

## **A Dynamical System Analysis of the Development of Spontaneous Lower Extremity Movements in Newborn and Young Infants**

Hirota Gima<sup>1),4)</sup>, Shohei Ohgi<sup>2)</sup>, Satoru Morita<sup>3)</sup>, Hiroshi Karasuno<sup>1)</sup>,  
Takayuki Fujiwara<sup>1),4)</sup> and Koji Abe<sup>4)</sup>

1) School of Physical Therapy, Koriyama Institute of Health Sciences

2) Department of Rehabilitation, Seirei Christopher University

3) Department of Systems Engineering, Shizuoka University

4) Interdisciplinary Graduate School of Science and Technology, Shinshu University

**Abstract** This study's aim was to evaluate the characteristics of newborn and young infants' spontaneous lower extremity movements by using dynamical systems analysis. Participants were 8 healthy full-term newborn infants (3 boys, 5 girls, mean birth weight and gestational age were 3070.6 g and 39 weeks). A tri-axial accelerometer measured limb movement acceleration in 3-dimensional space. Movement acceleration signals were recorded during 200 s from just below the ankle when the infant was in an active alert state and lying supine (sampling rate 200 Hz). Data were analyzed linearly and nonlinearly. As a result, the optimal embedding dimension showed more than 5 at all times. Time dependent changes started at 6 or 7, and over the next four months decreased to 5 and from 6 months old, increased. The maximal Lyapunov exponent was positive for all segments. The mutual information is at its greatest range at 0 months. Between 3 and 4 months the range in results is narrowest and lowest in value. The mean coefficient of correlation for the *x*-axis component was negative and *y*-axis component changed to a positive value between 1 month old and 4 months old. Nonlinear time series analysis suggested that newborn and young infants' spontaneous lower extremity movements are characterized by a nonlinear chaotic dynamics with 5 to 7 embedding dimensions. Developmental changes of an optimal embedding dimension showed a U-shaped phenomenon. In addition, the maximal Lyapunov exponents were positive for all segments (0.79–2.99). Infants' spontaneous movement involves chaotic dynamic systems that are capable of generating voluntary skill movements. *J Physiol Anthropol* 30(5): 179–186, 2011 <http://www.jstage.jst.go.jp/browse/jpa2>  
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**Keywords:** movement acceleration, dynamical systems analysis, infant, spontaneous movements

### **Introduction**

Researchers have been interested in studying the development of infants' spontaneous movements as a window to understanding the development of motor coordination and the generation of voluntary movements. Assessments of the quality of infants' spontaneous movements have provided insights into the functional integrity of the neonate's central nervous system (CNS), leading to the delineation of developmental profiles that may be useful in the evaluation of motor abilities and deficits in early infancy. Currently, the most widely used method for measuring qualitative changes in spontaneous movement in infants is visual observation. In addition to visual observation, evaluation also uses the electromyogram (Hadders et al., 1992), the 3-dimension motion analyzer (Taga et al., 1999), and the tri-axial accelerometer (Ohgi et al., 2008). Above all, evaluation using a tri-axial accelerometer was not undertaken due to the high cost and the need of a special evaluating environment. A newborn infant and young infants' spontaneous movements are characterized by complexity, variation, and fluency. There is empirical evidence that markedly abnormal movements reflect the presence of serious brain dysfunction (Bos, 1993; Guzzeta et al., 2003; Hadders et al., 1992). However, the impression of complexity, variation and fluency is very difficult to objectively evaluate.

A mathematical framework has lagged behind the traditional qualitative approach to the study of motor systems (Glass, 1991), but a mathematical understanding essentially adds to the base of knowledge of how a system works. On a more practical level, this understanding supports the ability to predict the future behavior of a motor system. The ability to predict this behavior, in turn, is crucial to the ability to control the behavior or the motor dysfunction. Ohgi et al. (2007) analyzed spontaneous upper extremity movements in 1-month-old healthy full-term newborn infants with nonlinear analysis

