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Temporal and spatial localisation of general movement complexity and variation—Why Gestalt assessment requires experience

Ying-Chin Wu[1] | Ilse M. van Rijssen[1] | Maria T. Buurman[1] | Linze-Jaap Dijkstra[1] | Elisa G. Hamer[1,2] | Mijna Hadders-Algra[1]

[1]University of Groningen, University Medical Center Groningen, Department of Paediatrics, Division of Developmental Neurology, Groningen, The Netherlands

[2]Department of Neurology, Radboud University Medical Center, Nijmegen, The Netherlands

Correspondence
Mijna Hadders-Algra, Hanzeplein 1, 9713 GZ Groningen, The Netherlands.
Email: m.hadders-algra@umcg.nl

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Abstract

Aim: General movements' assessment (GMA), based on Gestalt perception, identifies infants at risk of cerebral palsy. However, the requirement of ample experience to construct the assessor's inner criteria for abnormal movement hampers its widespread clinical use. This study aims to describe details of general movements (GMs) in various body parts and to investigate their association with GMA-Gestalt.

Methods: Participants were 24 typically developing infants and 22 very-high-risk infants. GMs were assessed during the writhing (0-8 weeks) and/or fidgety GM phase (2-5 months) by GMA-Gestalt and a semi-quantification of the duration of simple movements and complex movements in various body parts.

Results: During both GM phases, the quality of movement often varied within a single assessment, but the degree of complexity and variation of movements in trunk, arms and legs were interrelated (ρ = 0.32-0.84). Longer durations of complex movements in arms and legs (P < .042) were further associated with a better quality in GMA-Gestalt. Head movement was associated with movements in other body parts only in the writhing phase and not associated with GMA-Gestalt during both GM phases.

Conclusion: Infants did not show consistently over time and across body parts simple or complex movements. Detailed description of movement characteristics may facilitate the development of computer-based GMA.

KEYWORDS

general movements, general movements' assessment, motor behaviour, semi-quantification, variation

1 | INTRODUCTION

Motor development is a complex and long-lasting process, which starts with the temporary presence of general movements (GMs) and proceeds with the engagement in goal-directed movements. GMs are spontaneous movements involving all parts of the body, present between early foetal life and 3-5 months post-term. Their development is characterised by three phases: foetal-preterm, writhing and

Abbreviations: CP, Cerebral palsy; DA, Definitely abnormal; GM, General movement; GMA, General movements' assessment; MA, Mildly abnormal; TD, Typically developing; VHR, Very high risk.

Ying-Chin Wu and Ilse M. van Rijssen contributed equally.

fidgety. Our paper focuses on the last two phases due to their clinical relevance.[1] In the writhing phase (from 36 to 38 weeks postmenstrual age to 6-8 weeks corrected age [CA]), GMs have a forceful appearance; in the fidgety phase (from 2 to 5 months CA), the forceful movements have disappeared to be replaced by tiny, elegant and rhythmic movements, the so-called fidgety movements.

Currently, there are two variants in assessing the quality of GMs: Prechtl's method[2] and Hadders-Algra's classification.[3] These two assessments use different scoring systems for categorising abnormal GMs. Nevertheless, they both qualify the GMs based on the Gestalt perception with specific attention to the size of the motor repertoire, that is complexity and variation (the spatial and temporal variation of the movements), fluency (the velocity profile of the movements) and the presence of fidgety movements in all parts of body. Accumulating evidence showed that abnormal spontaneous movement with a reduced repertoire and fluency or the absence of fidgety movements indicates a high risk of cerebral palsy (CP).[4] However, GMs' assessment (GMA) is often criticised for its subjectivity, as it has not been quantitatively addressed what the criteria are for a reduced motor repertoire and the degree fidgety movements. Reliability of GMA is excellent among very specialised and experienced professionals, but lower reliability has been reported for medical staff after a training course and several years of experience.[5,6] The requirement of ample experience to construct the inner criteria for abnormal movements by individual raters hampers a widespread clinical use of GMA.

