



OPEN Movement smoothness at term-equivalent age is associated with motor developmental delay in preterm infants

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This prospective longitudinal cohort study aimed to quantify limb-movement smoothness at term-equivalent age and investigate whether limb-movement smoothness is associated with motor developmental delay (MDD) in very-preterm or very-low-birth-weight infants. Video recordings of limb movements were obtained at term-equivalent age, and the Bayley Scales of Infant and Toddler Development, Third Edition, was conducted at nine months of corrected age. Upper and lower limb movement smoothness was quantified using a pretrained 2D pose estimator and smoothness indices measured by log dimensionless jerk (LDJ) and spectral arc length (SPARC), with lower LDJ magnitude and less-negative SPARC indicating smoother movement. The quantified movement smoothness was compared between infants with and without MDD. Among 111 infants, 11 (9.9%) exhibited MDD. The LDJ measurements showed significant differences at the right shoulder, elbow, hip, knee, and left elbow between infants with and without MDD ($p < 0.05$, $d \approx 0.96$ – 1.12). The SPARC measurements showed significant differences at the right shoulder, hip, knee, and left knee between the two groups ($p < 0.05$, $d \approx 0.64$ – 0.89). The motor composite scores showed significant positive correlations with the absolute values of LDJ and SPARC at the multiple joints. Limb-movement smoothness at term-equivalent age is associated with MDD in very-preterm or very-low-birth-weight infants. Smoothness indices of limb movements can be potentially useful for the early detection of MDD.

Keywords Motor development, Movement, Pose estimation, Preterm, Smoothness

Very-preterm or very-low-birth-weight infants are at greater risk of adverse neurodevelopmental outcomes. Early detection of infants who may exhibit neurodevelopmental disorders is crucial for initiating early interventions in a time window of high neuroplasticity.¹ One of the validated screening methods for high-risk infants in the earliest stage of life is the General Movement Assessment (GMA), an evaluation tool based on infantile spontaneous movements developed by Prechtl et al.^{2,3} In the GMA, infantile spontaneous movements are observed and assessed from early fetal life until the end of the first 5 months.² Within this period, the writhing movements occur from birth to approximately 8 weeks post-term is characterized by variable sequences of neck, trunk, arm, and leg movements with differing intensity, speed, and range of motion.² A normally developing nervous system leads to variable and complex movements, whereas an impaired nervous system results in monotonous or cramped synchronized movements, which lack variability or involve rigid and simultaneous contraction of limbs and trunk.⁴ Although characteristics of infantile spontaneous movements may reflect the integrity of the neural networks of infants, the extent to which these qualitative observations correspond to later standardized motor assessments, such as the Bayley Scales of Infant and Toddler Development, remains

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incompletely understood. The GMA should be evaluated by certified assessors and requires high-quality training, regular practice, and recalibration, which impede establishing the GMA as a universal daily routine in clinical practice.⁵ These limitations highlight the need for quantitative and automated kinematic measures that can bridge early qualitative observations with subsequent developmental outcomes, thereby improving the clinical interpretability and applicability of early assessments.

Advances in motion analysis methods based on novel kinematic markers have contributed to automatic, quantitative, and objective measurements of infantile spontaneous movements.^{5,6} Particularly, the adoption of computer vision techniques to quantitatively analyze infantile spontaneous movements has been substantially increased in recent studies.⁷ Various motion features were extracted from the video recordings of infantile movements by capturing the trajectories of several body parts and analyzing kinematic parameters, such as velocity, acceleration, and periodicity.⁸ Mathematically calculated motion indices, including magnitude, balance, rhythm, and the body centers of infantile movements, along with spatio-temporal pose-based features that describe the scope, nature, and location of spontaneous limb movements were used to develop machine learning-based models to classify normal and abnormal movements or low- and high-risk infants.^{9,10} In typically developing infants, high movement complexity is reflected in diverse movement patterns involving multiple body parts with variations in amplitude, speed, and direction. A decreased movement complexity, which is one of the hallmarks in infants with cerebral palsy,¹¹ was quantified using sample entropy and reported to be associated with early neurological development.^{12–14} Since smoothness metrics reflect the temporal and structural organization of sub-movements, reduced complexity may present as smoother yet less varied movement patterns, supporting their potential as biomarkers for early neurodevelopmental outcomes.

