992] and revealed a mechanism that might lead to the formation of goal representations.

Data collection

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 with no medical problems during their first days of life. Their gestagational age 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 (50Hz) that focussed into a volume calibrated by means of 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 were analyzed.

Kinematic data

Movement kinematics were analyzed using the *Ariel Performance Analysis System (*APAS). Every 12 frames, the 2- dimensional positions of movement relevant joints were tracked 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. Distance trajectories of hands and feet from the center of the trunk in the xz-dimension were calculated from the coordinate data.

Data Analysis

Our strategy of analyzing the measured data consisted of two main steps: First, we transformed the kinematic time series into a sequence of symbols, comparable to the letters of some alphabet. This procedure simplifies the study of dynamics to the description of a sequence of symbols. By this way, the strategy of symbolic dynamics aims at extracting characteristic properties of the underlying dynamics, while some aspects of the details of the information are discarded [Hao 1991]. In a second step, we analyzed the distribution of the symbols both over the entire time series and in shifting windows along the time series, in order to get a quantitative evaluation of the evolution of the distribution of symbols.

Symbolic dynamics

Symbolic dynamics were applied to the movement behavior of neonates, by using a static two symbol coding (‘0’ and ‘1’) to capture the states of each of the four limbs at each sample point. To each value of the kinematic time series of one limb x_i ($i = 1,2, \dots, n$), a symbol s_n was assigned in the following way:

$$s_n = \{\ 0{:}\ x_i(t) < \theta_i\ ;\ 1{:}\ x_i(t) \geq \theta_i \}$$

where the threshold θ was defined as follows: In the first step, the first derivation of the distance trajectories was computed. In the second step, maxima extending the 0.9 quantil of the derivation trajectory were determined. Third, corresponding values of the distance trajectory were determined. In the last step, t was calculated as the mean of the estimated distance values and was assigned as limit between two states (figure 1). ‘0’ refers to a position proximal to the center of the trunk, ‘1’ refers to a distant position of the endeffector. From this procedure resulted four symbolic strings, one for each limb, consisting of a sequence of the single limb symbols 1 and 0.

The parallel processing of these four strings yielded a four dimensional symbolic sequence with each data point consisting of four single limb symbols, e.g. 1010 for a distant state of the right hand (1), a proximal state of the right foot (0), a distant position of the left hand (1) and a close position of the left foot (0).

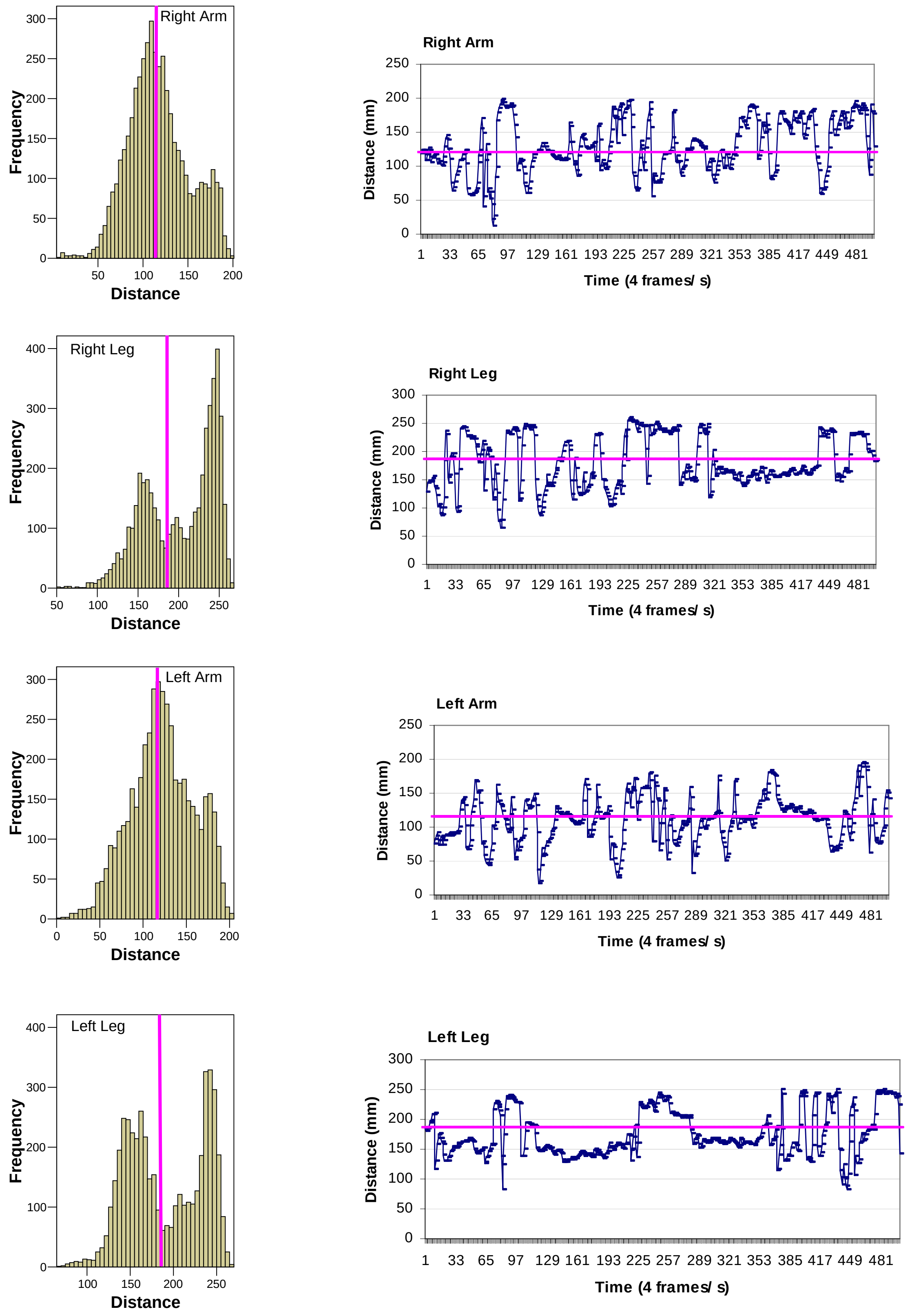


Figure 1. Left: Histograms of the distributions of the distance time series of the endeffectors hands and feet from the center of the trunk from a 20 minute (n = 4720) movement episode of infant 1. Right: Sections (n = 500) of the distance time series of the endeffectors hands and feet from the same time series as the histograms. The pink bars denote the thresholds for defining the symbols: values that are below the limits are transformed into the symbol 0, data points above the pink bars obtain the symbol 1.

