Original Article

A comparison of the developmental characteristics of spontaneous upper extremity movements between healthy full-term infants and premature infants with brain injuries.

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Abstract

This study's aim was to evaluate the characteristics of spontaneous upper extremity movements of premature infants with brain injuries by using dynamical systems analysis. Participants were 4 infants with brain injuries (3 boys and 1 girl, median birth weight and gestational age were 1367.5 g and 30.0 weeks) and 7 healthy full-term newborn infants (3 boys and 4 girls, median birth weight and gestational age were 2990.7 g and 39.0 weeks). We measured limb movement acceleration in 3-dimentional space using a tri-axial accelerometer. Movement acceleration signals were recorded during 200 s from the right wrist when the infant was in an active alert state and lying supine (sampling rate 200 Hz). Data were analyzed nonlinearly. The optimal embedding dimension (OED) values for infants with brain injuries at 3 months were significantly higher than healthy full-term infants, and the OED and MLE values in infants with brain injuries displayed uncorrelated change profiles. Uncorrelated change profiles of the OED and MLE values revealed that incoordination of the number of motor system component and complexity of appeared spontaneous movements. It suggests that infants with brain injuries have difficulties with self-organization processes. Our results suggest that this method makes it possible to detect early developmental disorders such as cerebral palsy.

Keywords : movement acceleration ; dynamic systems analysis ; periventricular leukomalacia

INTRODUCTION

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 dysfunction in early infancy. Currently, the most widely used method for measuring qualitative changes in an infant's spontaneous movement is visual observation. A newborn and young infant's spontaneous movements are characterized by complexity, variation, and fluency. There is empirical evidence that markedly abnormal movements reflect the presence of serious brain dysfunction[1-3]. However, the impression of complexity, variation and fluency is very difficult to

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objectively evaluate. Generally, the electromyogram[4], the 3-dimension motion analyzer[5], and the tri-axial accelerometer[6, 7] were used in addition to visual observation to evaluate these impressions. Above all, evaluation using a tri-axial accelerometer has the advantage of being both low cost and not requiring a specialized evaluation environment.

The application of mathematical methods is essential to understand the basic knowledge of how a motor system works. On a practical level, this understanding supports the ability to predict the future behavior. The ability to predict this behavior, in turn, is crucial to the ability to control the behavior or the motor dysfunction. Ohgi et al. analyzed spontaneous upper extremity movements in premature infants with brain injuries at 1-month of age using nonlinear analysis of the time series data for tri-axial acceleration[6]. They reported the differences in spontaneous movement characteristics between premature infants with and without brain injuries. Their research presents objectively the complexity of infants' spontaneous movements. However, the direction of change in movement quality over the duration of early development is perhaps the most important factor in predicting developmental disorders[1,2]. Currently, there are few tri-axial accelerometer and nonlinear analysis studies that focus upon this time period, and on the developmental changes of spontaneous upper extremity movements in premature infants with brain injuries. In this study, our main focus was to compare developmental characteristics and the direction of spontaneous upper extremity movements in premature infants with brain injuries and healthy full-term infants. A further aim of this study was to expand our knowledge base in order to be able to detect with greater efficiency developmental disorders during early development and the mechanism of motor dysfunction resulting from a brain injury.

METHODS

1.Subjects;

4 premature infants with brain injuries (3 boys and 1 girl, median birth weight and gestational age were 1,367.5 g and 30 weeks) and 7 healthy full-term newborn infants (3 boys and 4 girls, median birth weight and gestational age were 3,070 g and 39 weeks) participated in the present study. Participant characteristics are shown in Table 1. Brain injuries included Periventricular Leukomalacia (cases 8, 9 and 11) and Intraventricular Hemorrhage (case 10). At 2 years of age the neurological outcome was normal in cases 1-7, and Cerebral Palsy (CP) in cases 8-11. This study was approved by the institute' s ethical committee, and informed consent was provided by the participant's parents.