Attempts to establish methods to quantitatively analyze infantile spontaneous movements are ongoing as this can identify clinically meaningful movement features that are associated with motor development, which is essential for developing explainable artificial intelligence algorithms with clinical significance. Particularly, smoothness of infantile spontaneous movements has been recognized as a clinical hallmark associated with early neurodevelopmental outcomes and serves as a key feature in qualitative and semi-quantitative assessments, such as the GMA and general movement optimality score.¹⁵ Compared with other kinematic features, including velocity, acceleration, periodicity, magnitude, balance, and body centers, smoothness measures can reflect movement complexity in terms of superposition of sub-movements during the whole period of infantile spontaneous movements.^{8–10} Smoothness measures have been already used in the other fields of sports science and neurorehabilitation for motor learning and recovery analyses in neurologic disorders (e.g., stroke, Parkinson's disease).^{16–18} Although smoothness can be a potential movement metric associated with early neurodevelopmental outcomes, few studies have focused on quantifying movement smoothness and exploring its associations with neurodevelopmental outcomes. While previous study proposed presence of jerky spontaneous movements has been linked to poor neurodevelopmental outcomes, we propose overall smoothness reflecting sub-movement structure and complexity as an indicator of neurological development.¹⁹ Therefore, this study aimed to quantify the smoothness of spontaneous limb movements and investigate whether limb-movement smoothness at term-equivalent age is associated with motor developmental outcomes in very-preterm or very-low-birth-weight infants.

Methods

Study population

In this prospective longitudinal cohort study, infants born at gestational age of < 32 weeks or with a birth weight of < 1500 g were enrolled from two tertiary hospitals from March 2019 to August 2022. Informed consent was obtained from the parents or legal guardians. Infants with major congenital malformations or unstable medical conditions that affect infantile spontaneous movements, such as those requiring cardiovascular support, active sepsis, or surgery, were excluded. This study was approved by the institutional review boards of Seoul National University Hospital (1902-095-1011) and Chung-Ang University Hospital (2051-009-421). Written informed consent was obtained from the parents or legal guardians of infants who were enrolled in this study. The study was conducted in accordance with all relevant guidelines and regulations in each institution.

The clinical information of the infants in the perinatal and postnatal periods, including infantile characteristics, neonatal morbidities, and maternal characteristics, is presented in Table 1. Infantile characteristics include sex, gestational age, postnatal and postmenstrual age at the time of video recordings, birth weight (g), the global score of the Hammersmith Infant Neurological Examination (HINE) assessed at 4 months of corrected age, the motor composite score of the Bayley Scales of Infant and Toddler Development, Third Edition (Bayley-III) at 9 months of corrected age, and the categories of GMA at term-equivalent age. Two certified assessors, blinded to the infants' clinical information, determined the GMA categories. Infants with a birth weight < 1000 g, gestational age < 29 weeks, or severe intraventricular hemorrhage on brain ultrasonography underwent brain magnetic resonance imaging at a term-equivalent age.

Motor developmental outcomes

Experienced occupational therapists blinded to the infants' clinical information evaluated the motor developmental outcomes of infants at 9 months of corrected age using Bayley-III in accordance with the established guidelines.²⁰ Bayley-III is a widely used standardized measure of early development and comprises the following five domains: cognition, motor, language, socio-emotional, and adaptive behavior.²¹ We analyzed only the motor domain in Bayley-III. Bayley-III was carried out by well-trained and experienced therapists at the two tertiary hospitals: three therapists with over 5–10 years of experience at Seoul National University Hospital and a single therapist with over 10 years of experience at Chung-Ang University Hospital. Motor developmental delay (MDD) was defined as a motor composite score of < 80 on the Bayley-III with a clinical judgment of the necessity for rehabilitation.