From the combination of four values with two alternative states respectively resulted $4^2 = 16$ configurational symbols that represented body configurations defined by the combination of the four single limb symbols (in the order: right arm, right leg, left arm, left leg: 0000, 0001, 0010, 0100, 1000, 0101, 1010, 1001, 0110, 1100, 0011, 0111, 1011, 1101, 1110, 1111). These symbols can be further classified into 5 classes: (i) all effectors proximal (0000), (ii) one effector distant, three effectors close (0001, 0010, 0100, 1000), (iii) two effectors distant, two effectors proximal (1010, 0101, 1001, 0110, 1100, 0011), (iv) three effectors distant, one effector close (1110, 1011, 1101, 0111), (v) all effectors distant (1111). Figure 2 displays the resulting sequence of symbols from the single limb distance trajectories in figure 1.

Distribution of configurations

For the quantitative evaluation of the distribution of symbols, we estimated the occurrence and recurrence of each configuration. The occurrence is defined by the cumulative time of staying in a configuration, which is the sum of all data points that display this configuration. The recurrence is defined by the frequency of recurrence of each configuration, which is the sum of the first data points that a configuration occurs, irrespective of how long the configuration is maintained. These two measures were computed for 15 movement episodes first for the whole movement episode, and, secondly in sliding windows along the time series with a window size of 300 data points and a shift size of 20 data points. Then, we used the binomial score to test the statistical significance of deviations of the distribution of a configuration x in each of the sliding windows (x_1) from the distribution of the overall movement episode (x_2). Binomial z scores were computed according to:

$$z = p_1 - p_2 / [p\,(1-p)\,(1/n_1 + 1/n_2)]^{1/2},$$

with $p_1 = x_1/n_1$ and $p_2 = x_2/n_2$ being the relative frequencies of the absolute distributions x_1 and x_2 (with $n_1 = 300$ and n_2 = length of the movement sequence) of a configuration x, and $p = (x_1+x_2) / (n_1+n_2)$. The resulting z scores of the original time series were compared with the 0.05 and 0.95 quantils of z scores obtained from surrogate data by the same procedure.

Surrogate Data Analysis

The use of artificial random sequences, i.e. surrogate data, which mimic given aspects of the original time series but are random otherwise and correspond to a certain null hypothesis, has been successfully used in statistical testing for nonlinearity [Kantz & Schreiber 1997]. In this study, surrogates were created by the Iterated Amplitude Adjusted

Fourier Transform (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]. In this technique, the original distribution of the data is retained and linear correlations are preserved. Therefore, these surrogates correspond to the null hypothesis of a linearly correlated stochastic Gaussian process.

Results

In the supine position, newborn infants show spontaneous motor behavior that was analyzed on the basis of the movements of the four limbs, i.e. arms and legs. In former research, we focussed on the dynamics of the joint angle displacements and found that the movement behavior was structured by patterns of reference configurations [Aßmann et al. 2006, 2007]. To investigate the motor behavior of neonates in respect to the generation of goal representations, we analyzed the distance trajectories of the distal effectors, hands and feet. We first transformed the recorded time series separately for each limb into symbolic strings by a two-symbol coding and then put these symbolic sequences together and obtained strings with 16 symbols representing whole body configurations. In a second step, we analyzed the distribution of these symbols in the whole movement episode and in sliding windows along the time series and compared them with surrogate data.

Introduction of symbolic codes

Figure 1 displays the frequency distributions and trajectories of the distances of hands and feet to the center of the trunk of a typical movement episode. Pink bars denote the limits of the two symbol encoding between a proximal and distal position of the end effectors hands and feet. In general, the frequency distributions of the hands show a unimodal shape with a major peak in the middle range while the feet show a bimodal shape with two peaks: one in the lower range and one in the higher range. Some exceptional cases show unimodal distributions for the feet in the higher or lower range (data not shown). For the hands the limits are located near the unimodal peaks, indicating that the origin and end positions of hand movements are at the same distance to the trunk as the positions of maximal velocities. For the feet, the limits are located in the valley between the two peaks, indicating that peak velocity positions are at distances between start and target positions of the feet in leg movements. This means that the legs mostly moved between the proximal and distal position and rested in these scopes and rarely on the way in between. The unimodal distribution of the arms implicates that the arms mostly moved out of a position at medial distance in proximal and/or distant direction and came back to a resting position at a medial distance.

Now we consider the movement trajectories of the four limbs in parallel by combining the symbolic strings obtained from the first symbolic transformation by the two-symbol coding. From the combination of four binary values resulted $4^2 = 16$ defined configurations. Using this technique, the studied movements can be described as a discrete heterotype pattern sequence: limbs moved singularly or simultaneously together from one of the 16 configurations to the next configuration and stayed in successive configurations for varying spans of time. A switch from one configuration to the next one occured as soon as one of the limbs crossed the threshold from the proximal (0) to the distal (1) state or vice versa. Configuration switches normally were associated with velocity peaks, since the value of the threshold is computed via the mean of the peaks of the first derivation of the distance trajectory, which is the velocity. Figure 2 displays the sequence of configurations gained from the composition of the symbolic strings derived from the distance trajectories shown in figure 1.