2.Equipment;

The present study used a tri-axial accelerometer (Motion Recorder MVP-A304Ac Digitrac, Micro Stone Co., Nagano, Japan) to measure limb (right upper extremity) movement acceleration in 3-dimensional space. In this configuration, x-data corresponds to anterior-posterior movements of the upper extremity (in the perpendicular horizontal direction), y-data corresponds to abduction and adduction movements of the upper extremity (in the horizontal direction), and z-data corresponds to elevation movements of the upper extremity (in the vertical direction). The monitor weighs 4 g, and its dimensions (width, depth, and height) are 20, 12.5, and 7.5 mm. The monitor does not require manipulation during use. The acceleration signal sampled 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).

3.Procedure;

Figure 1 are shown the measurement protocol and methods. The acceleration signals were recorded on the right wrist when the infants were in active alert state and lying in a supine position on a firm crib mattress (5 cm 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.

Healthy full-term infants were measured during home visits, and infants with brain injuries were measured in hospital. A small motion sensor (accelerometer) was taped to the infant's right arm just before the wrist. The infant's state was defined by the use of the Neonatal Behavioral Assessment Scale as described by Brazelton and Nugent[8]. 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. Measurement was carried out when the infant was one-month old, and every fourth week thereafter for a total of four measurements. All movement acceleration data were filtered to use a low-path-filter (30 Hz), because quick movement in humans is less than 30 Hz. In addition, the acceleration data (x, y, z) was calculated using by using the following formula: $\sqrt{x^2 + y^2 + z^2}$. This reflects the whole of the movement of right upper extremity Movement acceleration data were analyzed using nonlinear analysis.

Table 1. The characteristics of study participants

Group	Case	Sex	Gestational Age (wk)	Birth Weight (g)	APGAR Score (5 min)	Duration of Intubattion (d)	Diagnosis	Outcome 2 years
Healthy Full-term	1	F	38	2855	10	0	-	Normal
	2	F	40	3436	10	0	-	Normal
	3	M	39	3070	10	0	-	Normal
	4	M	40	3356	10	0	-	Normal
	5	M	39	2518	9	0	-	Normal
	6	F	38	2740	9	0	-	Normal
	7	F	38	2960	10	0	-	Normal
With brain injuries	8	M	25	997	3	9	PVL	CP (quadriplegia, mild-severe)
	9	M	32	1640	8	0	PVL	CP (diplegia, mild)
	10	F	36	1890	5	3	IVH	CP (quadriplegia, mild-severe)
	11	M	28	1095	8	0	PVL	CP (diplegia, mild)

APGAR=appearance, pulse, grimace, activity, and respiration; F=female; M=male; PVL=periventricular leukomalacia; IVH=intraventricular hemorrhage; CP=cerebral palsy