	Normal (n = 100)	Motor developmental delay (n = 11)	p value
Infantile characteristics			
Sex (female)	34 (34.0%)	8 (72.7%)	0.019*
Gestational age (weeks:days)	29:3 (2:6)	27:3 (2:3)	0.039*
Gestational age			0.033*
<28 weeks	33 (33.0%)	8 (72.7%)	
28 to <32 weeks	49 (49.0%)	3 (27.3%)	
32 to <37 weeks	18 (18.0%)	0 (0.0%)	
Postnatal age (weeks:days) at video recordings	10:6 (3:0)	12:3 (2:3)	0.086
Postmenstrual age (weeks:days) at video recordings	40:2 (0:4)	40:0 (0:4)	0.174
Birth weight (g)	1171.5 (351.5)	1029.3 (383.0)	0.172
Birth weight			0.003*
<1000 g	34 (34.0%)	8 (72.7%)	
1000 to <1500 g	46 (46.0%)	0 (0.0%)	
1500 to <2500 g	20 (20.0%)	3 (27.3%)	
Global score of HINE	65.4 (7.3)	57.5 (10.1)	0.003*
Categories of GMA			<0.001*
Poor repertoire	20 (20.0%)	5 (45.5%)	
Cramped synchronized	0 (0.0%)	2 (18.2%)	
Chaotic	1 (1.0%)	2 (18.2%)	
Motor composite score of Bayley-III	100.7 (10.6)	60.8 (11.4)	<0.001*
Neonatal morbidities			
1-Min Apgar score	5.0 [3.5–6.0]	3.0 [1.0–4.0]	0.010*
5-Min Apgar score	7.0 [6.0–8.0]	5.0 [5.0–7.0]	0.001*
Bronchopulmonary dysplasia (moderate to severe)	27 (27.0%)	6 (54.5%)	0.081
Antenatal steroid	68 (68.0%)	4 (36.4%)	0.140
Periventricular leukomalacia	5 (5.0%)	5 (45.5%)	0.001*
Intraventricular hemorrhage (grade III-IV)	5 (5.0%)	4 (36.4%)	0.005*
Invasive ventilator use (days)	9.1 (14.7)	38.2 (31.2)	<0.001*
Patent ductus arteriosus	56 (56.0%)	10 (90.9%)	0.027*
Treatments of patent ductus arteriosus			0.522
Pharmacological closure	14 (14.0%)	3 (27.3%)	
Surgical closure	13 (13.0%)	1 (9.1%)	
Retinopathy of prematurity (stage 3–5)	7 (7.0%)	3 (27.3%)	0.060
Sepsis	12 (12.0%)	5 (45.5%)	0.012*
Seizure	1 (1.0%)	4 (36.4%)	<0.001*
Maternal characteristics			
Maternal preeclampsia	17 (17.0%)	0 (0.0%)	0.210
Gestational diabetes mellitus	12 (12.0%)	0 (0.0%)	0.605
Multiple gestations	56 (56.0%)	7 (63.6%)	0.754
Maternal chorioamnionitis	27 (27.0%)	2 (18.2%)	0.725

Table 1. Clinical characteristics (N = 111). Values are presented as mean (standard deviation), median [interquartile range], or number of participants (percentage%). Bayley-III, Bayley Scales of Infant and Toddler Development, Third Edition; HINE, Hammersmith Infant Neurological Examination; GMA, General Movement Assessment. *Statistically significant at $p < 0.05$.

Video data acquisition and preprocessing

Spontaneous limb movements were video-recorded at term-equivalent age using a conventional smartphone RGB camera, following standardized instructions established for GMA, as detailed in our previous study.¹² The camera captured a full view of the infant's entire body, including the head, trunk, arms, legs, fingers, and toes, while the infants were lying in supine position, unclothed, moving freely, and fully awake without agitation. Videos of the spontaneous limb movements were recorded for 3–5 min, ensuring a continuous recording of at least 2 min as per the GMA guidelines.²² The controlled environments had neutral backgrounds that contrasted with infants' bodies. Recordings were generally performed once at term-equivalent age. If the initial video images did not satisfy the standardized instructions, recordings were re-conducted within the same period. The videos were recorded by two therapists in each hospital while the infants were hospitalized and by the parents or guardians of the infants after they were discharged.

