2 Recurrence Plot Analyses suggests a novel Reference System involved in newborn spontaneous Movements

Abstract

Newborn movements are well-studied in terms of reflexes, muscle synergies, leg coordination and target-directed arm/hand movements. As former approaches concentrated mainly on separate accomplishments there remained a clear need for more integrated investigations. Here we report an inquiry that explicitly concentrated on such a perspective and additionally was guided by the methodological concept of home base behavior, which Ilan Golani developed for studies of exploratory behavior in animals. Methods from nonlinear dynamics, such as symbolic dynamics and recurrence plot analysis of kinematic data received from audiovisual newborn recordings, yielded new insights into the spatial and temporal organization of limb movements. In the framework of home base behavior, our approach uncovered a novel reference system of spontaneous newborn movements.

Introduction

Compared to mature skilled actions of adults and older children, which are smooth and precise, the movements of newborn and young infants lack the smooth temporal and spatial integration of coordinated actions. Limbs, head and trunk seem to move as random elements, without reference to each other. Peiper [1963] described this overall impression of disorganization by saying that these “mass movements” are “awkward and abrupt and follow each other without connection” (p. 254).

However, there are many examples, in which newborn actions show some elements of coordination, meaning that various muscle groups work together rather than as independent elements. These include well-known newborn reflexes such as the Moro, grasp, palmar, and plantar reflexes [Barnes et al. 1978, Capute et al. 1978), functional actions such as rooting, sucking, and swallowing [Crook 1979, Peiper 1963], hand mouth synergism [Korner & Beason 1972], reaching towards objects [Hofsten 1982] and the coordination of leg movements in spontaneous kicking [Thelen & Fisher 1983, Thelen et al. 1987c].

These results on coordinative features in the motor behavior of neonates motivated a more integrated investigation of the coordination of the overall system. New methods from nonlinear dynamics were combined with inspiration from models from animal exploratory behavior. This combination allowed a new understanding of the intrinsic dynamics of the unintentional movements of human infants. To establish a common language between biologists, psychologists and systems theory scientists, it is necessary to obtain a notation system of behavior, which corresponds to the natural morphology of behavior and is informative, parsimonious and of predictive value. Common movement patterns, that are masked by ‚ordinary language' used in the terminology of biology and psychology, can be revealed by a suitable notation system [Eilam & Golani 1988, Golani 1992]. According to the results of a recurrence plot analyses [Eckmann et al. 1987, Ott 1993], we applied symbolic dynamics [Engbert et al. 1997a,b, Graben & Kurths 2003) to transform the kinematic data into a simple but informative form of notation. These methods revealed a reference system involved in the behavioral motor organization that showed parallels to a methodological concept developed by Ilan Golani, to discuss rat exploratory behavior as a natural manifestation of spatial learning [Eilam & Golani 1989, Biegler & Morris 1996, Etienne et al. 1996]. When rats are placed in a novel environment, they typically establish a homebase. This is the place where they stay for the longest cumulative time and the number of visits is especially large [Eilam & Golani 1989].

In the case of spontaneous newborn movements, the homebase was 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, recurrence plot analyses of the newborn movements suggested a reference system that reminds - according to the above mentioned criteria - of homebase behavior. This concept provides a basis to discuss the role of a reference system in newborn spontaneous movements in terms of concepts of spatial learning. Our study was designed to test whether and how new methods and concepts from different research fields can come together and shed light on old topics. It suggests a reference system of static body/limb configurations that indicates a principle of coordination in newborn spontaneous movements.

Methods

Subjects

Subjects were 6 apparently normal, full-term infants, 3 boys and 3 girls. Two subjects, children 2 and 3 were dizygotic twins. Subjects were recruited in a maternity clinic to participate in a 'mini-longitudinal' study of the development of newborn spontaneous movements over 3 to 10 days, depending on how long the mothers stayed at the clinic.

Procedure

The design of these observations was a frame-by-frame movement microanalysis using videotape recording. To videotape awake infants, parents were asked to bring their infants to the laboratory between two anticipated feedings. Kinematic data collection used videorecording with three cameras (50Hz) in a volume 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 the 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 sequences showed continuous motor activity without resting or crying intervals longer than 20 seconds.