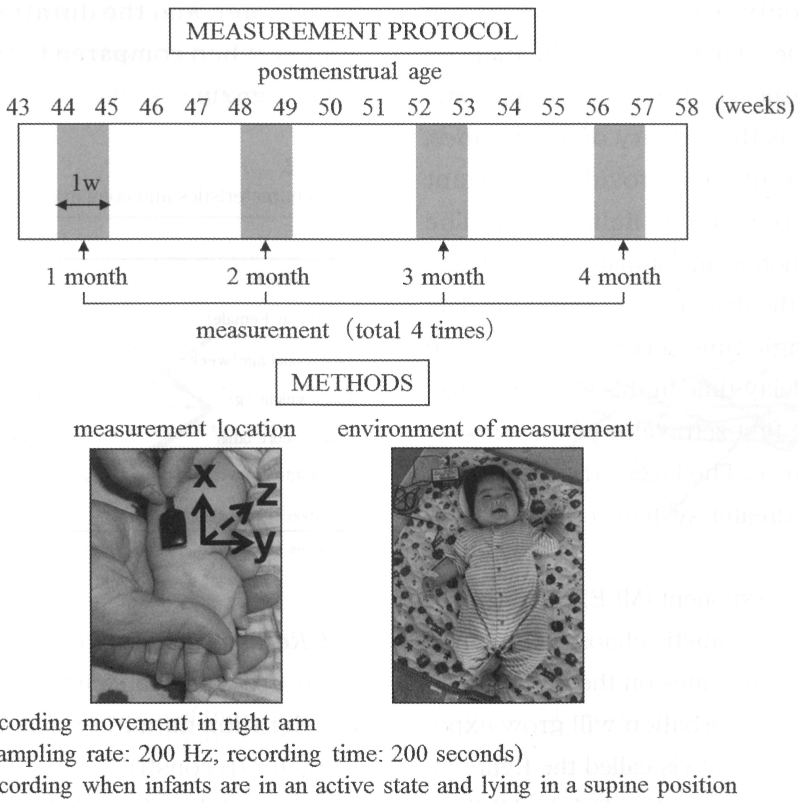

Figure 1. The measurement protocol and methods.
Measurement was carried out when the infant was one-month old, and every fourth week thereafter for a total of four measurements. We recorded acceleration signals on the right wrist when the infants were in active alert state and lying in a supine position on a firm crib mattress. We taped a small motion sensor (accelerometer) to the infant' s right arm just before the wrist.

4.Data analysis;

1) 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[9]. This method is used to reconstruct the m-dimensional state space with the delay coordinates. The present study calculated the optimal embedding dimension (OED) by using a False Nearest Neighbor (FNN) method[10]. The OED 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 OED 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 τ and the data at time ($t-\tau$) in a single time series. We chose 250 milliseconds as the delay time in this study because the best choice is the first zero value of the autocorrelation function curve. The larger the number of dimensions means a greater system complexity.

2) Maximal Lyapnov Exponent (MLE);

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 Lyapnov exponent. The present study estimated the MLE by using the algorithm introduced by Kantz[11]. 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 MLE. The lack of a robust linear region can be the result of several factors (e.g., noise, under-sampled time series, and small embedding dimension). Noise reduction was performed using the method described[12, 13]. This method was also used to add random noise to the original data. The estimate of the MLE was computed from the slope in 5 dimensions. The MLE determines the stability or instability of behavior and a higher value means greater difficultly in predicting behavior, and thus indicates that the system is more complex. In addition, if the MLE is positive then the behavior has characteristics of deterministic chaos.

RESULTS

1.Characteristics of study participants;

The characteristics of each infant group are presented in Table 2. In the infants with brain injuries group, gestational age was shorter, birth weight was lighter, Apgar score was lower, number of intubation cases was larger, and the duration of intubation was longer when compared to the healthy full-term infants group.

Table 2.
The characteristics and comparisons of infants each groups

	Healthy full-term	With brain injuries
No. of subjects	7	4
Sex (Male/Female)	3/4	3/1
Gestational age (week)†	39.0 (38-40)	30.0 (25-36)
Birth weight (g)†	2990.7 (2518-3436)	1367.5 (997-1890)
Apgar score 5min†	10 (9-10)	8 (6-9)
No. of intubation cases (%)	0 (0)	2 (50)
Duration of intubation (day)†	0 (0-0)	1.5 (0-9)

†: Values are median (range)

2. Reconstructed state space of acceleration data

Figure 2 are shown the calculated process of acceleration data in typical cases. The described attractor (reconstructed 3-dimentional attractor) in the typical data from infants with brain injuries appears unstable in comparison to the typical data from healthy full-term infants.

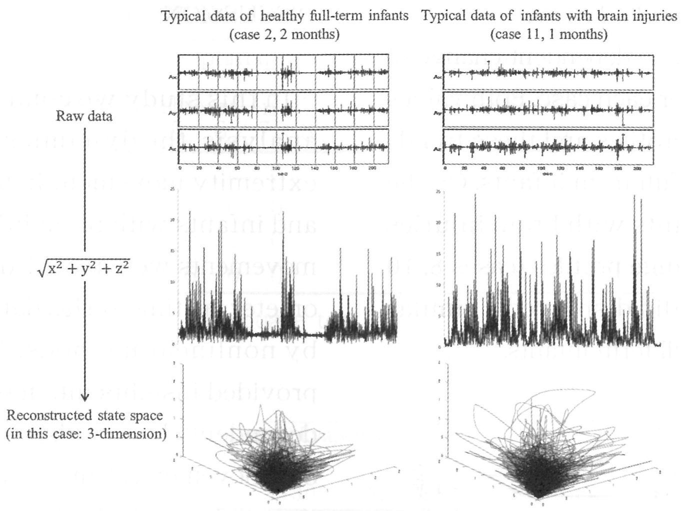

Figure 2. Reconstructed state space of acceleration data.
A typical example of 3-dimentional attractor in healthy full-term infants (case 2, 2 months) and infants with brain injuries (case 11, 1 months). Described attractor in infants with brain injuries were seem to unstable.

