Longitudinal assessment of U-shaped and inverted U-shaped developmental changes in the spontaneous movements of infants via markerless video analysis

Naoki Kinoshita1, Akira Furui2, Zu Soh2, Hideaki Hayashi3, Taro Shibanoki4, Hiroki Mori5, Koji Shimatani6, Yasuko Funabiki7 & Toshio Tsuji2*

Various attempts have been made to elucidate the development patterns in the spontaneous movements of infants through longitudinal evaluations. Movement complexity has been found to demonstrate u-shaped changes in the measurements focusing on limb movements. However, researchers have not yet clarified how other characteristics, besides movement complexity, change over time. This paper presents a longitudinal evaluation of spontaneous movements in infants using evaluation indices calculated through markerless video analysis. Nine infants with corrected ages from −1 to 15 weeks participated in the experiments. We confirmed the change in indices over time using statistical methods. Index changes can be classified as positively correlated, u-shaped, inverted u-shaped, and uncorrelated. We also confirmed that the u-shaped and inverted u-shaped indices are negatively correlated. Furthermore, the principal component analysis revealed that the first principal component had the inverted u-shaped changes with the corrected age. These results suggest that it is important to synchronize the inverted u-shaped variations in the movement and velocity with the u-shaped changes in the movement complexity for infant development.

Movement abnormality in infants has been linked to neurological disorders1,2. Spontaneous limb movement observations have been reported to be especially useful for neurological evaluations3–5. General movements (GMs) are a part of the spontaneous movement repertoire and are used for neurological evaluation. The evaluation of GMs can predict the prognosis of a disorder almost as effectively as a neurological examination6. A report stated that 98% of the 44 infants who did not exhibit fidgety movements, a type of normal GMs, were diagnosed with severe cerebral palsy 2 years later7. Therefore, observing spontaneous movements during infancy is effective for the developmental evaluation and early detection of disabilities.

To detect the developing problems in infants at the earliest, researchers have attempted to elucidate the developmental patterns of infants via the longitudinal evaluation of spontaneous movements8–12. For example, Piek and Gasson discovered strong synchronization in both legs from the longitudinal evaluation of lower-limb
movements, suggesting that variability in the leg movements of infants decreases as they develop. By analyzing the limb movement trajectory, Taga et al. found that the movement complexity shows a u-shaped change; moreover, they reported that this u-shaped change was not observed in infants with brain injury. Gima et al. also confirmed a u-shaped change in the lower-limb movement and reported that this phenomenon occurs so that infants can acquire more developed movements. However, there is a lack of research clarifying how characteristics other than the movement complexity change over time or why the u-shaped changes in movement complexity are necessary for movement development.

Meanwhile, attempts have been made in recent years to evaluate spontaneous movements using markerless video analysis, thereby reducing the measurement costs and the burden on the observed infants. Adde et al. calculated evaluation indices, such as the quantity of whole-body movement, from video images and demonstrated the possibility of predicting cerebral palsy. Moreover, Tsuji et al. proposed a markerless video analysis system that can calculate 25 evaluation indices, characterizing limb and whole-body movements, and demonstrated that the types of GMs can be identified with high accuracy using machine learning; however, this system has only been used for cross-sectional evaluation instead of longitudinal evaluation. The evaluation of longitudinal changes in the spontaneous movements accompanying infant development may help in further clarifying the developmental patterns in infants and possibly elucidate the role and meaning of u-shaped changes in spontaneous movement complexity for movement development. In this study, we analyzed video images taken over a long period and calculated the evaluation indices using the markerless movement measurement and evaluation system proposed by Tsuji et al. This system enables the longitudinal evaluation of spontaneous movements without the need to attach markers to the bodies of infants. The relationship between the changes in each index and the development process was examined through a significance test on the evaluation index values with the corrected ages of infants. In addition, the 25 calculated indices were compressed via principal component analysis (PCA) to interpret their meanings for infant development. This study aimed to evaluate infant developmental patterns both objectively and quantitatively.

**Methods**

We conducted experiments to measure the longitudinal changes observed in the spontaneous movements in infants. Figure 1 shows the procedures followed in these experiments.

**Participants.** Nine infants (Participants A–I) participated in this study and markerless measurements were taken of their spontaneous movements from −1 to 15 weeks of their corrected age. All participants were full-term infants (born between a gestation period of 37 and 41 weeks). The birth weights of all participants ranged between 2500 and 4000 g, and there were no complications during the perinatal period. The experiments were conducted in accordance with the Declaration of Helsinki and were approved by the Ethics Committee of Hiroshima University (Registration Number: E-1150-1). Informed consent was obtained from the parents of each infant, and the experimental purpose and methods were fully explained to them. The experiments were also conducted in accordance with the relevant guidelines and regulations. We took appropriate precautions to prevent any risk or burden on the infants.