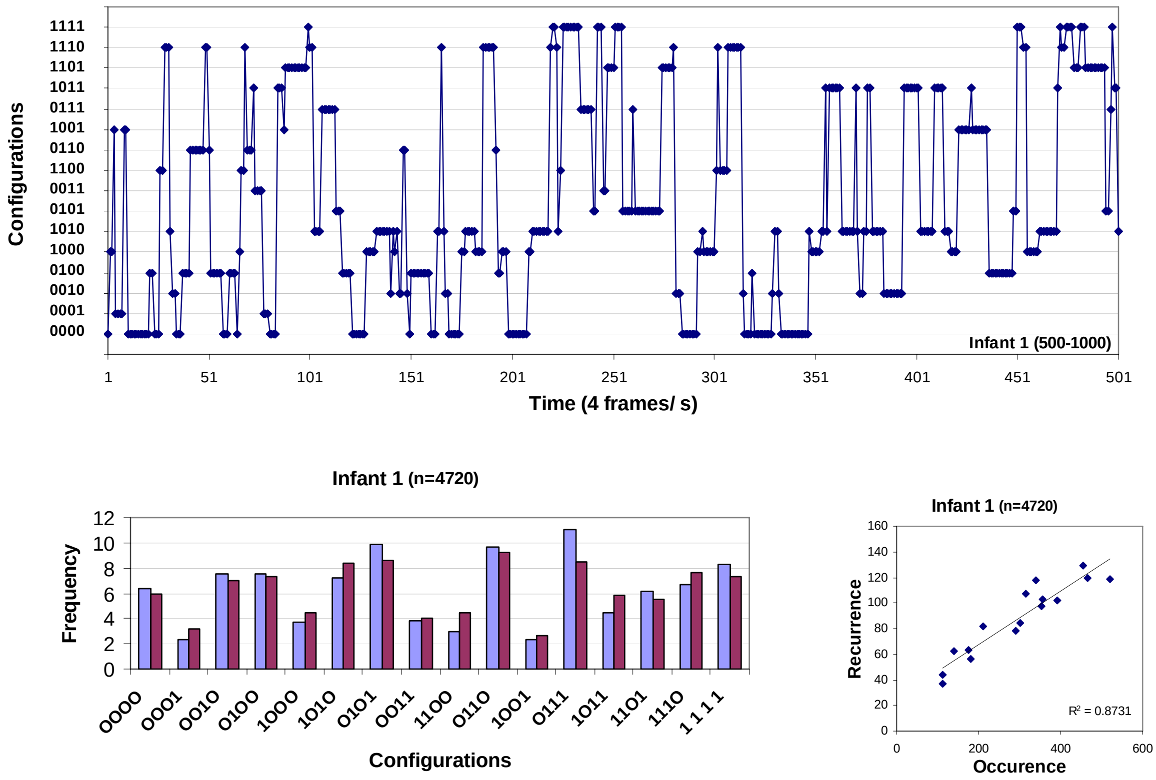


Figure 2. Top: Sequence of configurations derived via symbolic transformation from the time series displayed in figure 1 (data points 500-1000). Bottom: left: Histogram of occurrence (blue) and recurrence (purple) of each distinct configuration for the entire time series of infant 1 underlying the histograms in figure 1 (n = 4720). Right: Correlation diagram derived from plotting occurrence against recurrence of the entire time series (n = 4720).

Evaluation of the distributions of configurations

For a quantitative evaluation of the distributions of configurations, we estimated the cumulative percentage of the occurrence and recurrence of each configuration. The occurrence refers to the cumulative time of staying in a given configuration, which is the sum of all data points, in which this configuration was occupied. The recurrence refers to the frequency of recurrence to a certain configuration, which is the sum of the first data points that a configuration appeared, regardless of the maintenance of this configuration. Figure 2 displays the histogram of the occurrence and recurrence of each of the 16 configurations derived from the same data set underlying the histograms of figure 1. The occurrence plotted against the recurrence shows a distribution of data points along a line, which presents a high correlation between these two parameters ($R^2 = 0.87$). Figure 2 displays the correlation of the distributions of configurations derived from the same time series underlying the histograms presented in figure 1. The correlation shows that those configurations, in which newborns were staying for the longest cumulative time, were the same configurations, to which they returned with the highest frequency. Figure 3 presents the relative distributions of occurrence and recurrence of each configuration estimated for two movement episodes of six infants. In the distributions of single movement episodes, there are often certain configurations that show significant higher or lower values according to binomial test against uniform distribution ($p < 0.05$). Configurations with significant higher values are termed reference configurations. These configurations were variable in individual movement episodes, indicating that they were not constrained by the biodynamical properties of the physical body. Furthermore, not all movement episodes display significant values of one or more configurations. The presented histograms of the episodes of infant 6 and the histogram of the episode of infant 1 presented in figure 2 do not show any significant values. The absence of significant reference configurations might be due to switches between reference configurations within the time series, or to the absence of reference configurations over the entire episode. Significant values mostly concern values of occurrence, indicating that this parameter is more sensitive to nonlinearities than the parameter of recurrence.

In the distribution over all 15 movement episodes of all six infants studied (figure 4), there is no configuration that shows significant higher or lower values. However, the configurations 0000 and 1111, which are symmetrical over all four limbs (all four effectors proximal to the torso or all distal), show the highest values. The lateral symmetrical configurations 0011 and 1100 (right hand and foot proximal, left hand and foot distal or vice versa) show the lowest values.