Kinematic data

Movement kinematics were analysed 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 each perspective. The APAS Software allows by triangulation to compute from multiple two-dimensional frames a 3-dimensional picture. 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 the joint angle displacement of the elbow and shoulder of one arm and those of the hip and knee of the same leg displayed a correlation of 0.8 (data not shown), the movements of each limb could be captured by the displacement of one angle. The arms were defined by the angle of the elbow, the legs by the knee angle.

Recurrence plot analyses

This method was first introduced to visualize the time dependent behavior of a dynamical system, which can be represented as a trajectory $x_i \in \mathbf{R}^n$ ($i = 1, \ldots, N$) in a n-dimensional vector space [Eckmann et al. 1987]. It represents the recurrence of the trajectory in phase space to a certain state, which is a fundamental property of dynamical systems [Ott 1993]. The main step of this visualization is the calculation of the NxN matrix,

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

where ε is a cut off distance, $\| \cdot \|$ is the maximum norm, and $\Theta(\cdot)$ is the Heaviside function. The binary values in $\mathbf{R}_{i,j}$ can be simply visualized by a matrix with the colours black (1) and white (0). The recurrence plot (RP) exhibits characteristic large-scale and small-scale patterns that are related to typical dynamical behavior [Webber & Zbilut 1994]. For a periodic signal of period T, the plot looks like figure 1a for very small ε. This is a series of stripes at 45 degrees, with stripes separated by a distance of T in the vertical and horizontal directions. The RP of a chaotic system (figure 1b) has a more complicated structure. (i) Due to the exponential divergence of nearby trajectories, the diagonal lines are interrupted, and (ii) the distance between diagonal lines is not constant, due to the multiple time scales present in chaotic systems. Brief episodes of parallel stripes at 45 degrees are hints of almost periodic trajectories. For the RP of white noise (figure 1c), such a structure is not evident. It consists of mainly single points, indicating the randomness of the system. In all RPs, there is a stripe along the diagonal corresponding to i = j. While diagonals indicate similar evolution of different parts of the trajectory, horizontal and vertical black lines show, that the state does not change for some time.

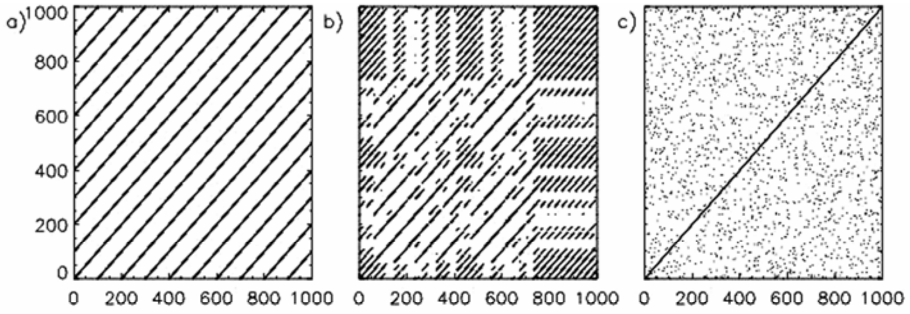

Figure 1. a) RP of a periodic function, b) RP of a chaotic system (the Rössler system with standard parameters), c) RP for random white noise.

To capture the spontaneous movements of newborns, the configurational state of their body was defined by the four joint angles of the limbs. Four values of the angles belonged to each sample point of the time series. For a sample point i the vector $x_i = (w_1(i), w_2(i), w_3(i), w_4(i))^T$ was generated, with $w_{1\text{-}4}(i)$ being the values of the four joint angles at sample point i. The same procedure was applied for the sample point j: $x_j = (w_1(j), w_2(j), w_3(j), w_4(j))^T$. These two vectors, which actually represented the same time series, depicted the state of the system at sample point i and j with four angles respectively. In the RP, the time series x_i on the horizontal axis and x_j on the vertical axis are compared to each other sample point by sample point. If the four values of the sample points i and j converge, there is a black dot, indicating that the state of the configuration in x_i and x_j are the same (according to the value of ε). If even one of the four values differs, there is a white dot representing different configurations.