The sampling frequency of the video recordings was 24 frames per second. Joint positional coordinates were extracted using an open-source post-estimation model, AlphaPose, which is a pre-trained model built on a convolutional neural network. Although AlphaPose was not originally trained on infant datasets, previous research has shown competitive performance in this age group without fine-tuning, and our prior study confirmed its validity for infant pose estimation.^{12,23} AlphaPose generates joint positional coordinates with confidence levels of 0–1 for each image frame. Positional coordinates with confidence levels < 0.5 were regarded as measurement errors and eliminated from the positional data. Positional coordinates were extracted for the following 12 joints: bilateral shoulders, elbows, and wrists in the upper limbs; and bilateral hips, knees, and ankles in the lower limbs. Subsequently, the joint angles and angular velocities were calculated and used as primary data for further analysis, as they are less affected by variations in camera placement or viewing angle compared to raw positional coordinates or intersegment distances. The joint angles were calculated as the angles formed by the positional coordinates of the corresponding joint and its two adjacent joints. The shoulder joint angle was defined as the angle made by the ipsilateral shoulder, contralateral shoulder, and ipsilateral elbow; the elbow joint angle as that formed by the ipsilateral elbow, ipsilateral shoulder, and ipsilateral wrist; the hip joint angle as that formed by the ipsilateral hip, contralateral hip, and ipsilateral knee; and the knee joint angle as that formed by the ipsilateral knee, ipsilateral hip, and ipsilateral ankle. The joint angle data were acquired for each frame and interpolated using a locally weighted smoothing method. The joint angular velocity was calculated using the symmetric difference quotient as a sequence of finite differences in the joint angles. We previously described the details and rationales for acquiring video images, extracting and processing positional coordinates, and calculating joint angles and angular velocities.¹²

Calculation of log dimensionless jerk (LDJ) and spectral arc length (SPARC)

The smoothness of infants' upper and lower limb movements was quantified using two smoothness metrics, LDJ and SPARC. LDJ is an acceleration-based parameter used to assess the rate of change in movement acceleration and has been regarded to be a highly validated and sensitive parameter for evaluating smoothness.²⁴ LDJ is calculated as the negative logarithm of the sum of the squared acceleration multiplied by the trial duration to a power of three and divided by the squared peak velocity of the joint angle,²⁵ examining the rate of change in movement acceleration. SPARC is an arc-based parameter representing the arc length of the Fourier magnitude spectrum of the velocity profile and is also a valid, sensitive, and reliable method for quantifying smoothness.²⁴ Regarding arc-length measures, less smooth movements are assumed to be more complex in relation to their frequency composition.²⁵ An increased magnitude of LDJ and SPARC indicates decreased smoothness. In this study, the LDJ and SPARC metrics were calculated using the NumPy and Pandas packages on Python (version 3.10; Python Software Foundation, Wilmington, DE, USA). The time-series data of the joint angles and angular velocities were edited to approximately 3 min to ensure a uniform duration. Illustrations of analyses of LDJ and SPARC in two cases with normal development and MDD are exhibited in Fig. 1.

Statistical analysis

Clinical characteristics were compared between infants with and without MDD using the Student's *t*-test or Mann–Whitney *U* test for continuous variables and Fisher's exact test for categorical variables. The LDJ and SPARC measurements were compared between the two groups using the Student's *t*-test or Mann–Whitney *U* test. Cohen's *d* was calculated to quantify effect sizes, using the pooled standard deviation with degrees-of-freedom weighting. Pearson or Spearman correlation coefficients were obtained to analyze the correlations between the motor composite scores of the Bayley-III and the absolute values of the LDJ and SPARC of joint angular velocities. The significance level was set at $p < 0.05$. Statistical analyses were performed using the SPSS software (version 31; SPSS Inc., Chicago, IL, USA).