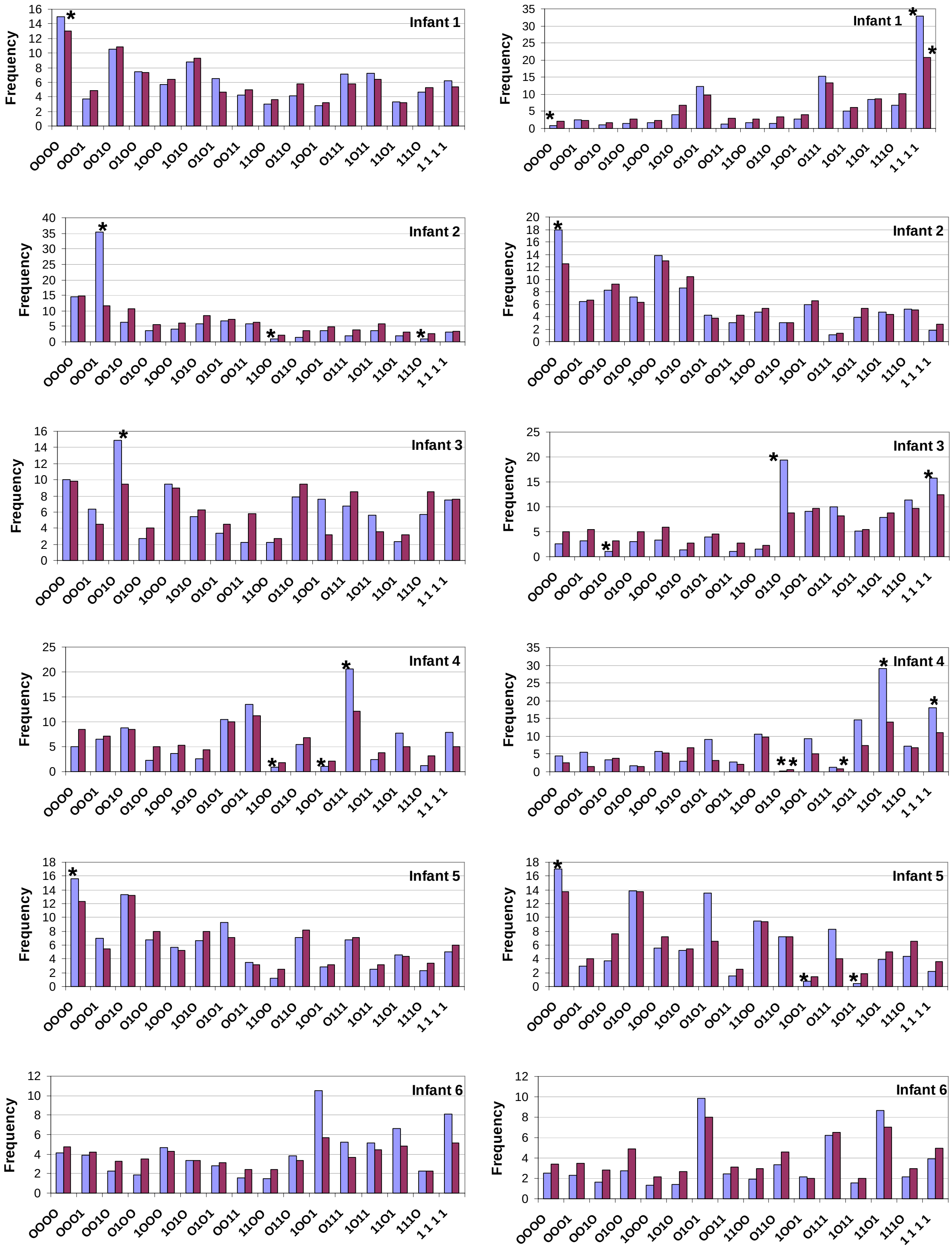


Figure 3. Relative frequency distributions of occurrence (blue) and recurrence (purple) for 12 movement episodes of six infants. Histograms in horizontal order correspond to the same infant on two different days respectively. Asterisks (*) mark significant deviations ($p < 0.05$) estimated by binomial testing against uniform distribution.

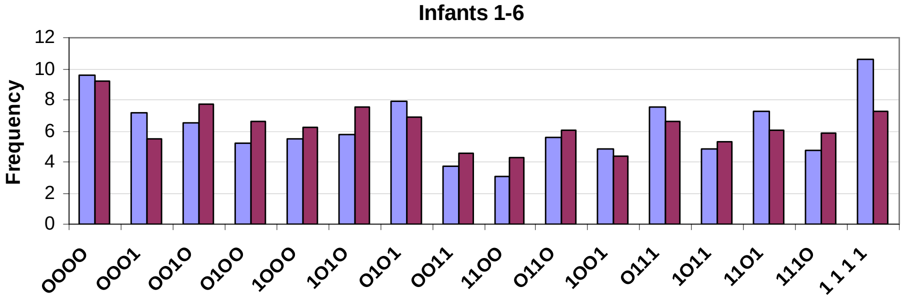
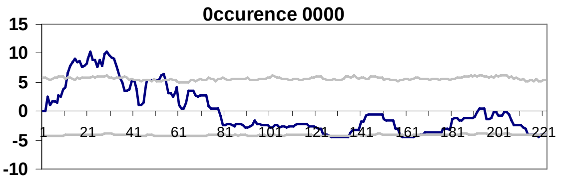


Figure 4. Relative frequency distributions of occurrence (blue) and recurrence (purple) pooled over all 15 studied time series over all six infants. There are no significant deviations estimated by binomial testing against uniform distribution.

In order to investigate the evolution of the relative distributions of occurrence and recurrence over time, we computed these parameters for each configuration in sliding windows over the time series and estimated the binomial scores against the relative distribution of the entire time series. The same procedure was applied to surrogate data derived from the original time series by an iterated amplitude adjusted Fourier transformation. The surrogates correspond to the null hypothesis of an underlying stochastic linear process generating the movement dynamics.

The individual configurations show significant sections of higher and lower z scores in comparison to the 0.05 and 0.95 quantils of the surrogates (figure 5). This means that in these sections nonlinearities occur in the occurrence and/or recurrence of the observed configuration. For example, configuration 0000 shows significant higher values at the beginning of the time series in both occurrence and recurrence. Configuration 0001 displays a section with significant higher binomial scores at the end of the time series in recurrence, but no significant sections in occurrence. Configuration 0010 shows significant higher values at the beginning of the time series in occurrence but not in recurrence. The most prominent deviations from the surrogates in occurrence and recurrence exhibits configuration 1001 in the middle of the time series.