using time series data for tri-axial acceleration. They suggested that the infants' spontaneous movements had nonlinear chaotic dynamics characteristics. Furthermore, Ohgi et al. (2008) analyzed spontaneous upper extremity movements in premature infants with brain injuries using the same method. They reported the differences in characteristic spontaneous movements between premature infants with and without brain injuries. Their research presents objectively the complexity of infants' spontaneous movements. However, the course of change in movement quality over the duration of early development is perhaps the most important factor in predicting developmental disorders. Currently, there are a few studies that include this time period in the developmental changes of spontaneous lower extremity movements in healthy newborn and young infants that uses a tri-axial accelerometer and nonlinear analysis. In this study, our main focus was to add to the understanding of the spontaneous lower extremity movement characteristics and developmental changes of newborn and young infants. A further aim of this study is to expand our knowledge base in order to be able to detect with greater efficiency developmental disorders during early development.

## Methods

### Participants

We recruited eight 0-months-old, healthy full-term Japanese newborn infants (3 boys, 5 girls). There was no attrition. The mean birth weight, height, head circumference, and gestational age were  $3070.6 \pm 287.8$  g,  $49.1 \pm 2.4$  cm,  $34.0 \pm 1.1$  cm, and  $39 \pm 1.1$  weeks, respectively. Participants were recruited when parents at the Koriyama Institute of Health Sciences with newborn infants responded to invitations to participate in the research. Parents provided informed consent and were not given financial incentives to participate. This study was approved by the Ethics Committee of the Koriyama Institute of Health Sciences.

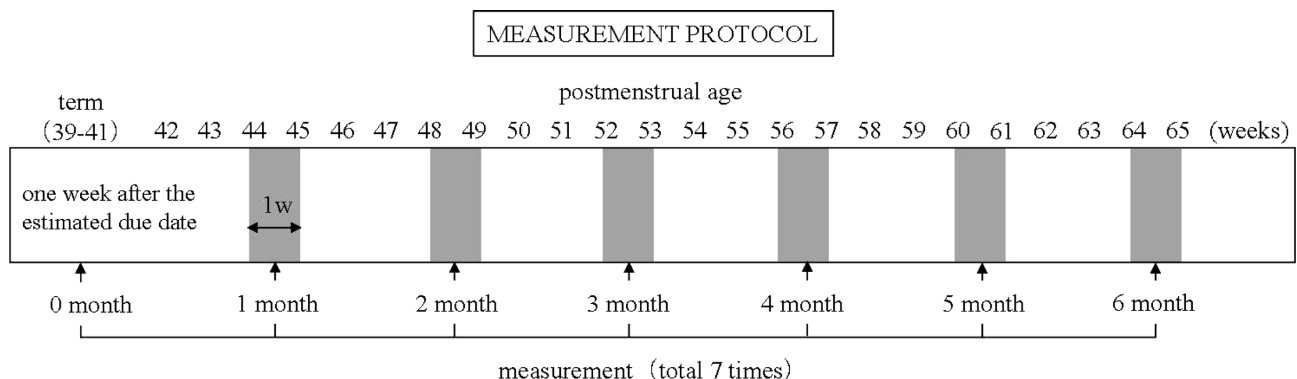
### Equipment

We used a tri-axial accelerometer (Motion Recorder MVP-

A304Ac Digitrac, Micro Stone Co., Nagano, Japan) to measure limb movement acceleration in 3-dimensional space. In this configuration,  $x$  data correspond to anterior-posterior movements of the lower extremity (in the perpendicular horizontal direction),  $y$  data correspond to abduction and adduction movements of the lower extremity (in the horizontal direction), and  $z$  data correspond to elevation movements of the lower extremity (in the vertical direction). The monitor weighed 4 g, and its dimensions (width, depth, and height) were 20, 12.5, and 7.5 mm. The monitor does not require manipulation during use. We sampled the acceleration signal at a rate of 200 Hz (1/0.005 second, 8 bits) and stored the signal in the system memory of the monitor until data collection was complete. Digitized data were transferred to a computer for subsequent processing with analysis software. We performed the data analysis individually with raw data (not data concatenated in one data stream).