**Video-based movement analysis.** Movement measurement. We recorded the infants in a supine position without any marker using a single video camera (HDR-PJ760V, Sony, Japan) situated just above them. The video camera was fixed directly above and parallel to the crib surface, which was covered by a unicolor fabric spread. The video images were stored on a personal computer with a frame rate of 30 Hz. The infants were recorded approximately twice a week until 15 weeks of corrected age (see Table 1). In our video image analysis, we used the periods during which the infants could be seen to be moving (mean: 249.7 ± 145.5 s; median: 180 s; range: 30–690 s), avoiding any period of sleeping and crying. We also excluded the periods that seemed to have external stimuli, such as parental interference, from the analysis.

| Participant | Corrected age (weeks) |
|-------------|-----------------------|
| A           | − − 4 5 2 2 2 5 4 5 3 6 3 5 3 4 5 |
| B           | − − − 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 |
| C           | − − − − − 1 4 2 3 6 − 6 3 5 4 5 2 |
| D           | 5 2 1 2 2 1 3 3 2 5 3 4 − − − − − |
| E           | − − − 2 1 3 3 2 4 2 3 3 1 3 3 3 3 |
| F           | − − − − − 2 2 2 2 2 2 2 2 2 2 2 2 |
| G           | − − 1 1 1 1 1 − 1 1 1 1 1 1 2 1 1 |
| H           | − − 1 1 1 − − − − 1 1 1 1 1 1 1 1 |
| I           | − − − − 1 1 1 − − − − 1 1 1 − − − |

**Table 1.** Measurement period and number of measurements.
Feature extraction. First, a background difference image was created from the measurement image. Using this image, we calculated the changes in the body posture \((A_k)P_l\), expressing the size of the infants’ body as follows:

\[
(A_k)P_l = \sum_{(x,y) \in A_k} O_l(x, y),
\]

where \(A_k (k = 1, 2, \ldots, 9)\) represents the area of the infants’ body. The left upper limb, right upper limb, left lower limb, and right lower limb are denoted as \(A_1, A_2, A_3, \) and \(A_4\), respectively. By combining these four areas, the upper and lower body, the left and right sides, and the whole body were determined as \(A_5, A_6, A_7, A_8, \) and \(A_9\), respectively. In addition, \((x, y) = (x = 1, 2, \ldots, W; y = 1, 2, \ldots, H)\) are the image coordinates, \(l = 1, 2, \ldots, L\) is the frame number of the image in the video, and \(O_l(x, y)\) is the pixel value of the background difference image (where \(O_l(x, y) = 1\) if the pixel is white, and \(O_l(x, y) = 0\) if it is black). Moreover, using the image center of gravity (COG) calculated from the background difference image, the COG velocity \((G_{lx}^y, G_{ly}^y)\), which is the distance moved by the COG between adjacent frames, and COG fluctuations, which is the change in COG from the average COG position \((G_{lx}, G_{ly})\) between \(1 \leq l \leq L\), were calculated using the following equations:

\[
(G_{lx}^y, G_{ly}^y) = \left( \frac{G_{lx} - G_{lx-1}}{\sqrt{\langle A \rangle}_{\text{avg}}}, \frac{G_{ly} - G_{ly-1}}{\sqrt{\langle A \rangle}_{\text{avg}}} \right),
\]

\[
(G_{lx}^y, G_{ly}^y) = \left( \frac{G_{lx} - G_{lx}}{\sqrt{\langle A \rangle}_{\text{avg}}}, \frac{G_{ly} - G_{ly}}{\sqrt{\langle A \rangle}_{\text{avg}}} \right),
\]

where \(\langle A \rangle_{\text{avg}}\) is an average value from the maximum value to the \(E\)-th value \((E \leq l)\) in \((A_k)P_l\) between \(1 \leq l \leq L\). It should be noted that \(G_{lx} = 0\) and \(G_{ly} = 0\); \(G_{lx}\) and \(G_{ly}\) represents the COG coordinates calculated from the background difference image by the following equation:

\[
G_{lx} = \frac{1}{\langle A \rangle_{\text{avg}}} \sum_{x=1}^{W} \sum_{y=1}^{H} xO_l(x, y),
\]

\[
G_{ly} = \frac{1}{\langle A \rangle_{\text{avg}}} \sum_{x=1}^{W} \sum_{y=1}^{H} yO_l(x, y).
\]

Next, an interframe difference image was created from the measurement image and motor alteration \((A_k)M_l\), expressing the magnitude of the movement with respect to the body size; it can be calculated as follows:

\[
(A_k)M_l = \frac{\sum_{(x,y) \in A_k} O_l'((x, y))}{\langle A \rangle_{\text{avg}}},
\]

\[
O_l'((x, y)) = |O_l(x, y) - O_{l-1}(x, y)|,
\]

where \(O_l'((x, y)) = 0\).