The alternation of sections, in which individual configurations show a significant higher magnitude of occurrence and/or recurrence, first shows that these parameters are not invariantly coupled. Secondly, these transient nonlinearities show sequential dependencies that go beyond the linear correlations of the surrogates. This means, that in parts of the time series, infants preferred individual configurations, while others were unincisive and then, within the same time series, switched to other configurations. Configurations that show significant high values of occurrence and recurrence are termed reference configurations.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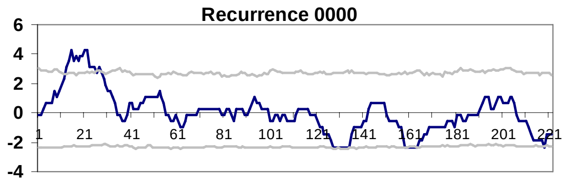
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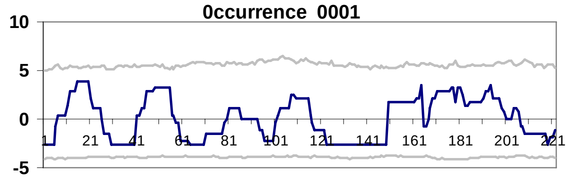
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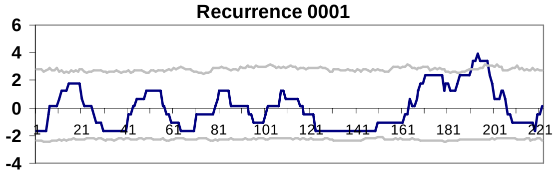
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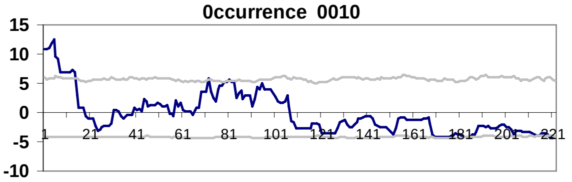
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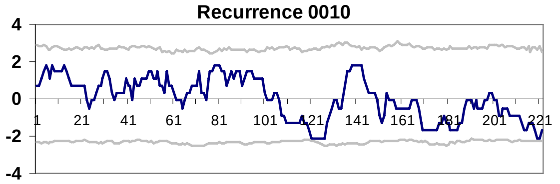
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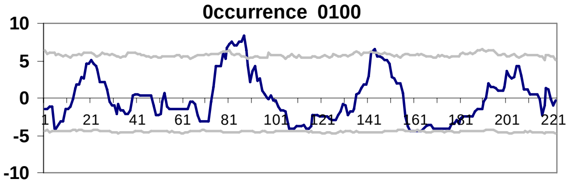
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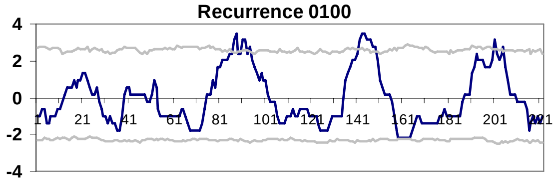
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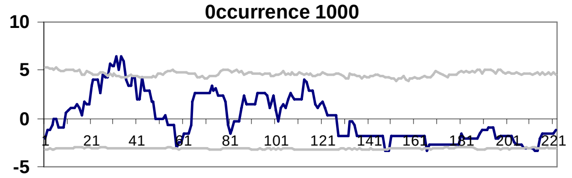
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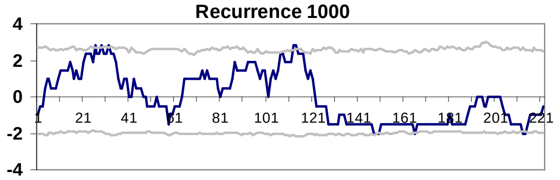
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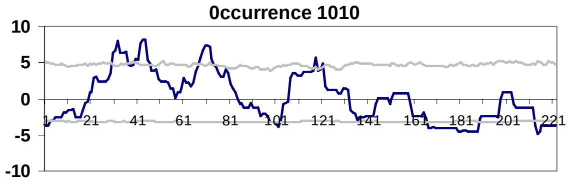
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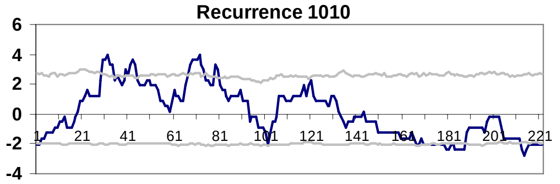
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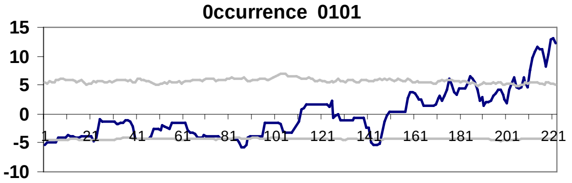
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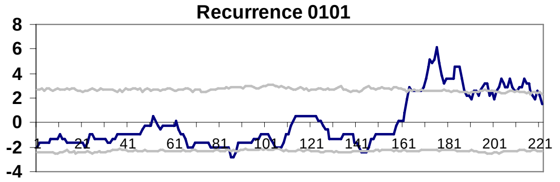
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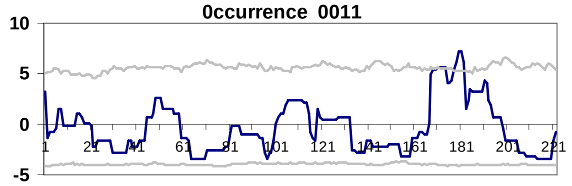
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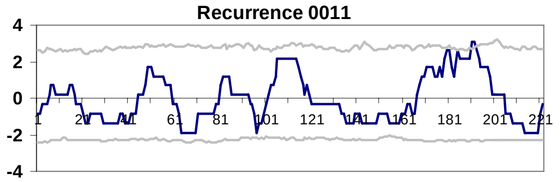
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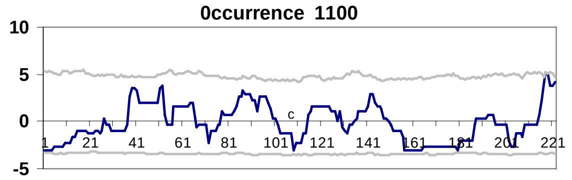
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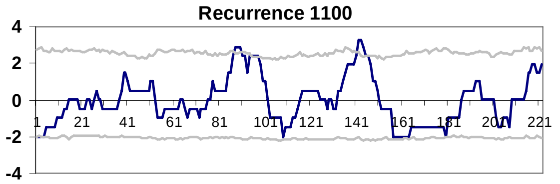
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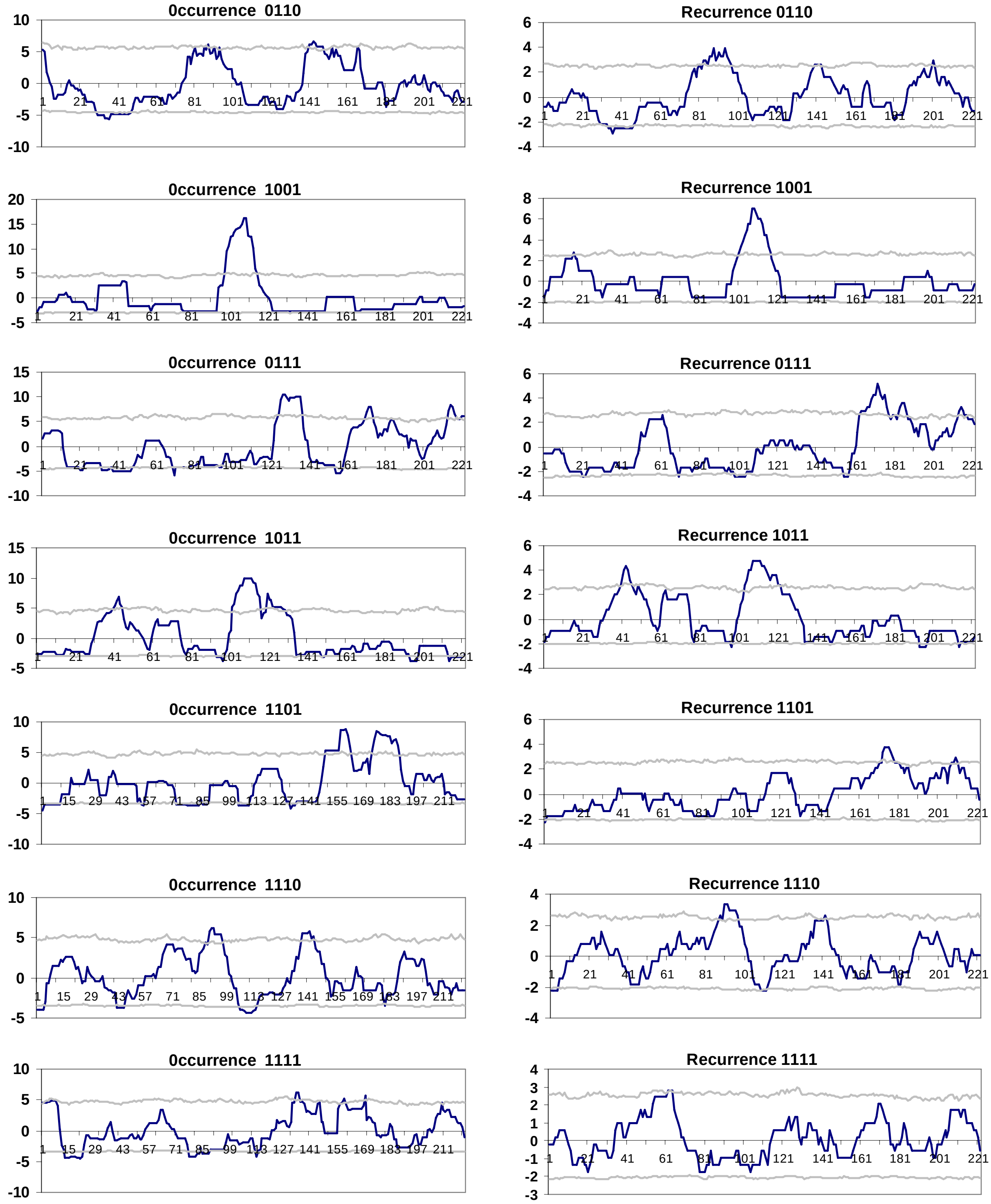