### Procedure

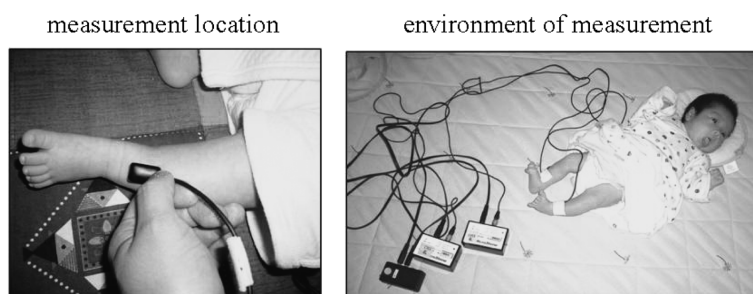
Figures 1 and 2 show the measurement protocol and methods, respectively. We recorded acceleration signals on the right and left ankle when the infants were in active alert state and lying in a supine position on a firm crib mattress (5cm thick). Infants were undressed or wore light underwear that did not interfere with either their freedom of movement or with the visualization of their arms and legs. Measurements were performed during home visits. We taped a small motion sensor (accelerometer) to the infant's leg just below the ankle. The infant's state was defined by the use of the Neonatal Behavioral Assessment Scale as described by Brazelton and Nugent (2004). During the active, alert state, the infant moves frequently and is more energetic, with both eye movement and vocalization. If the infant was in a crying or sleep state, the recordings were obtained between feedings, during active wakefulness, when spontaneous movements were present. If periods of prolonged fussing or crying were present, then we postponed the recordings. We chose a recording time of 200 seconds on the basis of recommendations for the characteristics of this accelerometer. This duration of recording is also consistent with that used in previous kinematic studies



**Fig. 1** The measurement protocol.

Measurement was carried out every fourth week after birth between the ages of 0 and 6 months old.

## METHODS



- recording movement in both lower extremities (sampling rate: 200 Hz; recording time: 200 seconds)
- recording when infants are in an active state and lying in a supine position
- measurement were performed during home visits

**Fig. 2** Methods.

Recorded acceleration signals on the right and left ankle when the infants were in an active alert state and lying in a supine position. We taped a small motion sensor to the infant's leg just below the ankle.

of infant limb movements (Fallang et al., 2000; Heriza, 1988; Jeng et al., 2002). Neonates spend the majority of their time in quiescent states (Giganti et al., 2001), and the opportunities to capture a sustained 200-second segment of spontaneous generalized movements are relatively limited. Measurement was carried out every fourth week after birth between the ages of 0 and 6 months old. All movement acceleration data were filtered to use a low-pass-filter (30 Hz), because quick movement in humans is less than 30 Hz.

Movement accelerations data were analyzed using linear and nonlinear analysis.

### Data Analysis

#### *Estimation of embedding parameters*

Phase space is the space in which all possible states of a system are represented. In phase space, every degree of freedom is represented as an axis of the space. In studies, time delay embedding is routinely used as the first step in the analysis of experimentally observed nonlinear dynamic systems (Kantz and Schreiber, 2004). This method is used to reconstruct the  $m$ -dimensional state space with the delay coordinates. We calculated the optimal embedding dimension by using a False Nearest Neighbor (FNN) method (Kennel et al., 1992). The optimal embedding dimension is a description of the number of dimensions needed to unfold the structure of a given dynamic system in space.