Symbolic dynamics

Symbolic dynamics is a natural way to describe data which appear as sequences of discrete states. This approach is based on a coarse-graining of the dynamics; i.e. the time series are transformed into symbolic sequences by using very few symbols. This way one loses some amount of detailed information, whereas some of the invariant, robust properties of the dynamics are kept [Hao 1991, Engbert 1997a,b, Graben & Kurths 2003). To describe the body configurations of newborns, we introduced a two-symbol encoding into the kinematic data. On the basis of the histograms in figure 2, each limb was defined into two states: either the limb was extended, or it was considered to be bent. In terms of the arms, an elbow angle shorter than 60 degrees was regarded as angled, higher than 60 degrees as stretched. Considering the legs, a knee angle shorter than 120° degrees was regarded as bent, higher than 120 degrees as extended. From the combination of four angles with two possible states respectively, there were 16 differently defined configurations.

To analyze the distributions of the configurations, we measured two parameters: The cumulative time of staying in a configuration was defined as the sum of all data points that showed this particular configuration. The second parameter was the frequency of recurrence to a configuration. It was the number of events that a specific configuration recurred, irrespective of how long the configuration was maintained.

Results

In our study, the spontaneous motor behavior of neonates was analyzed on the bases of the movements of the four limbs, i.e. arms and legs. For this purpose, we first focussed on single limbs and then examined how this behavior assembled into overall movement patterns. The following report starts with results of recurrence plot analyses and symbolic dynamics referring to a 20 minute movement sequence of one child.

Motor behavior of the single limbs

The frequency distribution of the segmentangles, in which the limbs resided, revealed one or two areas, in which the limbs stayed for a longer cumulative time than in other domains. Figure 2 shows for the arms a unimodal shape with a major peak in the lower range between 20 and 60 degrees; the legs show a bimodal shape with two equal peaks: one in the lower range between 50 and 90 degrees and one in the higher range between 130 and 170 degrees. These distributions indicate, that the arms were predominantly located in a bent position and relatively seldom in an extended position; the legs were with a comparable frequency located in an bent or extended position, whereas the intermediate range (90-130 degrees) was comparatively seldom found. This means that the legs mostly moved between the angled and the stretched position and rested in these ranges and rarely on the way in between. The unimodal distribution of the arms implicates that the arms mostly moved out of the bent position and back to the bent position and exhibited only one resting position.

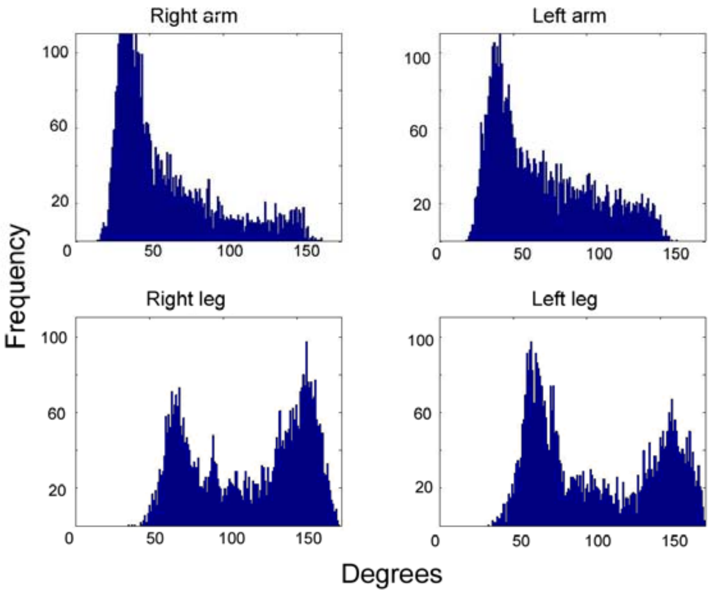

Figure 2. Frequency distribution of the joint angles of the single limbs for a 20 minute movement episode. The frequency on the y-axis is plotted against the values of the jointangles on the x-axis.