As a result, several computer-based assessment tools have been developed, aiming to discriminate more objectively between normal and abnormal GMs.[7] It has been shown that the presence of fidgety movements could be automatically detected by the computer via a conventional video recording.[8,9] The automated analyses indicated that healthy infants exhibited more fidgety movements and less slow movements than infants later diagnosed with CP.[10] Yet, automatic assessment of movement complexity and variation, the other major characteristics of GMs, has not been largely explored and is still far from clinical application. To capture the movement characteristics, many efforts have been made with motion sensors attached to the infants. For example, a stereotyped trajectory (reflecting reduced variation) of arm movements[11,12] and an abrupt change in acceleration (reflecting reduced fluency) of leg movements[13] were found in infants later diagnosed with CP. In addition, the combination of multiple parameters describing the trajectory and velocity of leg movements differentiated GMs of typically developing and high-risk infants.[14,15] Most studies on automatic analysis of GM characteristics focussed on movement characteristics in parts of the body. An exception to this rule is the recent study of Ihlen et al[16] in which movement complexity across six body parts (head, trunk, both arms and both legs) was taken into account. This implies that transfer of knowledge to GMA dealing with all parts of the body is hard, as the information on how GMs are quantitatively and qualitatively distributed over the entire body is unclear. Knowing that infant motor behaviour is characterised by variation, this also means that not only inter-individual but also intra-individual variation occurs.[17]

Keynotes

- Movement complexity and variation during a single assessment of general movements (GMs) often vary over time.
- Movement complexity and variation of trunk, arms and legs during the general movements' assessment (GMA) are interrelated.
- Clinical Gestalt in GMA is especially based on the complexity and variation of limb movements but less associated with that of head and trunk movements.

Hence, this study aims (a) to provide semi-quantitative information on the temporal and spatial distribution of movement complexity and variation during GMs classified by Gestalt GMA as normal or abnormal; and (b) to investigate the interrelations of the degree of movement complexity and variation in the various body parts. To this end, we applied a semi-quantitative analysis system in a selective sample of infants showing normal or abnormal GMs. The semi-quantification of the movements consisted of the percentage of time the infants spent performing simple or complex and varied movements in the various body parts. The selective sample consisted of a group of low-risk infants expected to have a high chance of having GMs with better movement qualities and a group of very-high-risk infants expected to have a high chance of having GMs with worse movement qualities. We hypothesised that the movement characteristics during a single assessment vary over time, that GMs classified by Gestalt GMA as abnormal are associated with shorter periods of complex and varied movements in head, trunk, arms and legs, and that movement complexity and variation in the various body parts are interrelated.

2 | METHODS

2.1 | Participants

Sixty-two infants were initially enrolled in the study, consisting of a group of 26 typically developing (TD) infants and a group of 36 very-high-risk (VHR) infants. The TD infants were born at term (≥37 weeks of gestation) without prenatal, perinatal or neonatal complications. The VHR infants had participated in the LEARN2MOVE study, a randomised controlled trial to investigate the effect of a family-centred intervention programme on motor performance and its working mechanisms. To be included in the LEARN2MOVE study the infants had to fulfil at the age of 0-9 months CA at least one of the following risks of CP: cystic periventricular leukomalacia diagnosed on serial ultrasound assessments of the brain, a parenchymal lesion of the brain, neonatal hypoxic-ischaemic encephalopathy with brain

lesions on magnetic resonance imaging, or clear neurological abnormalities suggestive of the development of CP. Their mobility-related activities were assessed at enrolment and at 3, 6 and 12 months after enrolment. The assessments included the evaluation of spontaneous movements at the youngest ages, including spontaneous movements in supine. Of the 43 infants enrolled in LEARN2MOVE 36 had been assessed at least once in the age period that GMs are present (up to 5 months CA). The Infants were excluded in case of additional severe congenital disorders or an insufficient understanding of the Dutch language by the caregivers.[18] All parents gave informed consent. The data collection was approved by the Medical Ethics Committee of the University Medical Center Groningen (TD infants' study: NL39954.042.12; VHR infants' study: NTR 1428).