The analysis parameters were set to \(L = 900\) and \(E = 10\). We used the system developed by Tsuji et al. for feature extraction and movement analysis\(^{14}\). Because \(W\) and \(H\) depend on the measurement environment, they differ for each image.

Movement analysis. By using medical knowledge and the features of the extracted movements, evaluation indices, such as the movement magnitude, balance, and rhythm, were calculated. Details for calculating each evaluation index are provided in Supplementary Material. In this analysis, we used some of the indices proposed by Tsuji et al. (see Table 2). In the table, \(A_5, A_6, \) and \(A_8\) represent the upper-, lower-, and whole-body areas of an infant, respectively. The evaluation indices were calculated every 30 s; subsequently, the average daily values were calculated. In addition, each index was standardized by calculating its average value and standard deviation within each participant.

Analysis of longitudinal changes in movements. The changes in each evaluation index with the corrected age were statistically analyzed. The developmental changes have been reported as linear and u-shaped\(^{11}\); therefore, linearity and u-shaped tests were performed on the evaluation indices with the corrected age. In the linearity test, the significance of the correlation coefficient between an evaluation index and corrected age was tested with a significance level of 5%. In the u-shaped test, a two-lines test\(^{15}\) was used, wherein an extreme value of the u-shaped change was first calculated based on the approximation by a quadratic function. The significance of the correlation coefficient was then tested for each side (right and left) of the data, separated by the extreme value. A significant u-shaped change was observed if the two correlation coefficients had opposite signs and were individually significant. When the two-lines test demonstrated a change from a decrease to an increase, with the extreme value as the boundary, the trend was defined as u-shaped, and when it showed a change from an increase to a decrease, it was defined as inverted u-shaped. If significant results were obtained for both the linearity and
Table 2. Description of evaluation indices.\textsuperscript{14}

| Category             | Index Description                                                                 |
|----------------------|-----------------------------------------------------------------------------------|
| Movement magnitude   | \(\langle A_k \rangle I_1, \langle A_k \rangle I_2\) Movement frequency          |
| Movement            | \(\langle A_k \rangle I_2, \langle A_k \rangle I_2\) Movement strength            |
|                      | \(\langle A_k \rangle I_2, \langle A_k \rangle I_3\) Movement count              |
| Movement balance     | \(\langle A_k, A_k \rangle I_4\) Ratio of index \(\langle A_k \rangle I_1\) in the upper body and index \(\langle A_k \rangle I_1\) in the lower body |
|                      | \(\langle A_k, A_k \rangle I_3\) Ratio of index \(\langle A_k \rangle I_1\) in the upper body and index \(\langle A_k \rangle I_1\) in the lower body |
|                      | \(\langle A_k, A_k \rangle I_6\) Symmetry in the upper and lower body             |
| Movement rhythm      | \(\langle A_k \rangle I_4, \langle A_k \rangle I_4\) Rhythm of motor alteration \(M\) |
|                      | \(\langle A_k \rangle I_6, \langle A_k \rangle I_6\) Standard deviations of indices \(\langle A_k \rangle I_2\) and \(\langle A_k \rangle I_2\) |
|                      | \(\langle A_k \rangle I_8, \langle A_k \rangle I_8\) Rhythm of the COG velocity |
|                      | \(\langle A_k \rangle I_9, \langle A_k \rangle I_9\) Standard deviations of indices \(\langle A_k \rangle I_6\) and \(\langle A_k \rangle I_6\) |
|                      | \(\langle A_k \rangle I_{10}, \langle A_k \rangle I_{10}\) Rhythm of the COG fluctuations |
|                      | \(\langle A_k \rangle I_{11}, \langle A_k \rangle I_{11}\) Standard deviations of indices \(\langle A_k \rangle I_{10}\) and \(\langle A_k \rangle I_{10}\) |
|                      | \(\langle A_k \rangle I_{12}, \langle A_k \rangle I_{12}\) Standard deviations of indices \(\langle A_k \rangle I_{11}\) and \(\langle A_k \rangle I_{11}\) |
| COG movement         | \(\langle A_k \rangle I_{13}, \langle A_k \rangle I_{13}\) Variations in the COG velocity |
|                      | \(\langle A_k \rangle I_{14}, \langle A_k \rangle I_{14}\) Variations in the COG fluctuations |

\[ X = U\Sigma W^T, \quad (7) \]

where \( U \in \mathbb{R}^{n \times n} \) and \( W \in \mathbb{R}^{25 \times 25} \) are square matrices and \( \Sigma \in \mathbb{R}^{n \times 25} \) is a rectangular diagonal matrix. The columns of \( W \) denote the eigenvectors of the covariance matrix and represent the loading vector of the principal component space. \( U\Sigma \) is the principal component score and represents the projection of \( X \) on the principal component space. PCA was used to examine the relationship between the principal component scores with the highest contribution rate and corrected age. We also evaluated the principal component space by confirming the indices with large loadings. The principal components extracted through PCA were selected based on the Kaiser criteria\textsuperscript{16}, with an eigenvalue greater than one.