Recurrence plot analysis

From the combination of the joint angle positions of the four limbs at each sample point resulted certain configurations, in which the body resided. The dynamics of the distributions of these configurations can be visualized by a recurrence plot (RP). Figure 3 presents the RP of the motor behavior of a newborn child defined by the described configurations. The first thing we learn from the RP is that the movement organization was static, not dynamic states. This is shown by the rectangular structure of the RP on a time scale of 10-15 sample points (3 seconds). Such structure results from the black rectangles being piled upon each other and interrupted by white rectangles. Black rectangles represent recurring configurations and white rectangles represent other configurations.

If we look at the recurrence pattern of a single configuration by following a vertical line, we see that certain configurations had a high rate of recurrence, indicated by a high number of black dots. Other configurations occurred rarely, indicated by a low number of black dots, seen as a white line. A closer look at single configurations reveals in parts of the plot predominantly black, in other areas 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 the rectangular structure on a higher time scale of 400-500 points of measurement. This pattern arose from particular configurations recurring with certain regularities in time windows of roughly 100 seconds. On this time scale alternations between different configurations become apparent and show that 2-3 configurations could serve as a reference system. Absent diagonal structures reveal, that there were no recurring movement sequences or sequential recurring successions of configurations.

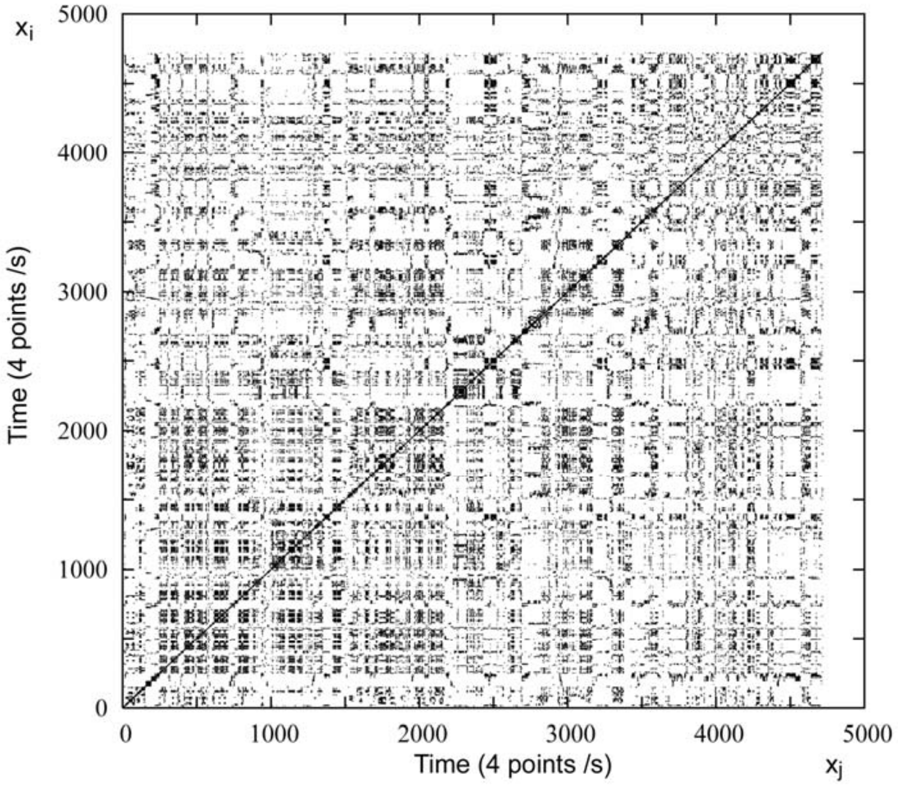

Figure 3. Recurrence plot of the integrated joint angle displacement time series with dimension m = 4 and ε = 30.0. The horizontal and vertical axis displays the time series x_i and x_j, respectively.

Another measure of RPs is the length of vertical structures. The length of black vertical lines shows how long a particular configuration was taken; the length of white vertical lines specifies the intervals between the recurrences of a configuration. Figure 4 exemplifies the frequency distribution of black vertical lines for two sample points and for white vertical lines for one sample point. Both the lengths of vertical black and white lines do not display predominant values if calculated over the overall time series. Such means that the time spans, with which a configuration was maintained, and the intervals of recurrence to this configuration were very variable.