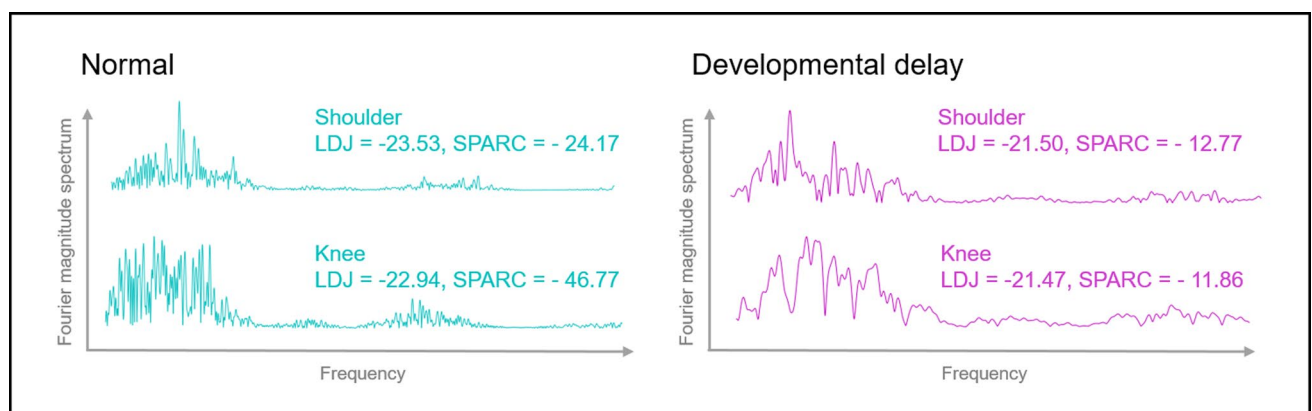


Fig. 1. Illustrations of analyses of log dimensionless jerk (LDJ) and spectral arc length (SPARC) in two cases with normal development and motor developmental delay.

Results
Clinical characteristics

After the exclusion of 69 infants, a total of 111 infants were enrolled, of whom 11 (9.9%) exhibited MDD. The infantile and maternal characteristics and neonatal morbidities are presented in Table 1. Infants with MDD differed significantly from those without MDD, being more often female, born at a lower gestational age, and with lower birth weight. They also had lower global scores on the HINE at 4 months corrected age and lower motor composite scores on the Bayley-III at 9 months corrected age. Significant differences were also observed in categories of GMA at term-equivalent age, with the MDD group showing a higher frequency of abnormal patterns. Additional perinatal differences included lower 1 min and 5 min Apgar scores, and higher prevalence of periventricular leukomalacia, severe intraventricular hemorrhage (grade III–IV), longer invasive ventilator use, and greater incidence of patent ductus arteriosus, sepsis, and seizures ($p < 0.05$).

Smoothness indices of spontaneous limb movements

The comparison results of the LDJ and SPARC measurements between infants with and without MDD are presented in Table 2. The LDJ measurements indicated significant differences between the two groups at the right shoulder, elbow, hip, knee, and left elbow, with infants with MDD showing decreased LDJ magnitude compared with those without MDD. The SPARC measurements significantly differed between the two groups in the right shoulder, hip, and knee and the left knee, with infants with MDD showing shorter SPARC magnitude compared with those without MDD, indicating higher smoothness in their global spontaneous movements. The correlation coefficients between the motor composite scores of the Bayley-III and the smoothness indices are presented in Table 3. The absolute values of LDJ at the right shoulder and those of SPARC at the right shoulder, hip, and knee and the left knee showed significant positive correlations with the motor composite scores of the Bayley-III.

Discussion

In this study, infantile spontaneous movements during the writhing period were selected for kinematical analyses of smoothness, as smoothness is one of the key features of infantile movements at this stage.¹⁵ In kinematic analysis for smoothness of movements, high smoothness indicates reduced variability or complexity. According to the GMA, normal writhing movements are characterized by sequential patterns and variable amplitude and speed, whereas abnormal writhing movements such as poor repertoire or cramped synchronized are characterized by monotonous movements that do not appear complex or rigid movements where the limbs and trunk contract and relax simultaneously.² The authors hypothesized that smoothness, which quantifies variable sub-movements and movement complexity, could be employed in analyzing writhing movements. The present study demonstrated that the quantified limb-movement smoothness, reflecting variability of sub-movements and overall movement complexity, at term-equivalent age was significantly higher in infants with MDD than those without MDD in very-preterm or very-low-birth-weight infants. Spontaneous limb movements were analyzed automatically, quantitatively, and objectively using a convolutional neural network-based pose estimation model and smoothness indices measured by LDJ and SPARC. Between infants with and without MDD, the LDJ measures indicated significant or nearly significant differences at all joints of the upper and lower limbs, and the SPARC measures showed significant differences at the multiple joints of the upper and lower limbs. Moreover, significant positive correlations were observed at the multiple joints of the upper and lower limbs between the