2.2 | Video recordings for GMA

The TD infants were assessed at 1 and 3 months of age. The VHR infants were assessed once or twice between 0 and 5 months CA, in line with the design of the LEARN2MOVE study.

Depending on parent's preference, infants were filmed for the assessment of GMs at home or at the baby-laboratory of Developmental Neurology of the University Medical Center Groningen. During the recording, the infant, wearing a diaper with or without a bodysuit only, was put in supine and the spontaneous movements were videotaped for at least 3 minutes. Electromyographic activity of various muscles was also recorded (results not reported in this paper). Care was taken to have the infant in an adequate, awake, non-crying behavioural state. When the infant started to cry, caregivers were invited to console the infant. This could happen multiple times during a recording, especially in the youngest infants. During the periods of consolation, the video recording continued.

Quality of the GMs was assessed offline by Gestalt (GMA-Gestalt) and detailed descriptions of movement characteristics (GM details). GMA-Gestalt and GM details were performed, respectively, by MHA and IMR, who were blinded for the infant's clinical history and age and each other's results.

2.3 | GMA-Gestalt

The present study used the GMA-Gestalt classification of Hadders-Algra [3]: normal-optimal (abundant complexity, variation and fluency), normal-suboptimal (sufficient variation and complexity, no fluency), mildly abnormal (MA, insufficient variation and complexity, no fluency) and definitely abnormal (DA, very limited or absent variation and complexity). Knowing that normal-optimal and normal-suboptimal GMs reflect typical brain function and do not differ in predicting neurodevelopmental outcomes,[19] we pooled these two categories into one labelled 'normal' GMs.

Fidgety movements were globally assessed in terms of the temporal organisation (continual, intermittent, sporadic and absent) and quality (normal and exaggerated).[2]

2.4 | GM details

The details of the GMs were analysed using the Observer XT software (version 9.0, Noldus Information Technology). This programme allows for a frame by frame coding of specific behavioural characteristics of video recordings and therewith for a semi-quantification of observed behavioural characteristics.[20] For the analysis of the GMs motor behaviour was classified and annotated in terms of start and end of the behaviour in the following way: (a) head: midline, turned to left, turned to right; (b) trunk: no movement, cramped-synchronised movement, hyperextension, varied motility; (c) arms: no movement, simple movements, complex and varied movements; (d) legs: no movement, simple movements, complex and varied movements. Movements were considered simple when both arms (or both legs) showed simple flexion-extension movements, simple abduction-adduction movements or isolated rotation (reduced complexity), or when one or both arms (or legs) repetitively produced the same movement sequences (reduced variation), or a combination of these two characteristics, or when a posture in one or both arms (or legs) did not change over time (reduced complexity and variation). Movements combining flexion-extension, abduction-adduction and rotation on various joints were considered complex and varied (Table S1). GM characteristics were only assigned when they lasted at least 2 seconds (trunk movements) or 4 seconds (limb movements). The 2 seconds interval was chosen as it was the minimum during which we were able to distinguish a cramped-synchronised movement, hypertension and varied trunk motility. For the classification of limb movements, 4 seconds turned out to be the minimum, as the interval had to cover potentially repetitive movements. The presence of interfering behaviours was also annotated from start to end. Interfering behaviours could consist of the following: handling by adult person, inappropriate behavioural state (sleeping, fussy, crying), presence of goal-directed activity, non-nutritive sucking or hiccup. The video frames with interfering behaviours were excluded from the GM analyses. From the remaining video frames the percentage of time each GM characteristic was present relative to the total duration of the assessment (without interfering behaviours) was calculated, generating information on the duration of GM characteristics. In order to obtain information on head movements, we also calculated the number of changes in head position relative to total assessment time without interference.