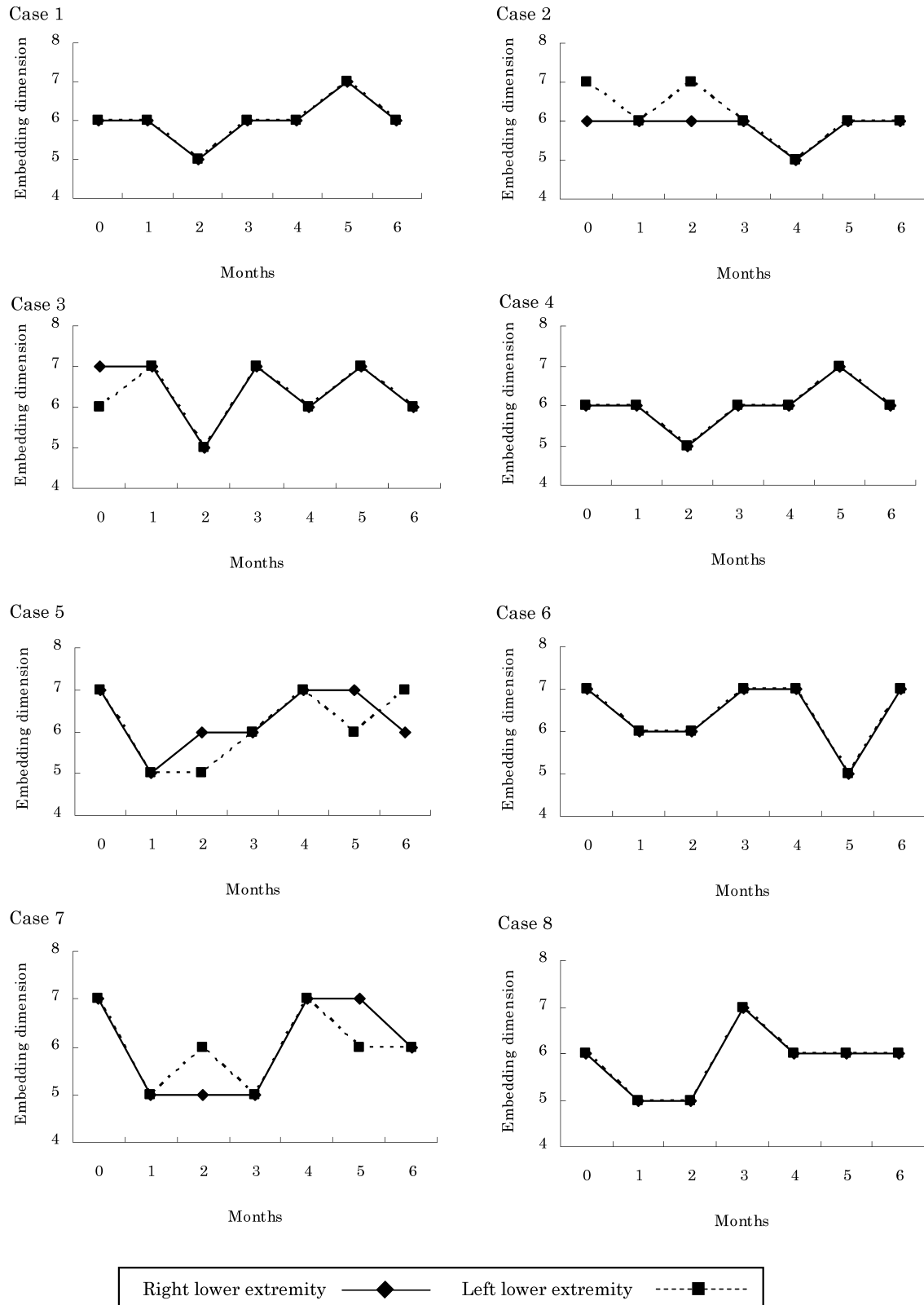
The main idea of the FNN method is that for deterministic systems, points that are close in the state space stay close under forward iteration. If the embedding dimension for reconstructing an attractor is too small, points may appear as close neighbors purely through projection effects. If, on the other hand, the embedding dimension is large enough, then FNNs are fully rejected and only real close neighbors are

resolved. Larger dimensionality in the fluctuations of a system may indicate a higher degree of freedom.

The first concern is the validity of delay times. The autocorrelation function provides important information about reasonable delay times. The autocorrelation function is an estimate of the cross-correlation between the data at time  $\tau$  and the data at time  $(t-\tau)$  in a single time series. We chose 250 milliseconds as the delay time in this study because a reasonable choice is the first zero of the autocorrelation function. A larger number of dimensions mean a more complex system.