Figure 5. Evolution of binomial scores of the distribution of occurrence (left) and recurrence (right) estimated in sliding windows with a window size of 300 data points and a step size of 20 data points against the distribution of the entire time series of infant 1 at day 10, the same time series as in figures 1, 2. Blue lines present the progression of the original time series. Grey lines display the 0.05 and 0.95 quantils of 1000 surrogate time series.

Discussion

In this study, we investigated the spontaneous motor behavior of neonates by transforming distance trajectories of hands and feet from the center of the trunk into strings of four dimensional configurational symbols with one value for each limb. Our results demonstrate that, for individual movement episodes, there were configurations that occurred and recurred with significant higher or lower magnitudes than all other configurations. Reference configurations were variable in individual movement episodes. There were no significant values for occurrence or recurrence of a configuration, if relative distributions of these parameters were estimated over the sum of all 15 studied movement episodes. Investigation of the progressions of relative distributions of occurrence and recurrence of particular configurations within individual movement episodes revealed that all configurations displayed sections of significant higher and lower magnitudes compared to the distributions of the respective overall time series. Sections of higher and lower magnitudes of occurrence and/or recurrence of a particular configuration indicate an alternation of linear and nonlinear sections concerning these parameters. Alternation of linear and nonlinear segments in newborn movements concerning individual parameters have already been demonstrated in a former study analyzing joint angle displacement trajectories [Aßmann et al. 2007]. On the basis of recurrence plots, this study also suggested the emergence of reference configurations on different time scales. In the present work, we evaluated the distributions of individual configurations derived from distance trajectories of distal effectors on the time scale of movement episodes and on a lower time scale within episodes. The emergence of reference configurations was found on both time scales.

The detection of reference configurations brings up questions about the underlying mechanisms that generate these nonlinearities and their biological significance. Regarding the underlying mechanisms, a wide range of research has investigated the neurogenic and myogenic basis of neonatal spontaneous motor activity. Electromyograhpic studies revealed that newborn leg movements are characterized by phasic antagonist co-activation to initiate the flexion phase and almost no muscle intervention during the initiation of the extension phase [Thelen & Fisher 1982, 1983, Thelen 1984, Okamoto et al. 2003]. Reciprocal excitation of antagonist motoneurons by primary afferent fibers in spinal pathways has also been found in studies of the newborn stretch reflex [Myklebust 1990, Myklebust & Gottlieb 1993]. The resulting movement is thought to be due to quantitative differences in the strength of antagonistic contraction and passive forces [Lestienne 1979]. Therefore, supine limb movements appeared to rely on the interplay of actively supplied and reactive forces with the whole limbs as elementary units of control (or behavior) rather than individual muscles or joints.