Reliability of output generated by the Observer programme can be assessed on the basis of a sample of five infants.[20] Therefore, five TD infants and five VHR infants were randomly selected from the participants and their GM details were annotated and quantified by a second assessor (MTB) to evaluate the interrater reliability of GM details. The assessors of the GM details, IMR and MTB, had received the following training. In order to understand the basic idea of movement complexity and variation they were trained by MHA to assess GMA-Gestalt on the basis of another sample of 40 infants. Next, they practised the detailed annotation of the specific movements with the help of a sample of another 7 infants. Excellent agreement on the duration of the specific GM characteristics (intraclass correlation coefficients: 0.884-1.000) was present (Table S1).

2.5 | Statistical analysis

Data in the writhing and fidgety phases were analysed separately. Associations between GMA-Gestalt (normal, MA and DA) and the duration of GM characteristics were assessed with the Kruskal-Wallis test. Post hoc analyses were done by Mann-Whitney *U* tests with alpha at 0.017 to adjust for multiple testing. The associations between GMA-Gestalt and fidgety movements were examined by Fisher's exact tests with adjusted alpha at 0.017 in the comparisons of pairs of groups. In order to assess the interrelations between GM characteristics of the different body parts, Spearman's rank correlation coefficients were calculated. Apart from the exceptions already mentioned, a *P* value < .05 was considered to be statistically significant. All analyses were conducted with SPSS package version 23 (SPSS InC.).

3 | RESULTS

3.1 | Study group characteristics

Of the 62 original enrolees, 60 GM assessments from 46 infants were available for analysis. The reasons for data-exclusion are reported in Figure 1. The background information of the final study group is shown in Table 1.

In the writhing phase, GMA-Gestalt revealed 12 assessments with normal GMs, 3 with MA and 2 with DA GMs (Figure 1). Infants were filmed for GMA for 605 seconds (median value; range 382-991 seconds). After excluding the time frames with interfering behaviours, recordings with a duration of 368 seconds (median value; range 201-633 seconds) were used for the semi-quantitative GM analysis.

In the fidgety phase, GMA-Gestalt revealed 19 assessments with normal GMs, 7 with MA and 17 with DA GMs (Figure 1). Infants were filmed for GMA for 528 seconds (median value; range 238-1205 seconds). After exclusion of the time frames with interfering behaviours, recordings with a duration of 382 seconds (median value; range 76-795 seconds) were used for the semi-quantitative GM analysis.

3.2 | Associations between GMA-Gestalt and GM details

Our data analysis indicated that cramped-synchronised GMs were rare (1% of time in one VHR infant), precluding further analysis. Figure 2 shows typical examples of the time course of the movement characteristics during a recording of normal, MA and DA GMs. It illustrates that infants during a GM assessment do not consistently show only simple or only complex and varied movements.