3. OED;

In this study, the OED was estimated in healthy infants and infants with brain injuries by using the FNN method. Figure 3 are shown the time dependent change of the OED value in each case. The healthy infants' OED value showed more than 5 for all segments and changed from 5 to 7. In comparison OED values for infants with brain injuries showed 8 and 4 in two of the cases. The characteristics of the time dependent change were similar to healthy infants, however the range was greater.

4. MLE;

In this study, the MLE was estimated by using the algorithm introduced by Kantz. Figure 4 are shown the time dependent change of the MLE value for each case. The MLE value showed a positive value for all segments in both groups (healthy infants: 1.14-2.34, infants with brain injuries: 0.68-2.99) and their time dependent change has a similar profile with the lowest value at 2-3 months. The greatest deviation in infants with brain injuries MLE, to the normal case value, is also at two months.

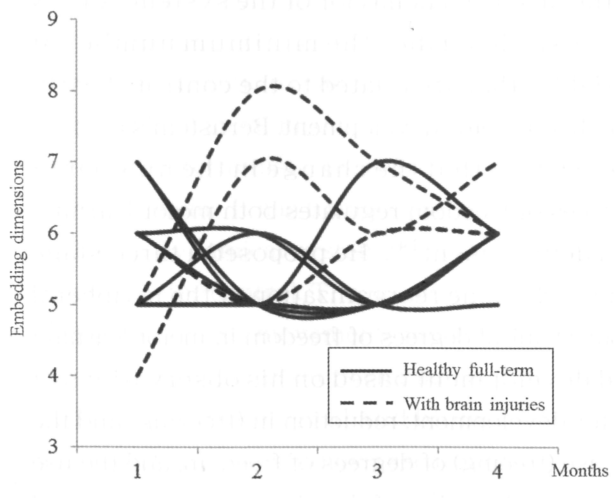

Figure 3. The time dependent changes of the optimal embedding dimension values calculated with the False Nearest Neighbor method.
The healthy infants' OED value showed more than 5 for all segments and changed from 5 to 7. In comparison OED values for infants with brain injuries showed 8 and 4 in two of the cases. The characteristics of the time dependent change were similar to healthy infants, however the range was greater (case 8 and 9 were the same line).

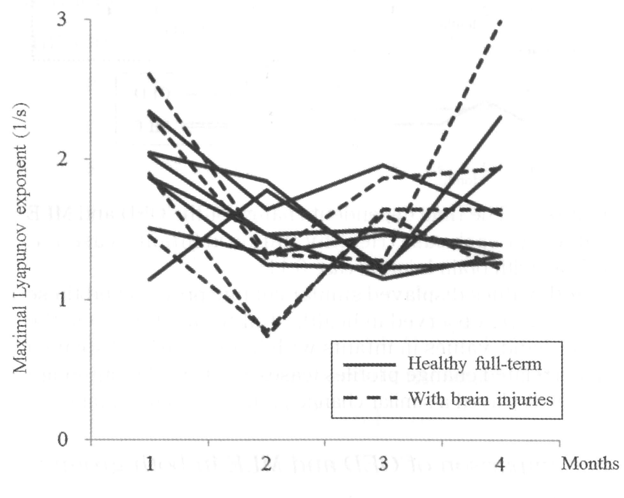

Figure 4. The time dependent changes of the maximal Lyapnov exponents values in 5 dimensions.
The MLE value showed a positive value for all segments in both groups (healthy infants: 1.14-2.34, infants with brain injuries: 0.68-2.99) and their time dependent change has a similar profile with the lowest value at 2-3 months. The greatest deviation in infants with brain injuries MLE, to the normal case value, is also at two months.

5. OED and MLE for individual cases;

Figure 5 are shown the time dependent change of the OED and MLE values for each case. Both values displayed similar change profiles and these trends were observed in healthy full-term infants. On the other hand, values in infants with brain injuries displayed uncorrelated change profiles (cases 8, 10 and 11), although case 9 did displayed a similar change profile to healthy full-term infants.