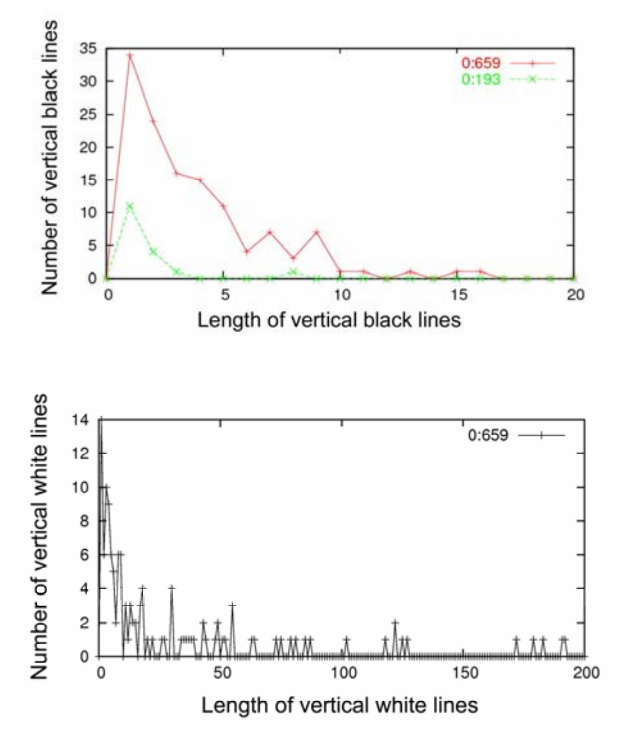

Figure 4. Frequency distributions of vertical structures in the recurrence plot. a) The number of vertical black lines on the y-axis is plotted against the length of vertical black lines on the x-axis for sample points 193 and 659. b) The number of vertical white lines on the y-axis is plotted against the length of vertical white lines on the x-axis for sample point 659.

Frequency distribution of the configurations

The RP demonstrates that decisive configurations were taken very long and often, while others were taken much less frequently and with shorter duration. For further quantification we introduced symbolic dynamics. On the bases of Figure 2, each limb was defined by a bent or extended state. From this two-symbol coding of four limbs resulted 4^2 defined configurations. By the use of this technique, the studied movements were understood as a sequence of configurations: limbs moved singularly or simultaneously from one of the 16 configurations to the next one and stayed in each configuration for varying spans of time. The cumulative time of staying in a given configuration plotted against the frequency of recurring to the same configuration shows a distribution of datapoints along a diagonal. This presents a high correlation between these two parameters (Figure 5). This correlation shows that those configurations, which were taken for the longest cumulative time were the same ones that were taken with the highest frequency. Furthermore, the plot demonstrates that there was one configuration that clearly showed the highest values.

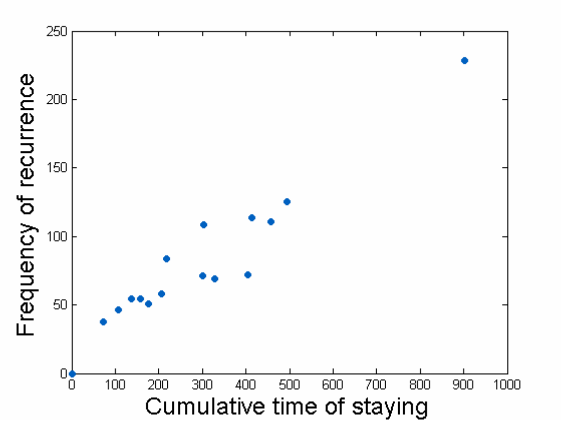

Figure 5. Correlation of the cumulative time of staying in a given configuration on the x-axis versus the frequency of recurrence in this configuration on the y-axis.

Discussion

Our analyses of motor behavior uncovered preferred configurational positions of single limbs that displayed confined ranges of joint angles. Whereas the unimodal distribution of the arm positions in a lower scope of angles is biomechanically plausible, the bimodal shape of the distribution of the angles of the legs in the low and high range of angles appears somehow remarkable. Here, the peaks in the distributions of leg- and arm-related data can be understood as reference points in the movement patterns of limbs.