		Normal (n = 100)	Motor developmental delay (n = 11)	p value	Cohen's d
Log dimensionless jerk	Right shoulder	− 22.97 (0.84)	− 22.02 (1.33)	0.007*	1.062
	Left shoulder	− 22.89 (0.84)	− 22.07 (1.38)	0.059	0.909
	Right elbow	− 23.04 (0.91)	− 22.02 (1.45)	0.016*	1.046
	Left elbow	− 23.05 (0.82)	− 22.04 (1.43)	0.017*	1.121
	Right hip	− 22.99 (0.82)	− 22.15 (1.28)	0.035*	0.961
	Left hip	− 22.95 (0.85)	− 22.32 (1.14)	0.106	0.704
	Right knee	− 23.02 (0.81)	− 22.08 (1.39)	0.023*	1.072
	Left knee	− 23.03 (0.81)	− 22.26 (1.36)	0.053	0.883
Spectral arc length	Right shoulder	− 33.91 (8.85)	− 27.09 (10.92)	0.041*	0.753
	Left shoulder	− 33.44 (8.64)	− 29.07 (11.19)	0.125	0.491
	Right elbow	− 34.26 (9.30)	− 28.64 (10.70)	0.093	0.595
	Left elbow	− 33.11 (8.79)	− 27.89 (15.95)	0.161	0.540
	Right hip	− 33.46 (8.71)	− 27.63 (11.18)	0.043*	0.650
	Left hip	− 33.66 (9.41)	− 29.70 (9.44)	0.188	0.421
	Right knee	− 32.86 (9.09)	− 26.89 (10.89)	0.045*	0.644
	Left knee	− 33.84 (9.61)	− 25.25 (9.57)	0.006*	0.893

Table 2. Comparison of smoothness indices for joint angular velocity between preterm infants with and without motor developmental delay. Values are presented as means (standard deviations). *Statistically significant at $p < 0.05$.

		Correlation coefficients	<i>p</i> value
Absolute values of log dimensionless jerk	Right shoulder	0.208	0.029*
	Left shoulder	0.117	0.223
	Right elbow	0.088	0.358
	Left elbow	0.160	0.093
	Right hip	0.139	0.147
	Left hip	0.053	0.582
	Right knee	0.167	0.079
	Left knee	0.076	0.428
Absolute values of spectral arc length	Right shoulder	0.318	0.001*
	Left shoulder	0.119	0.212
	Right elbow	0.111	0.246
	Left elbow	0.169	0.076
	Right hip	0.211	0.026*
	Left hip	0.118	0.219
	Right knee	0.234	0.014*
	Left knee	0.219	0.021*

Table 3. Results of correlation coefficient analysis between the motor composite scores of the Bayley Scales of Infant and Toddler Development and absolute values of smoothness indices in all infants (N = 111).
*Statistically significant at $p < 0.05$.

absolute values of the LDJ and SPARC measures and the motor composite scores of the Bayley-III at 9 months of corrected age.

Smoothness is a quantitative measure to evaluate the quality related to the continuity or non-intermittency of movements, which is characterized by alternating deceleration and acceleration.²⁴ Higher intermittency indicates less smooth movements. Given that movements are a superposition of several discrete sub-movements, decreased movement smoothness indicates that more sub-movements are superposed with sparsely arranged temporal intervals.²⁶ Thus, higher limb-movement smoothness may reflect fewer sub-movements resulting from less variable movements in infants with MDD. This is consistent with previous research on GMA, where typically developing infants exhibited variable writhing movements at term-equivalent age, whereas infants with neurological impairment exhibited monotonous movements.^{2,4} Reduced variability is a hallmark of spontaneous movements in infants with cerebral palsy, represented as poor repertoire or cramped synchronized movements.^{27,28} Smoothness, which is a metric that can evaluate time-series signals, can be used to quantify the complexity of spontaneous limb movements in high-risk infants.²⁵

Generally, smoothness parameters are categorized into the following three types: velocity-based, acceleration-based, and arc length-based parameters.²⁵ The present study adopted LDJ and SPARC as the acceleration- and arc length-based parameters to analyze spontaneous limb movements. In the current study, infants with MDD exhibited a decrease in magnitude for both LDJ and SPARC compared with those without MDD, indicating that the spontaneous movements of infants with MDD showed high smoothness. Smoothness has been used to evaluate movements during specific tasks related to motor skill learning or recovery; less smoothness indicates poor motor planning or execution due to impaired control ability, which is observed in patients with neurological injuries, such as stroke, Parkinson’s disease, or even infants > 5 months old.^{17,29–31} It should be noted that movement smoothness is strongly task-dependent,²⁴ and spontaneous limb movements at term-equivalent age may completely differ from intentional movements targeted at specific tasks typically conducted by mature individuals, such as reaching, drawing, writing, and gait. Although conventional analyses of smoothness are usually performed for task-oriented activities at short intervals confined to the duration of task execution,²⁶ this study analyzed spontaneous limb movements for long intervals across the entire duration of the video recordings, which reflect the variability and complexity of sub-movement organization. To accurately capture spontaneous movement smoothness in this context, it is important to place infants in an unrestricted environment that could suppress the occurrence of spontaneous movements.