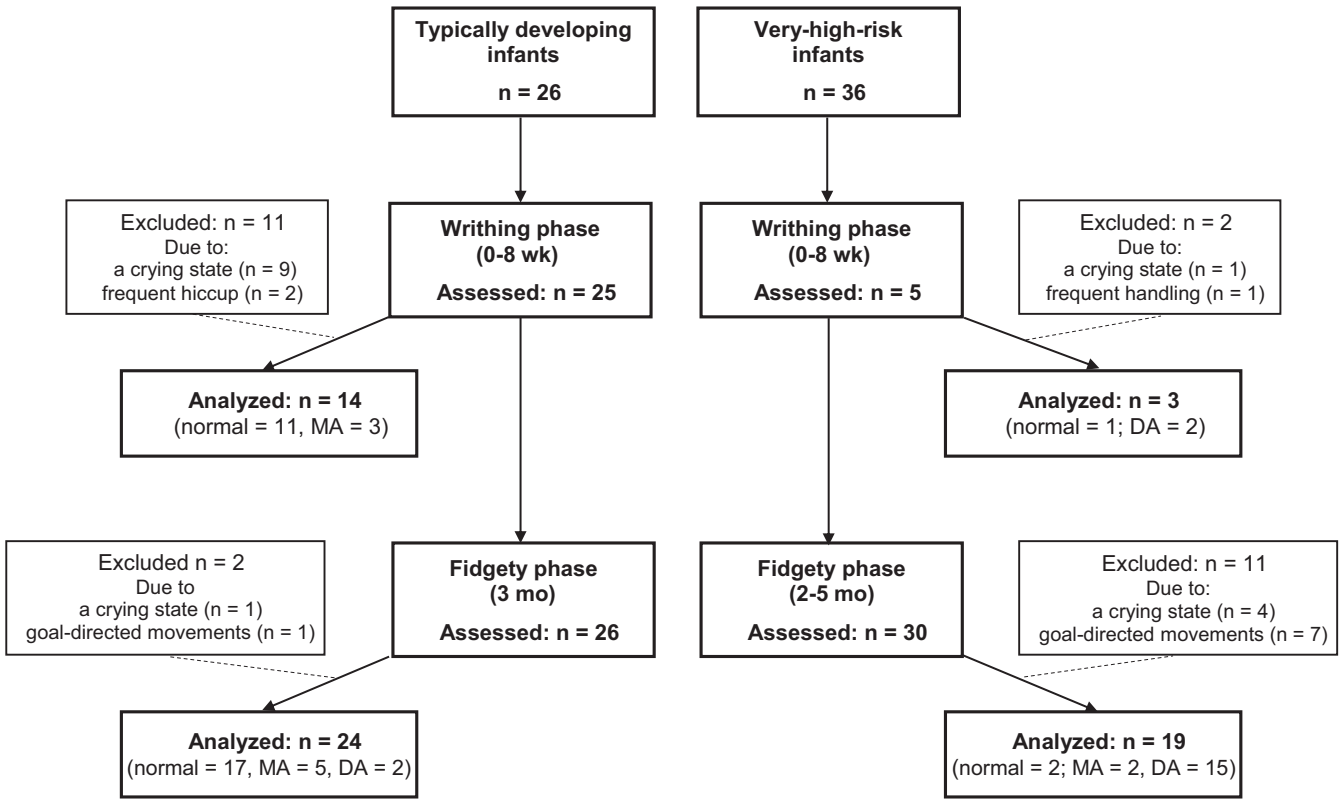


FIGURE 1 Flow chart of assessments. A diagram of the assessment schedule and data collection. MA = mildly abnormal GMs, DA = definitely abnormal GMs

TABLE 1 Background characteristics of the study sample

	Typically developing infants (n = 24)	Very-high-risk infants (n = 22)
Neonatal characteristics		
Male, n (%)	11 (46)	12 (54)
Preterm birth (<37 wks), n (%)	0 (0)	16 (72)
Gestational age in weeks, median (range)	40.2 (37.0-41.7)	31.9 (25.9-41.3)
Birthweight in gram, median (range)	3710 (2680-4200)	1669 (720-4410)
Type of brain lesions	-	
No or nonsignificant lesion, n		5
Basal ganglia/thalamic lesion, n		3
Cortical infarction, n		2
Posthemorrhagic porencephaly, n		5
Periventricular leukomalacia, n		7
General movement (GM) assessments, n	38	22
Number of infants with		
Single assessment, n	10	22
Two assessments, n	14	0
Assessments in writhing phase		
Number of assessments, n	14	3
Corrected age in weeks post-term age, median (range)	4.6 (3.9-5.7)	7.1 (4.4-7.6)
Duration of total assessment in seconds, median (range)	681 (382-991)	525 (460-605)
Duration of the assessment without interfering behaviours in seconds, median (range)	380 (201-633)	364 (314-568)
Assessments in fidgety phase		
Number of assessments, n	24	19
Corrected age in months, median (range)	3 (3-3)	3 (2-5)
Duration of total assessment in seconds, median (range)	652 (305-1205)	450 (238-1066)
Duration of the assessment without interfering behaviours in seconds, median (range)	461 (118-795)	307 (76-481)