#### *Maximal Lyapunov exponent*

The hallmark of deterministic chaos is the sensitive dependence of future states on the initial conditions. An initial small perturbation will grow exponentially, and the growth rate is called the Lyapunov exponent. We estimated the maximal Lyapunov exponent by using the algorithm introduced by Kantz (1994). In that algorithm, the average expansion rate is estimated as a function of the time span. If the average expansion rate shows a robust linear increase in some range of the time span, its slope is an estimate of the maximal Lyapunov exponent. The lack of a robust linear region can be the result of several factors (e.g., noise, undersampled time series, and small embedding dimension). Noise reduction was performed by use of the method described (Schreiber, 1993; Schreiber and Schmitz, 1996). This method was also used to add random noise to the original data. The estimate of the maximal Lyapunov exponent was computed from the slope in 5 dimensions. The maximal Lyapunov exponent determines the stability or instability of behavior. Higher values mean it is difficult to predict the behavior, indicating that the system is a more complex system. Also if the maximal Lyapunov exponent is positive, the behavior has characteristics of deterministic



**Fig. 3** The time-dependent changes of the optimal embedding dimension values calculated with the False Nearest Neighbor method.

The optimal embedding dimension showed more than 5 for all segments and both lower extremities displayed similar changes and these trends were observed in all cases. This number changed from 5 to 7. For all participants the number of the optimal embedding dimension was 6 or 7 at the start of sampling and over the next four months it decreased once or twice to 5 and increased again to 6 or 7 from 6 months of age.

chaos.

### *Correlation between movements of left and right legs*

To evaluate the correlation between the movements of the left and right legs, we used mutual information of the movement acceleration direction and the Pearson correlation coefficient of the movement acceleration on each axis. The mutual information (transinformation) of two variables is a quantity that measures the mutual dependence of the two variables. Intuitively, mutual information measures the information that X and Y share: it measures how much knowing one of these variables reduces our uncertainty about the other. For example, if X and Y are independent, then knowing X does not give any information about Y, and vice versa, so their mutual information is zero. At the other extreme, if X and Y are identical then all information conveyed by X is shared with Y. Knowing X determines the value of Y, and vice versa. In this study, the variables X and Y are the direction of movement acceleration of the left and right legs, respectively. When calculating the mutual information, we took no account of the time interval when the movement acceleration was small. Thus, the mutual information uses detection of phase synchronization in time series analysis. In addition, we calculated the Pearson correlation coefficient. A positive correlation coefficient suggests that the directions of the movements tend to coincide, and a negative one implies that the directions are inverse.

## **Results**

### *Optimal embedding dimension*

We estimated the optimal embedding dimension by using the FNN method. The optimal embedding dimension showed more than 5 for all segments. Figure 3 shows the time-dependent change of the optimal embedding dimension value in each case. Both lower extremities displayed similar changes and these trends were observed in all cases. This number changed from 5 to 7. For all participants the number of the optimal embedding dimension was 6 or 7 at the start of sampling and over the next four months it decreased once or twice to 5 and increased again to 6 or 7 from 6 months of age.

### *Maximal Lyapunov exponent*

We estimated the maximal Lyapunov exponent by using the algorithm introduced by Kantz. The maximal Lyapunov exponents showed a positive value for all segments (0.79–2.99). Figure 4 shows the time-dependent change of the maximal Lyapunov exponent value in each case. Both lower extremities displayed similar changes and these trends were observed in all cases. A similar tendency was not seen in the time-dependent change value of the maximal Lyapunov exponent between each case.