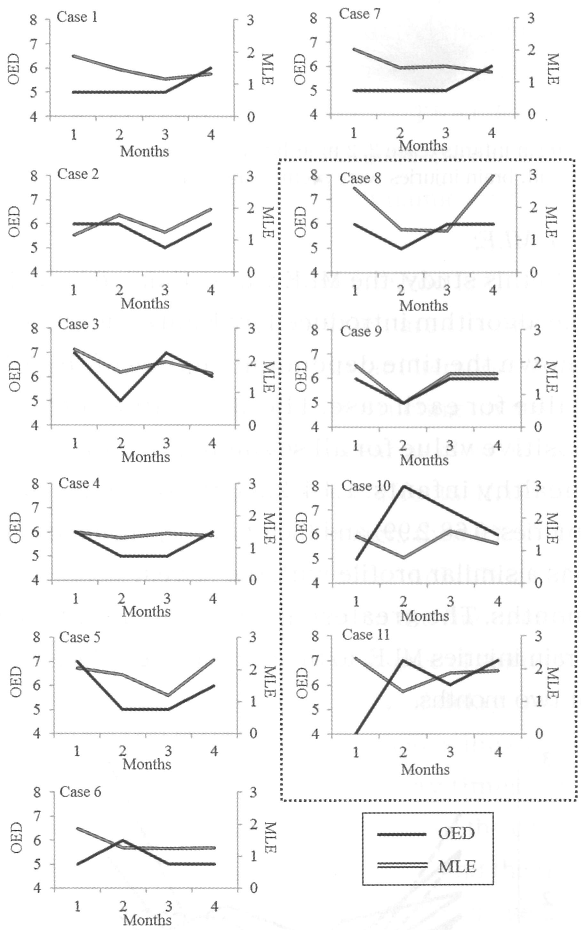

Figure 5. The time dependent change of the OED and MLE values for each case (Healthy full-term infants; case 1-7. Infants with brain injuries; case 8-11).
Both values displayed similar change profiles and these trends were observed in healthy full-term infants. On the other hand, values in infants with brain injuries displayed uncorrelated change profiles (cases 8, 10 and 11), although case 9 displayed a similar change profile to healthy infants.

6. Comparison of OED and MLE in both groups;

Tables 3 and 4 are shown a comparison of the OED and MLE values in both groups respectively. The OED values for infants with brain injuries at 3 months were significantly higher values than healthy full-term infants (p=0.01). There were no significant intergroup differences in the MLE values at 1-4 months.

DISCUSSION

In this study we compared, using time series analysis, the dynamics of spontaneous upper extremity movement in healthy full-term infants and infants with brain injuries. Infants' right arm movements were recorded, using a tri-axial accelerometer, as time series data, and the data analyzed by nonlinear methods. The nonlinear analysis provided insights into motor control and the time dependent characteristics change in the spontaneous movements. Our results suggest that nonlinear time series analysis of the time series accelerometer data can be used successfully to quantitatively assess infants' spontaneous movement development.

The major findings of the present study were that (a) the OED values for infants with brain injuries at 3 months were significantly higher values than healthy full-term infants and (b) the OED and MLE values in infants with brain injuries displayed uncorrelated change profiles. These results suggest that this method makes it possible to detect early developmental disorders such as CP.

The OED values can be thought of as a measure of 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. A FNN analysis describes the minimum number of variables that are related to the control of early childhood motor development. Bernstein's original theory was that the change in the number of degrees of freedom regulates both motor learning and development[14]. 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 the phenomena "U-shaped phenomenon". The present study clarified that the developmental changes of the OED values showed "the U-shaped phenomenon" in healthy full-term infants, but that these changes in the infants with brain injury (case 10 and 11) did not show "the U-shaped phenomenon". The significant difference

Table 3.Comparison of the OED values

	Optimal Embedding Dimension		
Months	Healthy full-term (n =7) (OED 4 / 5 / 6 / 7 / 8)	With brain injuries (n = 4) (OED 4 / 5 / 6 / 7 / 8)	p value§
1	0 / 3 / 2 / 2 / 0	1 / 1 / 2 / 0 / 0	.33
2	0 / 5 / 2 / 0 / 0	0 / 2 / 0 / 1 / 1	.19
3	0 / 6 / 0 / 1 / 0	0 / 0 / 3 / 1 / 0	.01
4	0 / 1 / 6 / 0 / 0	0 / 0 / 3 / 1 / 0	.31