The smoothness of joint angles and angular velocities during spontaneous limb movements at term-equivalent age increased at the multiple joints of the upper and lower limbs of infants with MDD compared with those of infants without MDD. The LDJ measurements in all of the upper- and lower-limb joints indicated significant or nearly significant associations with motor developmental outcomes. The SPARC measurements significantly differed between the two groups at the right shoulder, hip, and bilateral knees. The present study suggests that these smoothness measures can be potentially useful parameters for the early detection of infants at high risk of neurodevelopmental disorders. While smoothness measures are associated with motor developmental outcomes in infants at 9 months of corrected age, they may not necessarily exhibit a linear correlation with Bayley-III scores. The relatively weak correlation coefficients may reflect the complexity of motor development, which is influenced by various neurological and environmental factors. Moreover, these results could be attributed to the dilution of the relationship between the LDJ and SPARC measures and motor composite scores of Bayley-III, given that the majority of the infants in this study exhibited normal motor development. There are additional factors that could contribute to the associations between smoothness measures and later motor outcomes,

including relatively small proportion of infants with severe brain injury, the predominance of normal motor development by 9 months of corrected age, and environmental influences such as post-discharge caregiving and access to early interventions.

The characteristics of infantile spontaneous movements are early markers of the integrity of the developing nervous system.^{27,28,32} The first human fetal movements occur at 7 weeks and become more complex at 9–10 weeks of post-menstrual age.³³ Normal writhing movements until 2 months of post-term age are described as variable sequences of neck, trunk, arm, and leg movements with diverse intensity, speed, range of motion, and gradual onset and end pattern, which forms a gross impression of the complexity of infantile spontaneous movements.² Although the neurophysiological underpinnings of infantile spontaneous movements remain unclear, the neural activities of infantile spontaneous movements are hypothesized to originate from the central pattern generator networks located in the spinal cord and brainstem.²⁷ During brain development, their movement pattern gradually becomes more complex, modulated by the activity of the supraspinal structures, such as the subplate or cortical plate.^{28,33} Particularly, the characteristics of writhing movements may be an expression of the increased motoneuronal excitability, associated with transient overexpression of the noradrenergic and glutamatergic receptors and the high serotonergic innervation and dopamine turnover.²⁷ Absent or reduced complexity is a crucial characteristic of spontaneous infantile movements and is caused by neurological injuries or dysfunction of the subplate, cortical plate, or efferent connective fibers in the periventricular white matter.²⁸ This is one of the main rationales that underscores the importance of quantitatively analyzing the diverse aspects of infantile spontaneous movements for the early detection of high-risk infants. LDJ and SPARC can be potentially useful parameters for the early detection of infants at high risk of neurodevelopmental disorders. This is because they sensitively measure the smoothness of infantile spontaneous movements, especially considering the presence of overlapping sub-movements that contribute to spatiotemporal complexity.