### *Correlation between movements of left and right legs*

Figure 5 shows the mutual information of movement

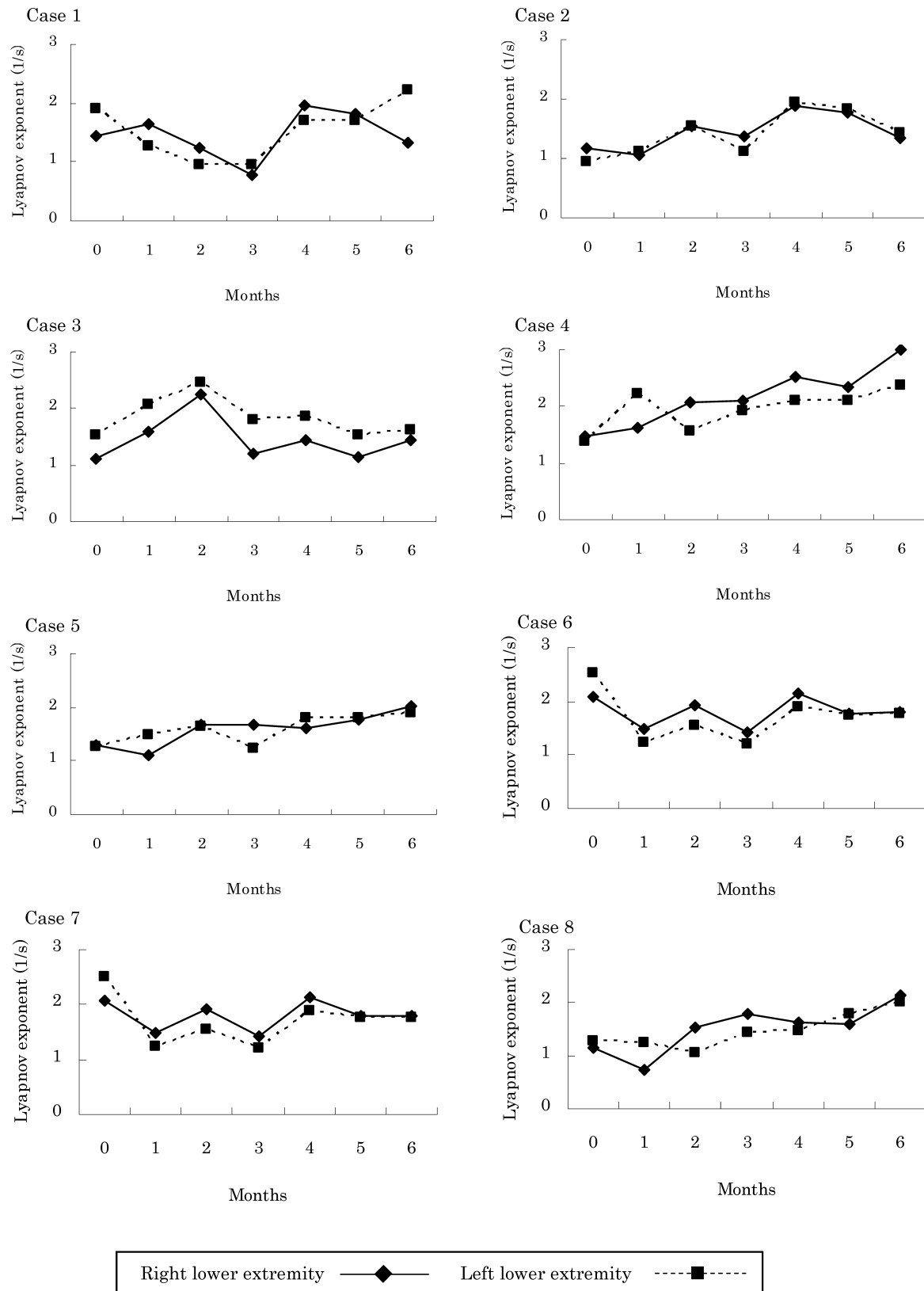
acceleration of both lower extremities and the mean coefficient of correlation for both lower-extremities (*x*-axis component and *y*-axis component). The mutual information is at its highest value and greatest range at 0 months. Between 3 and 4 months the range in results is very narrow and also at its lowest value. The mean coefficient of correlation for *x*-axis component showed a negative value and the *y*-axis component changed from a negative value to a positive value between 1 month old and 4 months old. In addition, the coefficient for each case at all segments was significant at  $p < 0.01$ .

## **Discussion**

Greater understanding of how newborn and young infants' spontaneous movements develop from involuntary action into controlled, voluntary motor skills can only add to our understanding of motor control. In this study we examined how the psychomotor system translates a voluntary skill movement into an invariant spatial output within biomechanical and environmental contexts. Using an accelerometer we recorded young infants' lower extremity movements as time series data. To provide insights into motor control and the time-dependent changes in the characteristics of these spontaneous movements we used dynamical analysis and the time series data were analyzed using nonlinear analysis. The results revealed (a) the positive maximal Lyapunov exponent values, (b) characteristics of the time-dependent change of the optimal embedding dimension, and (c) developmental changes of mutual information and coefficient correlation (*x*- and *y*-axis components) for spontaneous lower extremity movements. These results revealed that infants' spontaneous movements are not meaningless motion but come from a deterministic dynamic, which has a significant embedded order. These findings provide evidence that chaotic dynamical systems generate the dynamics of spontaneous movements and they may reflect deterministic processes by the neuromuscular system.