Results
Figure 2 illustrates examples of the motor alteration (upper body: \(\langle A_k \rangle M\), lower body: \(\langle A_k \rangle M\)) and power spectral density of the COG fluctuations (\(x\)-axis: \(G^{x}_x\), \(y\)-axis: \(G^{y}_y\)) of Participants A and B at 2 and 11 weeks, respectively. Examples for other participants (C–I) are presented in Figs. S1 and S2.

Figure 3 shows the changes in each index value with the corrected age in all participants. For indices that produced significant results in the linearity and u-shaped tests, one and two straight lines have been shown in the figure, respectively. Among the 25 indices, 9 positive, 1 u-shaped, and 7 inverted u-shaped correlations were obtained. Eight of the indices were uncorrelated with the corrected age. The mean and standard deviation of the extreme values of the u- and inverted u-shaped changes were 9.92 ± 0.98 weeks, which converged to the same approximate value. Table 3 presents the correlation coefficients and \( p \) values of the indices for which significant relationships were obtained.

Figure 4 shows the interrelationship between the u-shaped and inverted u-shaped indices. The horizontal axis shows the standard deviations of the rhythm of the COG fluctuations \(\langle A_k \rangle I_{13} \), which is the only u-shaped index, and the vertical axis represents the evaluation indices with an inverted u-shaped. Only the three highest correlation coefficient values \(| r | \geq 0.4 \) are shown.

Table 4 presents the principal component loading of each index in the principal component, whose eigenvalue is greater than one according to the Kaiser criteria. Figure 5a illustrates a biplot visualizing the influence of each index on the principal component with respect to the first and second principal components. Figure 5b shows the first principal component score with the corrected age. The correlation coefficient and \( p \) value obtained after the test are also shown in Fig. 5b.

Discussion
In Fig. 2a, the motor alteration \(\langle A_k \rangle M, \langle A_k \rangle M\) of the upper and lower body at a corrected age of 2 weeks is smaller than that at 11 weeks; it should be noted that the motor alteration of the lower body is very small. Moreover, in Fig. 2b, the power spectral density of the COG fluctuations \(G^{x}_x, G^{y}_y\) at 2 weeks of corrected age was concentrated in the narrow band of the low-frequency range, in comparison to 11 weeks of corrected age. These tendencies were also observed in other participants (see Figs. S1 and S2), and they suggest that as the...
development progresses, whole-body movements may increase and become more complex by incorporating a variety of velocities.

In Fig. 3, we can observe the changes in the movements of participants with the corrected age; accordingly, the different changes in each index can be confirmed.

An index that demonstrates a positive correlation with the corrected age denotes the symmetry of movements \((A_s, A_b)_{I_6}\), representing the correlation between the upper- and lower-body movements. This positive correlation indicates that as development progresses, the upper- and lower-body movements become synchronized. We believe that increased movement symmetry can be attributed to lifting legs, which is a spontaneous movement. The lifting of legs increases movements in the lower body as well as the contact between knees and hands. In addition, the rhythm of motor alteration \((A_s)_{I_7}\), \((A_b)_{I_2}\) and the rhythm of the COG fluctuation \((A_s)_{I_{11x}}, (A_b)_{I_{11y}}\) increased significantly, showing that the movement velocity increases with development. These indices increase owing to spontaneous swiping movements, which have a large amplitude and fast velocity. Moreover, the standard deviations of movement rhythm \((A_s)_{I_8}, (A_b)_{I_8}\) may increase owing to the increase in fast motions.

It should be noted that only the standard deviations of the rhythm of the COG fluctuations \((A_b)_{I_{12y}}\) exhibited a u-shaped change, a finding that corroborates previous reports. The changes in this index demonstrate that complicated movements are first simplified, and then become complex again. Therefore, it is possible that the \((A_b)_{I_{12y}}\) index reflects the conventionally reported u-shaped change.