Thelen et al. [1987b] described single kicking movements as spring-like oscillatory movements. Energy pulses from co-active muscle bursts provide a forcing function for the whole leg, so that the space time trajectory naturally falls out from the dynamic properties instead of a one- to- one correspondence between the neural impulses and the limb trajectory. In support of such a view are studies of spontaneous leg movements in infants with cortical lesions (periventricular leukomalacia) and unilateral weight manipulation of the legs. They suggest that the corticospinal tracts are not involved in the patterning of spontaneous kicking movements [Vaal et al. 2000, 2002]. From observations of supine kicking in anencephalic fetuses [Visser et al. 1985] and stepping in the erect position in anencephalic newborns [Peiper 1963], it has been concluded that the activity of early leg movements originates in spinal networks [Forssberg 1985]. Network driven spontaneous activity has been extensively studied in the spinal cord of the chick [e.g. O'Donovan et al. 1998, O'Donovan & Chub 1997, Wenner & O'Donovan 2001] and is a common feature of developing circuits in neural systems [O'Donovan 1999].

From these examinations, reference configurations of neonates as found in the present study probably arise from dynamic interaction of spontaneous network activity of the spinal cord and biodynamic properties of the physical body. An illustrative model from dynamic systems theory that provides an explanation to the emergence and disappearance of reference configurations is the concept of chaotic itinerancy (figure 6). According to this idea, a system wanders from one quasi-attractor (in our case a configuration or set of configurations) to another and gets entrained in each attractor (high recurrence rates to one configuration or a set of configurations) only for a while [Tsuda 1991].

Chaotic itinerancy is a phenomenon that addresses the underlying dynamics of complex systems and can explain the emergence of entirely new patterns of behavior. It has been used as a theoretical tool to understand nonstationary behavior of high dimensional complex systems that consist of complex subsystems [Ikeda 1989, Kaneko 1989, 1990, Tsuda 1990, 2001]. It also is involved in a baby model by Kunioshi & Sangawa [2006], in which chaotic oscillators are coupled through embodiment. The idea of chaotic itinerancy is related to other dynamic concepts like heteroclinic cylces or unstable periodic orbits [Rowe 2002, Ott & Spano 1995] and has been applied to e.g. physiological neural nets [e.g. Kay et al. 1996, Freeman 1995, 2003, Kozma & Freeman 2001], optical systems [Otsuka 1990] and artificial neural networks [e.g. Tsuda 1996, 2001, Kanamaru 2006, Namikawa 2006, Cortes 2007].

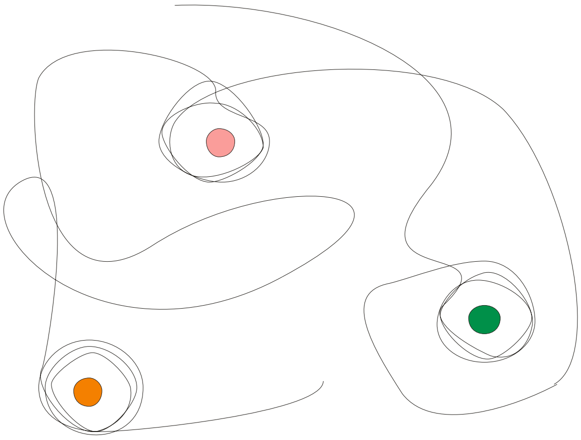

Figure 6. Schematic representation of chaotic itinerancy. The dynamic orbit representing the behavior of the system is attracted to certain attractors, stays for a while around it and then leaves it towards an other attractor. In chaotic itinerancy, attractors are referred to as attractor ruins that are destabilized Milnor attractors [Milnor 1985]. This means that attractors are unstable and transient (quasi attractors). In newborn motor behavior, attractors (orange, pink and green points) represent single reference configurations (point attractor) or alternation between several reference configurations (limit cycle attractor).

Characteristics of chaotic itinerancy are (i) the existence of quasi-stable attractors, (ii) switches between these quasi-stable states and (iii) the interplay between low dimensional and high dimensional behavior. Looking at parallels to our findings of transient reference configurations in the motor behavior of neonates, (i) quasi-stable attractors are reference configurations defined by high values of occurrence and recurrence to one (point attractor) or several (limit cycle attractor) reference configurations. (ii) Switches between reference configurations indicate that these attractors are quasi-stable. (iii) Surrogate data testing uncovered transitions between sections of low- and high dimensional behavior: Low dimensional behavior corresponds to nonlinear movement segments in the vicinity of an attractor, which means significant high binomial z scores for a particular configuration. High dimensional behavior corresponds to linear behavior segments at considerable distance from an attractor, which means the absence of high recurrence rates to any one configuration.

The idea of itinerant underlying dynamics offers two appealing possibilities: first, entering of the orbit into the vicinity of an attractor reduces the dimension or degrees of freedom of the system and allows for a high dimensional system to behave like a low dimensional system. The latter is both assumed to be the precondition for effective computations [Sato et al. 2000] and a solution to the degrees of freedom problem asked by Bernstein [1967]. Secondly, behavior around the attractors is defined by new variables that describe the low dimensional process. Thus, the emergence of completely new systems becomes possible. Looking at the movement behavior of neonates as a nascent system, 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 of new forms of behavior. The latter are indicated by new reference configurations that emerge and disappear and can be referred to as freezing and freeing of degrees of freedom.