It has traditionally been thought that chaotic dynamical systems reveal the mechanisms for motor control. The production of young infants' spontaneous movements involves a chaotic oscillator whose parameters change as a result of the given environmental and biomechanical context. In previous studies, researchers applied chaotic dynamics to reveal the self-organization mechanism in motor control (Kelso et al., 1981; Schöner and Kelso, 1988). Chaotic dynamical systems have characteristics of self-organization and this is the principle underlying the formation of coordinative structures. Our results support these findings and suggest that motor development orients the processes of self-organization on the basis of nonlinear chaotic dynamics, evoking a contrast between infants' movement as a self-organized nonlinear system and the traditional view of infants' behavior as simple reflexes.

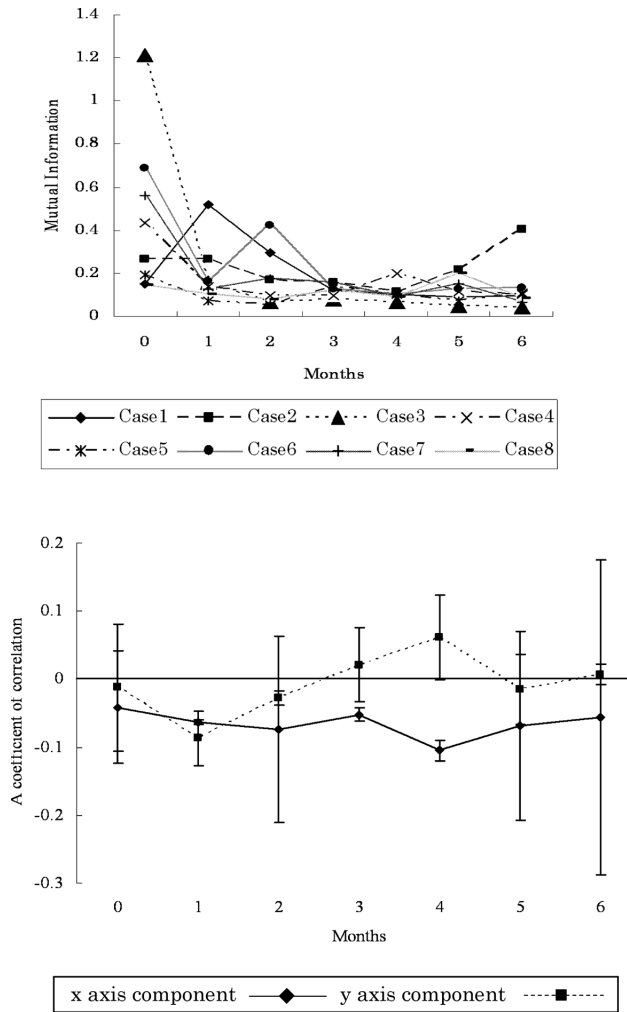
We calculated the optimal embedding dimension by using an FNN analysis. FNN values can be thought of as a measure of



**Fig. 4** The time-dependent changes of the maximal Lyapunov exponent values in 5 dimensions.

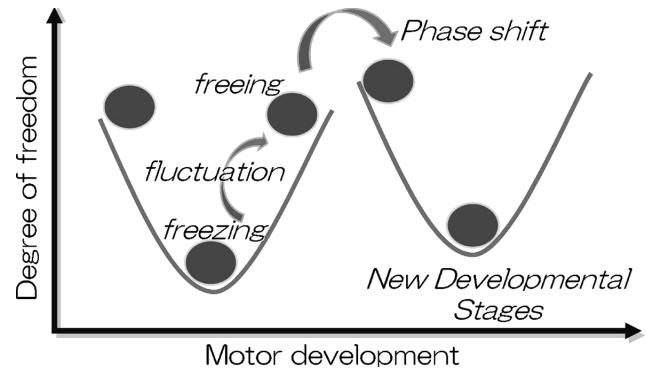
The maximal Lyapunov exponents showed a positive value for all segments (0.79–2.99) and both lower extremities displayed similar changes and these trends were observed in all cases.