During the writhing phase, the percentage of time the infants spent on specific head positions and the frequency of head turning did not differ between the groups of infants with normal, MA and DA GMs (Figure 3A). Also the percentage of time the infants spent performing specific trunk movements was not associated with the clinical GMA-Gestalt (Figure 3B). The GMA-Gestalt was significantly associated with the time the infants spent on simple movements and complex and varied movements (in the following denoted as complex movements) in arms (P = .019 and P = .021, respectively, Figure 3C) and complex movements in legs (P = .042, Figure 3D). Post hoc analyses indicated that there were no significant differences in the comparisons of pairs of groups (normal vs MA GMs, MA vs DA GMs and normal vs DA GMs). However, infants with normal GMs tended to spent less time on simple arm movements than infants with MA GMs (P = .031) and infants with DA GMs (P = .044) and more time on complex arm movements (P = .022) and complex leg movements (P = .022) than infants with DA GMs.

`Infants with DA GMs showed significantly less fidgety movements (in the fidgety phase) than infants with normal and MA GMs (P = .002 and P = .004, respectively). During normal GMs fidgety movements were continual in one infant (5%), intermittent in 14 (74%) and sporadic in 4 (21%); none showed exaggerated fidgety movements. During MA GMs fidgety movements were intermittent in 7 infants (100%), of whom two showed exaggerated fidgety movements. In the group of infants with DA GMs, 4 infants (24%) had intermittent fidgety movements, 8 (47%) had sporadic and 5 (29%) showed no fidgety movements; exaggerated fidgety movements were observed in 3 infants with DA GMs.