In addition, our analyses have shown that all configurations with the longest cumulative time of staying were at the same time those with the highest frequency of recurrence. This phenomenon reminds of the concept of homebase behavior, developed by Eilam & Golani [1989] for studies of exploratory behavior of rats placed in a novel environment. Crucial characteristics of the homebase are the longest cumulative time of staying in this place and the highest number of visits. In spite of the clear differences between the two accomplishments, i.e. the locomotion of a rat and the spontaneous movements of a newborn, there are parallels that suggest considering the special static states or configurations of newborn movements as analogous bases, in which the system can settle and start new movements.

The RP of the kinematic data shows that (i) the dynamics of the system can be characterized by static states that (ii) certain configurations were taken especially often in defined time windows, characterizing these time frames by certain combinations of configurations and (iii) that the durations of staying and the intervals of recurrence of decisive configurations were variable. Referring to these features, the RP indicates that in given time windows, also combinations of configurations acted as homebase configurations. This reveals another parallel to the homebase behavior of rats, which establish several transient homebases in the course of the exploratory process [Tchernikowsky et al. 1995].

Repeating patterns of the RP on different time scales suggest the existence of principles of organization that could play a role at different hierarchical levels [Anderson 2000]. On a lower level, single limbs seemed to indicate reference points to which they returned. On a higher level, however, the organization of configurations seemed to be more complex and related to association groups that required a special reference system. We tend to presume that the combinations of reference configurations in the spontaneous newborn movements can be considered as groups of temporally associated configurations, and also that the spontaneous movements can be characterized by a structural hierarchy. Such presumption requires further inquiries into the temporal diversity of intervals within and between the various association groups, which can be tested e.g. by analysing the lengths of vertical structures in the RP.

Since all individuals showed one or several, but different reference configurations, which even changed over time, the tendency to establish these reference points appeared quite notable. We assume that these features do not simply reflect physiological properties or constraints of the body, and thus tend to explain them as an endogenous component of the motor behavior. Such a view would, however, require further inquiries into the reference system of static configurations and the dynamic part of the spontaneous movements, as well. Future investigations could be done by analysing the temporal parameters represented by the lengths of the vertical structures in the RP in reference to the homebase configurations.

Our finding that the spontaneous movements were structured by static configurations and that the newborns returned to specific configurations could be explained also by a mechanism that supplements the model cited above. That is, there could be some kind of memory system, which captured the spatial relationship of the limbs and provided a reference frame to return into this configuration. The mechanism that allows the animal to return to its homebase is called path integration system [Biegler & Morris 1996, Etienne et al. 1996]. It permits position and direction to be updated solely on the basis of ideothetic information. McNaughton et al. [1996] proposed “an intrinsic, two-dimensional manifold within a high-dimensional neuronal representation space, in which locations are defined by stable patterns of neural activity, and in which there are orderly proximity relationships among the locations” (p. 180). The preconfiguration of a state space topology of “a two-dimensionally organized system of stable attractors would provide a robust mechanism for the spontaneous, off-line reactivation of recent experience that is thought to be necessary for memory consolidation" [McNaughton et al. 1996, p. 183]. It seems rewarding to assume that also newborns may use their physical body to examine or develop such a two-dimensionally organized system of attractors. Support for this assumption can be derived from our evidence that multiple reference configurations can be coded on the bases of angular (two-dimensional) motion signals.

Our findings of reference configurations in newborn movements remind of a theory suggesting postural coding as a general method of movement control. This concept has been particularly successful in the study of speech and of facial expression [Fowler et al. 1980] and in limb movements [Rosenbaum et al. 1995]. The theory was supported also by neurological research in nonhuman primates [Niemitz 1989, 2002]. More recently, electrical stimulation of special motor cortex areas induced movement patterns of the related body parts from any initial configuration toward a single final posture [Graziano et al. 2002a]. The performance features of these movements are remarkably consistent with the characteristics of configurations, which in our study had been uncovered for start and target postures in newborn motor behavior. With this as a reference, we like to advertize non-invasive methods, like the methodological concept introduced here, also for further applications in the research of motor behavior and control.