**Fig. 5** The mutual information of movement acceleration of both lower extremities and the Pearson correlation coefficient of the movement acceleration on each axis (x-axis component and y-axis component). The mutual information is at its highest value and greatest range at 0 months. Between 3 and 4 months the range in results is very narrow and also at its lowest value. The coefficient of correlation for the x-axis component showed an almost negative value and the y-axis component changed from a negative value to a positive value between 1 month old and 4 months old.

the number of active degrees of freedom and as a guide to the number of variables that contribute to the observed behavior of the system. An FNN analysis describes the minimum number of variables that are related to the control of early childhood motor development, as the neurobehavioral system evolves over time, and that are required to form a valid state space from a given time series. In this study, the displayed optimal embedding dimension was 5 or greater for all segments, providing evidence that the infants' spontaneous lower extremity movements have systems with at least 5 optimal embedding dimensions. In addition, the time-dependent change in the number of optimal embedding dimensions was at the start 6 or 7, but over the next four months it decreased once or twice to 5 and then increased again to 6 or 7 from 6 months



**Fig. 6** The degrees of freedom in motor learning and development.

A three-stage approach to the reorganization of the peripheral biomechanical degrees of freedom in motor learning and development on the basis of observations of motor development, reduction (freezing) and release (freeing) of degrees of freedom, and the use and exploitation of phenomena (U-shaped phenomenon).

of age in all cases. Bernstein's original theory (1967) was that the change in the number of degrees of freedom regulates both motor learning and development. He proposed a three-stage approach to the reorganization of the peripheral biomechanical degrees of freedom in motor learning and development based on his observations of motor development: reduction in (freezing) and the release (freeing) of degrees of freedom; and the use of and exploitation of phenomena (U-shaped phenomenon; Fig. 6). Therefore, our results of developmental change in the optimal embedding dimension suggested that the U-shaped phenomenon is spontaneous in lower extremity movements in newborn and young infants.

Our results of mutual information showed a convergence at the lowest value to occur between 3 and 4 months of age. The mean coefficient of correlation for the x-axis component displayed a negative value, and the y-axis component changed from a negative value to a positive value between 1 and 4 months of age. Spontaneous movements are qualitatively changed from approximately 9 weeks post-term (Prechtl et al., 1997) and our results of mutual information changes may objectively show these qualitative changes. The negative value of the coefficient of correlation for the x-axis component suggested that spontaneous lower extremity movements in newborn and young infants were orientated in the alternation of the right and left kicking movements. The changes in the y-axis component, from a negative value to a positive value between 1 and 4 months old in healthy infants, may suggest that a change in the pattern of lower extremity movement enables the infant to gain the ability to roll over.

Our results suggest that nonlinear time series analysis of the time series accelerometer data can be used successfully to quantitatively assess newborn and young infants' spontaneous movement development. Ohgi et al. (2008) has already reported the characteristics of spontaneous upper extremity movements in premature infants with and without brain injuries that were examined by using a tri-axial accelerometer and time series analysis. In the future, there may be the need

for analysis focused on spontaneous lower extremity movements in order to detect early developmental disorders such as cerebral palsy.

We acknowledge that the small sample size and the lack of comparison between healthy infants and those with brain injuries is a limitation of this study. Future research requires the inclusion of investigations into the differences in the developmental course of spontaneous lower extremity movements in healthy infants and infants with brain injury.

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Correspondence to: Hirotaka Gima, School of Physical Therapy, Koriyama Institute of Health Sciences, 2–9–3 Zukei, Koriyama, Fukushima 963–8834, Japan

Phone: +81–24–936–7784

Fax: +81–24–936–7778

e-mail: h-gima@k-tohto.ac.jp