Seven indices were confirmed to show inverted u-shaped changes. However, the phenomenon of movement change characteristics taking an inverted u-shape with development has not been reported in the past. Therefore, we decided to find the relationship between such indices and conventionally reported the u-shaped changes (see Fig. 4). In Fig. 4, we confirmed that the indices showing u- and inverted u-shaped changes were significantly negatively correlated. The vertical axes of Fig. 4a–c show the movement count \((A_b)_{I_3}\) and rhythm of the COG velocity \((A_s)_{I_{9z}}, (A_b)_{I_{9z}}\), which reflect the movement degree and velocity. Therefore, when the movement is complex, it is possible to confirm that a relatively smaller number of slow movements are performed, and when the movement is simple, a larger number of fast movements are performed. Infants must practice and organize many movements to gain mature dexterity; this can be implemented by sending sensations from the body muscles and joints to the brain and integrating them. Hence, infants may increase the sensory input

| Category              | Index         | Relationship         | Correlation coefficient | p value |
|-----------------------|---------------|----------------------|-------------------------|---------|
| Movement magnitude    | \((A_s)_{I_1}\) | Inverted u-shaped    | 0.230, – 0.295          | \(1.10 \times 10^{-2}, 2.43 \times 10^{-4}\) |
| Movement balance      | \((A_s)_{I_1}\) | Uncorrelated         | –                       | –       |
| Movement balance      | \((A_s)_{I_2}\) | Uncorrelated         | –                       | –       |
| Movement balance      | \((A_s)_{I_2}\) | Uncorrelated         | –                       | –       |
| Movement balance      | \((A_s)_{I_3}\) | Inverted u-shaped    | 0.236, – 0.329          | \(6.21 \times 10^{-3}, 7.51 \times 10^{-5}\) |
| Movement balance      | \((A_s)_{I_3}\) | Inverted u-shaped    | 0.337, – 0.335          | \(4.10 \times 10^{-3}, 9.72 \times 10^{-3}\) |
| Movement balance      | \((A_s, A_b)_{I_4}\) | Uncorrelated       | –                       | –       |
| Movement balance      | \((A_s, A_b)_{I_5}\) | Positively correlated | 0.286                | \(1.65 \times 10^{-6}\) |
| Movement rhythm       | \((A_s)_{I_5}\) | Positively correlated | 0.271                | \(5.99 \times 10^{-6}\) |
| Movement rhythm       | \((A_s)_{I_6}\) | Positively correlated | 0.229                | \(1.39 \times 10^{-4}\) |
| Movement rhythm       | \((A_s)_{I_6}\) | Positively correlated | 0.287                | \(1.45 \times 10^{-6}\) |
| Movement rhythm       | \((A_s)_{I_{10a}}\) | Inverted u-shaped | 0.489, – 0.304          | \(9.69 \times 10^{-12}, 2.14 \times 10^{-7}\) |
| Movement rhythm       | \((A_s)_{I_{10a}}\) | Inverted u-shaped | 0.608, – 0.438          | \(1.65 \times 10^{-10}, 4.57 \times 10^{-7}\) |
| Movement rhythm       | \((A_s)_{I_{10a}}\) | Positively correlated | 0.457                | \(2.65 \times 10^{-15}\) |
| Movement rhythm       | \((A_s)_{I_{10a}}\) | Inverted u-shaped | 0.563, – 0.410          | \(4.33 \times 10^{-16}, 3.28 \times 10^{-15}\) |
| Movement rhythm       | \((A_s)_{I_{11x}}\) | Positively correlated | 0.354                | \(1.86 \times 10^{-9}\) |
| Movement rhythm       | \((A_s)_{I_{11x}}\) | Positively correlated | 0.355                | \(1.49 \times 10^{-8}\) |
| Movement rhythm       | \((A_s)_{I_{12y}}\) | U-shaped            | – 0.344, 0.278         | \(2.58 \times 10^{-6}, 6.63 \times 10^{-3}\) |
| Movement rhythm       | \((A_s)_{I_{12y}}\) | Uncorrelated        | –                      | –       |
| COG movement          | \((A_s)_{I_{15a}}\) | Uncorrelated        | –                      | –       |
| COG movement          | \((A_s)_{I_{15a}}\) | Positively correlated | 0.137                | \(2.40 \times 10^{-2}\) |
| COG movement          | \((A_s)_{I_{16a}}\) | Inverted u-shaped   | 0.149, – 0.255         | \(4.03 \times 10^{-2}, 2.17 \times 10^{-2}\) |
| COG movement          | \((A_s)_{I_{16a}}\) | Uncorrelated        | –                      | –       |

Table 3. Correlation coefficient and p value in Fig. 3. The u- and inverted u-shaped indices have two correlation coefficients and p values, which were calculated for the left- and right-sided data, separated by the extreme value.
Figure 1. Movement measurement method and analysis procedures. An infants’ movement is recorded without markers for a long time. In feature extraction, image processing is used to capture the characteristics of the recorded movement. In movement analysis, the evaluation indices are calculated using medical knowledge.

to the brain by performing faster movements when their movements are simpler (i.e., the peak of the u-shaped changes), thereby organizing their movements.