A process parallel to the emergence of reference configurations as found in neonate movement behavior has been observed for the acquisition of speech by Tomasello et al. [1997]. Acting on the assumption of the highly item-based nature of early patterns of speech, complement clauses are suggested to be introduced by ‘constructional islands’ or ‘verb islands’ that act as reference points, around which formulaic frames are centred [Tomasello et al. 1997, Tomasello 2006]. In this case, ‘verb islands’ can be considered as parallel to reference configurations in spontaneous movements, around which movement trajectories and their relation to other configurations are explored. Another mechanism parallel to the emergence of reference configurations is the emergence of ‘home bases’ in the exploratory behavior of animals [Eilam & Golani 1989]. The relation to this concept has been discussed in a study investigating the dynamics of joint angle displacements in human newborn motor behavior [Aßmann et al., 2006]. On a broader time scale, Thelen & Smith [1994] suggested that infant development can be understood as “sequences of system attractors of varying stability, evolving and dissolving over time” (p. 86).

Concerning the biological significance of the mechanism of transient reference configurations found in our study, they might be a facility, by which goal representations are generated. As mentioned above, spontaneous limb movements of neonates are assumed to be due to network driven spontaneous neural activity rather than controlled by the corticospinal tract [Vaal et al. 2000, 2002]. Furthermore, movement patterns of neonates were more patterned than the electromyographic activity that reflects the neural control of the motor behavior [Thelen & Fisher 1983].

In newborn kittens and monkeys, it has been shown that stimulation of corticospinal axons impacts the excitability of spinal neurons throughout the entire grey matter, but does not produce effective muscle contractions [Armand et al. 1997, Meng & Martin 2003]. From these findings, it has been presumed that functional corticospinal innervation in humans also occurs postnatally. However, functional synaptic corticospinal projections to spinal α-motor neurons and Group Ia inhibitory interneurons were found in humans prior to birth [Eyre et al. 2000, 2001]. Monosynaptic input from the motor cortex to spinal α-motor neurons via the corticospinal tract provides the capacity of skilled movements of the extremities [Armand et al. 1996]. However, independent finger movements for example are far away of being present at birth and develop between 6 and 12 months of life [Lawrence & Hopkins 1976, Eyre et al. 2000]. From these findings, Eyre [2003] concluded, that “rather than furthering motor control per se, this early innervation most likely occurs to allow activity in the corticospinal system as a whole to shape the development of the motor cortex and the spinal motor centers” (p. 94). From this perspective, early movement coordination is a dynamic interaction between the neural and musculoskeletal systems within the external environment [Heriza 1991, Thelen & Smith 1994, Vaal et al. 1995, Vaal et al. 2000]. Early motor experiences are important for functioning of the corticospinal tract [Martin et al., 2004], and therefore, the structuring of the afferent input, that relies on the biomechanical properties of the body influences and shapes the manner of this functioning.

For example, Piek & Gassen [1999] already suggested that rhythmical behavior like kicking establishes basic representations of leg movements. Hopkins & Prechtl [1984] proposed that kicking functions in terms of kinaesthetic calibration of the limbs. Turvey & Fitzpatrick [1993] suggested that strong interjoint couplings provide pattern stability, within which the exploration of intrinsic limb dynamics becomes possible. From our findings, transient reference configurations can be considered as providing transient pattern stability that allows for the exploration of intrinsic limb dynamics and trajectory formation. The result of this biomechanical self-organization into reference configurations is an input into the cortex via proprioceptive afferents that might provide the basis for goal representations. ‘Non-directed’ neural activity is transformed via the biomechanical properties of the body into goal-directed input into the nervous system. Goal-directedness appeared to be a natural feature of the biodynamical physical condition of the body, manifesting e.g. in simple extensions and flexions of limbs and resulting configurations of the latter.

The generation of goal-directed movements by the spinal cord and the impact of individual limb positions has been shown by experiments with spinalized frogs. Goal-directed multi-joint movements were elicited by electrical stimulation of distinct areas of the spine of spinalized frogs [Fukson et al. 1980, Berkinblit et al. 1986]. The movement of the hindlimb in the wiping reflex consists of an intermediate posture irrespective of forelimb posture and an end position that was determined by forelimb position [Fukson et al. 1980]. Limb position in general appears to strongly influence the direction of force resulting from spinal cord microstimulation [Giszter et al. 1993].

The idea of target-positions of effectors is well-known from the concept of postural coding as a general method of movement control, which has been originally utilized in the study of speech production and facial expression [Fowler et al. 1980, Ekmann 1993].

Imitation of facial expressions in newborns is considered to provide evidence for an innate coupling of action and perception, which points towards a common neural coding [Meltzoff & Moore 1997]. Recently, Graziano et al. [2002a,b] found that electrical stimulation of motor cortex neurons in monkeys caused the relevant joints to move into specific final postures, independent of the starting position.

Our findings that newborns '*spontaneously*' displayed certain preferred configurations that are due to biomechanical constraints rather than goal-directed in the sense of adult reaching movements, suggests that neonatal movements self-organize towards stable regions in phase space. The latter can be conceptualized as perceptual goals that serve as reference points in the exploration procedure of postures and trajectories. In dynamic terms, a set of propriosensory inputs acts as a quasi-attractor that is used to explore the different neuromuscular activation patterns and leads the effector into the attractive posture. In this view, final goal postures are matched to experiences of trajectory formation on a perceptual level and lead to a common representation of action and perception.

Many studies have demonstrated the strength and regularity of effector interactions as a means to reduce the degrees of freedom problem [Turvey 1990, Kelso & Zanone 2002]. In the case of newborn movements, the reference configurations that arose spontaneously from effector interactions, can be considered from an action-perception point of view as perceptual goal-configurations. Familiar sets of proprioreceptive activation attract the system. During exploratory motor behavior, fluctuations in subsystems (single limbs) lead to new combinations of sensory input. From the amplification of such fluctuations, recurrent passing through certain proprioceptive states occurs, and - after the cumulative process of familiarization - new reference configurations emanate. In the process of self-exploration through spontaneous activity, reference configurations can act as match points between perception and action that provide information of stable regions in the high-dimensional space of potential movements. We assume, that the recurrence of reference configurations in the spontaneous motor behavior of neonates reflects a self-organizing mechanism of the early embodied cognitive system, by which information about bodily dimensions and movement limitations are laid down in the synaptic connectivity of the sensori-motor system.