§: As determined with the Chi-square test

Table 4. Comparison of the MLE values

	Maximal Lyapunov exponent		
Months	Healthy full-term (n = 7) (MLE 0-1.0 / 1.0-1.5 / 1.5-2.0 / 2.0-2.5 / 2.5-3.0)	With brain injuries (n = 4) (MLE 0-1.0 / 1.0-1.5 / 1.5-2.0 / 2.0-2.5 / 2.5-3.0)	p value§
1	0 / 1 / 3 / 3 / 0	0 / 1 / 1 / 2 / 0	.81
2	0 / 4 / 3 / 0 / 0	2 / 2 / 0 / 0 / 0	.07
3	0 / 5 / 2 / 0 / 0	0 / 1 / 3 / 0 / 0	.14
4	0 / 4 / 2 / 1 / 0	0 / 1 / 2 / 0 / 1	.36

§: As determined with the Chi-square test

of the OED value at 3 months revealed that the spontaneous movements in infants with brain injuries were disorganized (greater instability), and the displayed anomalous OED values in infants with brain injuries were 4 and 8 (healthy full-term infants showed 5-7), suggesting underlying problems with self-organization processes for co-ordination.

The MLE showed a positive value for all cases, revealing that infants' spontaneous movements are not meaningless motion but come from a deterministic dynamic, which has a significant embedded order. The result of the MLE values provides 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[15]. Chaotic dynamical systems have characteristics of self-organization and this is the principle underlying the formation of coordinative structures. The results of MLE values in healthy full-term infants 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. However, MLE values for infants with brain injuries were not significantly different to healthy full-term infants at 1-4 months in this study, this result suggested the need further study and to include more subjects. The MLE is a measure of the local stability of dynamic system and its dependence on initial conditions. The results of the significant differences between healthy full-term infants and infants with brain injuries may indicate that a more stationary and a more predictable (a weakness of complexity in motor system) spontaneous movement characteristics is present in infants with brain injuries. The quality of spontaneous movements at around 2-3 months (the fidgety movements' period) has a strong relationship with the infants' neurodevelopmental outcome[16, 17]. The MLE values at 2-3 months can be used as an early prognostic tool to identify infants with neurodevelopmental disabilities.

Ohgi et al. reported the differences in spontaneous movement characteristics between premature infants with and without brain injuries at 1-month of age. However, prior to this study, no study has examined the direction of change in movement quality over the duration of early development. In the presents study the most interesting points were the results of the OED and MLE values in infants with brain injuries; these displayed uncorrelated change profiles (case 8, 10 and 11). These results were shown by longitudinal study, and it is novelty of presents study. Usually, the time dependent changes of OED and MLE values are parallel. However, such a tendency was not shown in each infant with brain injuries case in the OED and MLE values. The non-parallel nature of the time dependent changes of the OED and MLE values revealed a lack of coordination between the motor system components, and the complexity of the displayed spontaneous movement. It suggests that infants with brain injuries have difficulties with self-organization processes. The processes involved in motor coordination and the generation of voluntary movements may be disrupted or compromised in infants with brain injuries. It also suggested that infants with PVL displayed uncoordinated, spontaneous movements, such as jerky, over-shooting, and poor-quality repertoires[18, 19]. The behavioral characteristics of infants with PVL are considered to be based on the separation of the OED and MLE values. The results of this study lead to some clinical implications in the practice of physical therapy for infants with disabilities. Physical therapy should support self-organization through interactions of multiple subsystems (such as the CNS; vision, hearing, sensory-tactile, musculoskeletal, and the environment), as cooperation among many interacting systems contributes to motor performance and development. It is important to provide infants the opportunities to engage in adaptive problem solving for movement-related tasks, so as to reinforce learning through feedback systems for sensory-perceptual motor information[20].

We acknowledge that the small sample size is a limitation of this study. Future investigations with this methodology should include more subjects and a measure of lower extremity and trunk movements in healthy infants and infants with brain injuries. In addition, it is necessary to examine the fluency of infant's spontaneous movement.

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