For indices showing no correlation, we confirmed the changes in the indices for each participant. The variations in the COG velocity (A9)I13 exhibited a common tendency toward having no correlation with the corrected age in almost all participants; this index may reflect features that do not change with time. By contrast, alternating trends of increase and decrease in the movement strength (A5, A6)I2 (A5, A6)I2 and the ratio of movement strength (A5, A6)I5, which were uncorrelated to the corrected age in all participants, were observed. These indices

Table 4. PCA results. Eight principal components were selected according to the Kaiser criteria. Values in bold indicate loadings with an absolute value greater than 0.5.

| Category | Index | PCA loadings |
|----------|-------|--------------|
|          |       | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 | PC7 | PC8 |
| Movement magnitude | (A5)I1 | 0.69 | 0.37 | -0.45 | 0.13 | -0.15 | 0.02 | -0.15 | 0.03 |
|          | (A6)I1 | 0.84 | 0.42 | 0.14 | -0.02 | 0.01 | -0.04 | -0.01 | -0.07 |
|          | (A5)I2 | 0.36 | 0.31 | -0.71 | -0.01 | 0.07 | -0.21 | -0.07 | -0.10 |
|          | (A6)I2 | 0.61 | 0.49 | 0.04 | -0.10 | 0.17 | -0.16 | -0.33 | -0.05 |
|          | (A5)I3 | 0.72 | 0.23 | -0.20 | 0.24 | -0.14 | 0.19 | -0.27 | 0.07 |
|          | (A6)I3 | 0.83 | 0.25 | 0.14 | 0.07 | -0.02 | 0.05 | 0.09 | -0.13 |
| Movements balance | (A5, A6)I4 | -0.19 | -0.21 | -0.66 | 0.28 | -0.25 | 0.17 | -0.16 | 0.24 |
|          | (A5, A6)I5 | -0.26 | -0.12 | -0.80 | 0.17 | -0.14 | 0.02 | 0.19 | -0.09 |
|          | (A5, A6)I6 | 0.32 | 0.07 | -0.25 | -0.04 | 0.44 | -0.22 | -0.41 | -0.24 |
| Movements rhythm | (A5)I7 | 0.20 | -0.45 | 0.43 | 0.42 | 0.19 | 0.31 | -0.22 | -0.15 |
|          | (A6)I7 | -0.06 | -0.60 | -0.13 | 0.49 | -0.05 | 0.34 | -0.09 | -0.08 |
|          | (A5)I8 | 0.39 | -0.49 | 0.21 | 0.39 | 0.26 | -0.01 | -0.16 | -0.19 |
|          | (A6)I8 | 0.61 | 0.49 | 0.04 | -0.10 | 0.17 | -0.16 | -0.33 | -0.05 |
|          | (A5)I9 | 0.13 | -0.69 | -0.14 | 0.31 | 0.12 | -0.12 | 0.14 | -0.03 |
|          | (A6)I9 | 0.75 | -0.40 | 0.01 | 0.01 | 0.04 | -0.19 | 0.12 | 0.26 |
|          | (A5)I10 | 0.81 | -0.34 | 0.05 | -0.01 | 0.16 | -0.11 | 0.12 | -0.05 |
|          | (A6)I10 | 0.64 | 0.58 | -0.03 | -0.13 | 0.07 | -0.13 | 0.04 | 0.34 |
|          | (A5)I11 | 0.64 | -0.49 | -0.12 | -0.18 | -0.09 | 0.15 | -0.26 |
|          | (A6)I11 | 0.26 | -0.70 | -0.06 | -0.32 | 0.22 | -0.14 | -0.14 | -0.41 |
|          | (A5)I12 | 0.37 | -0.63 | -0.15 | -0.49 | -0.04 | 0.10 | 0.04 | -0.31 |
|          | (A6)I12 | -0.56 | -0.24 | -0.04 | -0.33 | 0.12 | 0.14 | -0.50 | 0.24 |
|          | (A5)I13 | -0.25 | -0.36 | -0.22 | -0.60 | -0.05 | 0.33 | -0.11 | -0.34 |
|          | (A6)I13 | 0.65 | 0.28 | 0.06 | -0.18 | 0.02 | 0.48 | 0.08 | 0.20 |
|          | (A5)I14 | 0.69 | 0.23 | -0.03 | -0.18 | 0.01 | 0.50 | 0.12 | 0.15 |
|          | (A6)I14 | 0.26 | -0.06 | -0.25 | -0.06 | 0.70 | 0.16 | 0.22 | -0.09 |
|          | (A9)I15 | -0.02 | 0.13 | -0.25 | -0.06 | 0.70 | 0.16 | 0.22 | -0.09 |
|          | (A9)I16 | -0.18 | 0.16 | -0.26 | 0.10 | 0.68 | 0.12 | 0.29 | 0.12 |
|          | (A9)I17 | 0.65 | 0.28 | 0.06 | -0.18 | 0.02 | 0.48 | 0.08 | 0.20 |
|          | (A9)I18 | 0.69 | 0.23 | -0.03 | -0.18 | 0.01 | 0.50 | 0.12 | 0.15 |