Recent advancements in human recognition technologies have established sensor- and vision-based approaches for analyzing spontaneous limb movements.³⁴ The sensor-based approach adopts wearable accelerometers to measure the velocity and acceleration, quantifying movement characteristics, such as kurtosis, skewness, and periodicity of infantile limb movements.³⁵ The wearable inertial sensors and machine learning technologies capture and analyze spontaneous limb movements, enabling the classification of normal and abnormal movement patterns and the automation of GMA for perinatal screening.³⁶ Wearable inertial sensors offer advantages in data acquisition for spontaneous limb movements with privacy preservation and cost efficiency. However, this approach presents challenges in attaching the sensor to the infantile body and potential interference with natural movement patterns in infants.³⁷ The vision-based approach has been popularized with the rapid development of computer vision technologies. The widespread use of RGB cameras, especially in smartphones, has extended this approach to various real-world applications.³⁴ Previous studies based on the vision-based approach have focused on extracting diverse movement characteristics, including magnitude, area, shape, spatial center, balance, rhythm, and complexity of spontaneous limb movements, to classify normal and abnormal movement patterns in high-risk infants.^{9,10,12,13,38,39} The minimal disturbance during spontaneous limb movements and relatively high accuracy and robustness in movement detection are the strengths of the vision-based approach.³⁷ Furthermore, deep learning frameworks, a more advanced vision-based approach, have been used to develop prediction models with high diagnostic accuracy for the early screening of cerebral palsy.^{40,41} The current study used a vision-based approach by automatically acquiring positional coordinates of multiple joints in the upper and lower limbs from movement videos captured using the RGB cameras in conventional smartphones and an open-source pose-estimation model, AlphaPose. The characteristics of spontaneous limb movements were quantified using smoothness indices calculated based on infantile movement data. This allowed to observe the natural movements of infants within familiar environments, providing a more authentic representation of their typical activity patterns. This can be a promising method in digital healthcare systems to facilitate the remote and automated evaluation of neonates or infants in the home environment.

This study had several limitations. First, the sample size of infants with MDD was smaller than that of infants without MDD. This study did not perform a priori sample size calculation or post hoc power analysis, which may limit the statistical power. This study did not investigate normative or cutoff values of LDJ and SPARC measures or perform discriminatory analysis between infants with and without MDD due to the limited sample size of infants with MDD. Moreover, the predominance of significant associations in right-sided joints may be attributable to positional bias, technical limitations of 2D pose estimation, or statistical artifacts rather than true lateral asymmetry. Future studies with larger cohorts and formal sample size calculations are necessary to establish the normative or cutoff values of smoothness measures to develop machine learning-based predictive models in high-risk infants, and the clinical relevance of each LDJ and SPARC would be additionally explored. Clinical evaluations previously demonstrated to be useful tools for predicting MDD, such as HINE, could be considered to be utilized with smoothness measures in developing a predictive model to improve diagnostic accuracy. Additionally, more detailed analyses based on movement smoothness according to diverse related factors (e.g., GMA categories) will be conducted in larger cohorts. Second, motor developmental outcomes regarding Bayley-III scores were assessed at 9 months of corrected age, presenting the possibility of additional diagnoses at a later stage. Despite the relative earliness, identifying the smoothness indices associated with MDD at this developmental milestone is clinically important because early intervention usually begins before 9 months of corrected age. Further research is required to examine the long-term longitudinal associations between smoothness indices at term-equivalent age and adverse motor developmental outcomes. Third, this study analyzed two-dimensional images captured using conventional smartphone RGB cameras, not three-dimensional images captured using depth cameras. Despite the loss of in-depth information in the quantitative analyses of body movements, using widely accessible devices offers both utility and cost-effectiveness advantages. Notably, MDD was associated with the smoothness indices derived from two-dimensional images recorded in a standardized manner.

In conclusion, this study demonstrated the association between limb-movement smoothness at term-equivalent age and motor developmental outcomes in very-preterm and very-low-birth-weight infants. Quantifying limb-movement smoothness was feasible using a convolutional neural network-based pose-estimation model and smoothness indices measured by LDJ and SPARC. The smoothness indices of limb movements can be potentially useful in developing automatic methods for the early detection of high-risk infants. Future studies with larger cohorts are necessary to establish cutoff values for the smoothness measures. These can serve as adjunctive tools to support clinicians during the decision-making processes for predicting developmental outcomes in high-risk infants.

Data availability

The datasets used and/or analyzed in the current study are available from the corresponding author upon reasonable request.

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YLL: Investigation; formal analysis; writing—Original Draft; visualization. HIS: Writing—Review & Editing; supervision. MSB: Conceptualization; writing—Review & Editing; supervision. SHS: Investigation; writing—Review & Editing. EKK: Investigation; writing—Review & Editing. ESL: Writing—Review & Editing. SBJ: Formal analysis; writing—Review & Editing. HIS2: Conceptualization; methodology; investigation; formal analysis; writing—Original Draft; supervision; project administration. WHL: Conceptualization; methodology; investigation; formal analysis; data curation; writing—Original Draft; visualization; supervision; project administration; funding acquisition. All the authors have read and approved the final version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

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