Proportion of variance explained 0.27 0.17 0.10 0.07 0.06 0.05 0.04 0.04

Cumulative proportion 0.27 0.44 0.54 0.61 0.67 0.72 0.76 0.80
potentially reflect the large individual differences accompanying the development. In future work, we plan to increase the number of participants and study them in detail.

Figure 5b shows that the first principal component (PC1) with the corrected age acquired an inverted u-shape after being plotted. Figure 5a and Table 4 illustrate that the indices with the largest main component loadings of PC1 included movement frequency \( A_5 \), movement count \( A_5 \), \( A_6 \), \( A_9 \), and rhythm of COG velocity \( A_9 \), which all demonstrated an inverted u-shape. Therefore, increasing or decreasing the frequency and velocity of movement to an inverted u-shape at approximately the same time may be important in infant development.

Interestingly, in Fig. 5b, the extreme value of the inverted u-shape occurred at approximately 10 weeks. In healthy infants, 9–10 weeks of corrected age is the time at which writhing GMs transition to fidgety GMs \(^{19}\). In general, writhing GMs are movements of small to moderate amplitude and slow to moderate speed, whereas fidgety GMs are movements of smaller amplitude and moderate speed with variable acceleration of the neck, trunk, and limbs \(^{20,21}\). The transition from writhing GMs to fidgety GMs occurs at 6–9 weeks of the corrected age, with sporadic fidgety patterns in this period \(^{22–24}\). Accordingly, infants gradually acquire faster and more complex movements with the transition from writhing GMs to fidgety GMs. It has also been reported that fidgety GMs become slower and smoother movements at 11–16 weeks of the corrected age after the transition to fidgety GMs \(^{24}\). These previous findings correspond with our results stating that the indices related to the frequency and speed of motion that strongly contributed to PC1 increased toward the extreme value and then decreased, i.e., the inverted u-shaped change was observed around the extreme value of 10 weeks. Therefore, the extreme value of the inverted u-shaped PC1 and GM development state may be related. In the future, if we could confirm the loss of inverted u-shape or deviations in their extreme values by analyzing participants who may have an abnormality, we may be able to determine whether the findings obtained in this study can be applied for the early detection of a disorder.

In this study, we analyzed nine infants to confirm the changes in their spontaneous movements from markerless video images. In these experiments, we confirmed that the 25 evaluation indices calculated by the system change with the corrected age. The trends in these changes suggest the possibility of classification as previously reported u-shaped changes, as well as newly reported u-shaped and inverted u-shaped changes. Furthermore, PCA suggested that the major changes over time demonstrate an inverted u-shape.

The length of the video images used in the analysis varied (from 30 to 690 s) depending on the participants and recording date. Relatively long periods were extracted from some of the videos, but in most cases, the data length was 180 s. This is because we excluded the periods when the infants were sleeping and crying, or when external interference was observed, from the analysis. Therefore, although the mood of infants was not completely controlled, we believe that the intrinsic spontaneous movement characteristics of infants could be analyzed with a high degree of sensitivity. To conduct more extensive and detailed analyses in the future, it is necessary to establish an experimental protocol to control the behavioral states efficiently, including the moods of infants,
Figure 3. Relationships between the corrected age and each evaluation index in all participants. (a) Movement magnitude. (b) Movement balance. (c) Movement rhythm. (d) COG movement. The red, purple, and light blue lines show the changes in the index with positive, u-shaped, and inverted u-shaped correlations to the corrected age, respectively.
as well as the criteria for selecting videos for the analysis. We also plan to perform measurements at neonatal intensive care units and clarify these developmental patterns in greater detail.

Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 30 January 2019; Accepted: 23 September 2020
Published online: 08 October 2020

References
1. Prechtl, H. F. R. State of the art of a new functional assessment of the young nervous system An early predictor of cerebral palsy. Early Hum. Dev. 50, 1–11 (1997).
2. Teitelbaum, P., Teitelbaum, O., Nye, J., Fryman, J. & Maurer, R. G. Movement analysis in infancy may be useful for early diagnosis of autism. Proc. Natl. Acad. Sci. 95, 13982–13987 (1998).
3. Jeng, S. F., Chen, L. C. & Yan, K. I. T. Kinematic analysis of kicking movements in preterm infants with very low birth weight and full-term infants. Phys. Therapy 82, 148–159 (2002).
4. Fetters, L., Chen, Y. P., Jonsdottir, J. & Tronick, E. Z. Kicking coordination captures differences between full-term and premature infants with white matter disorder. Hum. Movement Sci. 22, 729–748 (2004).
5. Meinecke, L. et al. Movement analysis in the early detection of newborns at risk for developing spasticity due to infantile cerebral palsy. Hum. Movement Sci. 25, 125–144 (2006).
6. Cioni, G. et al. Which better predicts later outcome in fullterm infants: quality of general movements or neurological examination?. Early Hum. Dev. 50, 71–85 (1997).
7. Prechtl, H. F. R. et al. An early marker for neurological deficits after perinatal brain lesions. *Lancet* **349**, 1361–1363 (1997).
8. Thelen, E. Rythmical stereotypes in normal human infants. *Animal Behav.* **27**, 699–715 (1979).
9. Piek, J. P. & Carman, R. Developmental profiles of spontaneous movements in infants. *Early Hum. Dev.* **39**, 109–126 (1994).
10. Piek, J. P. & Gasson, N. Spontaneous kicking in fullterm and preterm infants: intralimb and interlimb coordination. *Austr. Edu. Dev. Psychol.* **14**, 23–34 (1997).
11. Taka, G., Takaya, R. & Konishi, Y. Analysis of general movements of infants towards understanding of developmental principle for motor control. *IEEE Int Conf Syst Man Cybern* **5**, 678–683 (1999).
12. Gima, H. et al. A dynamical system analysis of the development of spontaneous lower extremity movements in newborn and young infants. *J. Physiol. Anthropol.* **30**, 179–186 (2011).
13. Adde, L. et al. Early prediction of cerebral palsy by computer-based video analysis of general movements: a feasibility study. *Dev. Med. Child Neurol* **52**, 773–778 (2010).
14. Tsuchi, T. et al. Markerless measurement and evaluation of general movements in infants. *Sci. Rep.* **10**, 1422 (2020).
15. Simonsohn, U. Two-lines: the first valid test of u-shaped relationships (2016).
16. Kaiser, H. F. The application of electronic computers to factor analysis. *Edo. Psychol. Meas.* **20**, 141–151 (1960).
17. Einspieler, C., Marschik, P. B. & Prechtl, H. F. R. Human motor behavior prenatal origin and early postnatal development. *J. Psychol.* **216**, 148–154 (2008).
18. Ayres, A. J. & Robbins, J. *Sensory Integration and the Child: Understanding Hidden Sensory Challenges* (Western publisher Psychological Services, Torrance, 2005).
19. Van der Meulen, J. & Prechtl, H. F. R. Developmental transformations of spontaneous movements in early infancy. *Early Hum. Dev.* **14**, 233–238 (1986).
20. Einspieler, C., Prechtl, H. F., Ferrari, F., Cioni, G. & Bos, A. F. The qualitative assessment of general movements in preterm, term and young infants: review of the methodology. *Early Hum. Dev.* **50**, 47–60 (1997).
21. Einspieler, C. et al. Early markers for cerebral palsy: insights from the assessment of general movements. *Future Neurol.* **7**, 709–717 (2012).
22. Prechtl, H. F. & Hopkins, B. Developmental transformations of spontaneous movements in early infancy. *Early Hum. Dev.* **14**, 233–238 (1986).
23. Beccaria, E. et al. Poor repertoire general movements predict some aspects of development outcome at 2 years in very preterm infants. *Early Hum. Dev.* **88**, 393–396 (2012).
24. Ferrari, F. et al. The ontogeny of fidgety movements from 4 to 20 weeks post-term age in healthy full-term infants. *Early Hum. Dev.* **103**, 219–224 (2016).

Acknowledgements
This work was supported by JSPS KAKENHI Grant Number 15H01584.

Author contributions
N.K and A.F. wrote the initial draft and prepared figures. N.K. conducted the analysis. Z.S., H.H., T.S., H.M., and K.S. contributed to data interpretation and assisted in the preparation of the manuscript. Y.F. cooperated with the measurement experiments. T.T. designed the study and conceived experiments. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41598-020-74006-y.

Correspondence and requests for materials should be addressed to A.F. or T.T.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2020