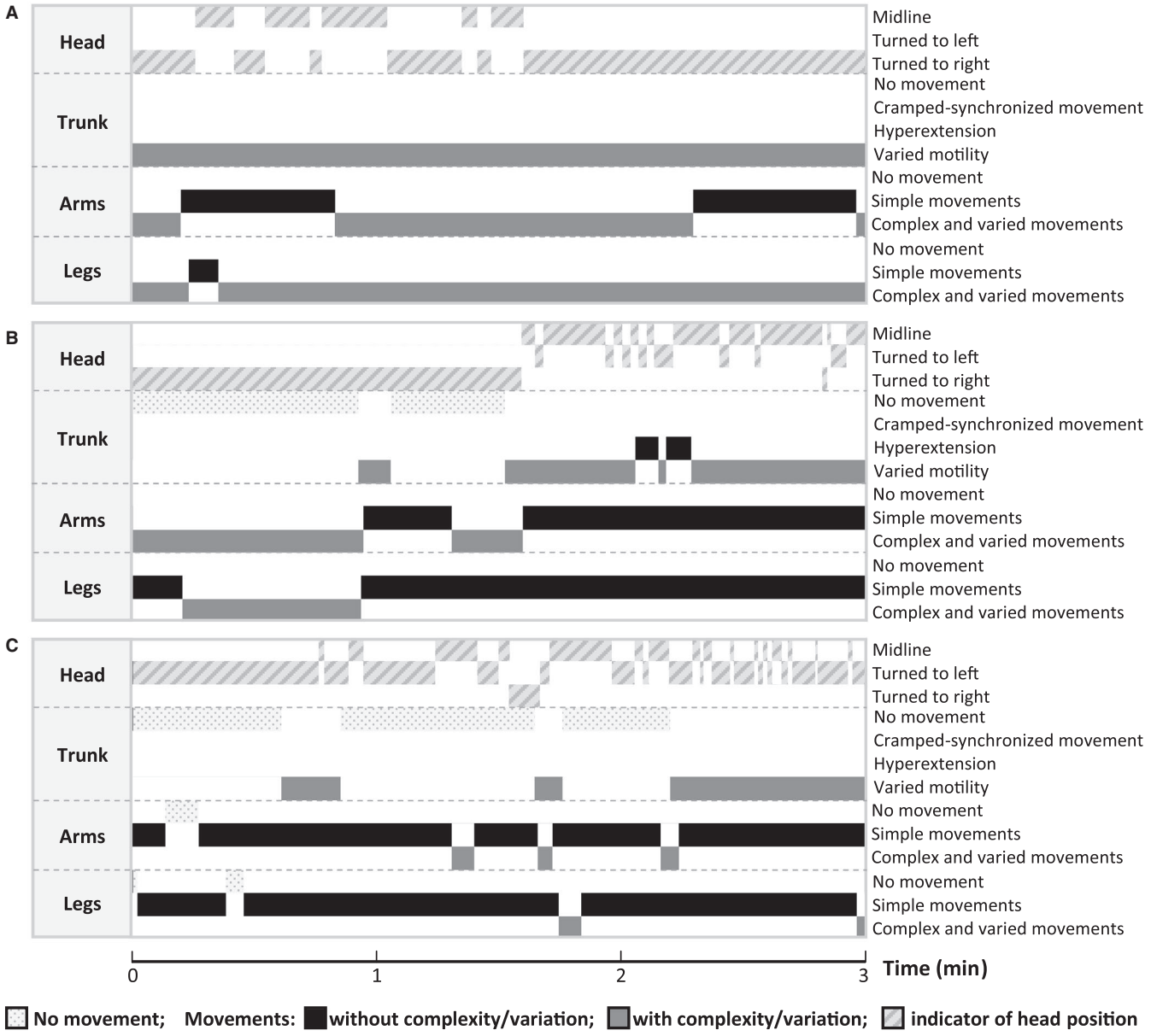
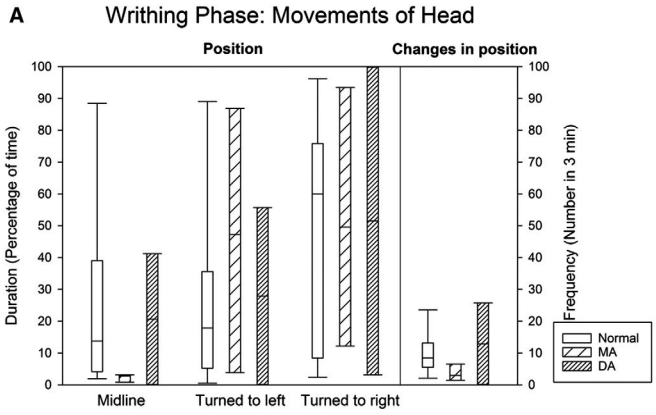


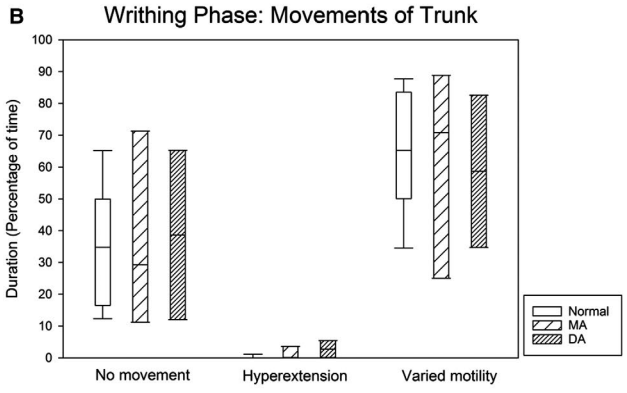
FIGURE 2 Examples of the semi-quantified analysis of general movement (GM). Details of GM characteristics in various body parts during minutes of (A) an infant with normal GMs, (B) an infant with mildly abnormal GMs and (C) an infant with definitely abnormal GMs. The bars indicate the time when a specific movement characteristic was observed. The three infants show frequent head turns and varied trunk movements. They differ, however, in arm and leg movements. Infant (A) frequently shows complex and varied movements, but also short periods of simple movements are present. Infant (B) shows many simple movements, interchanged with some complex movements. Infant (C) has short bursts of complex movements embedded in predominantly simple movements of the arms and legs

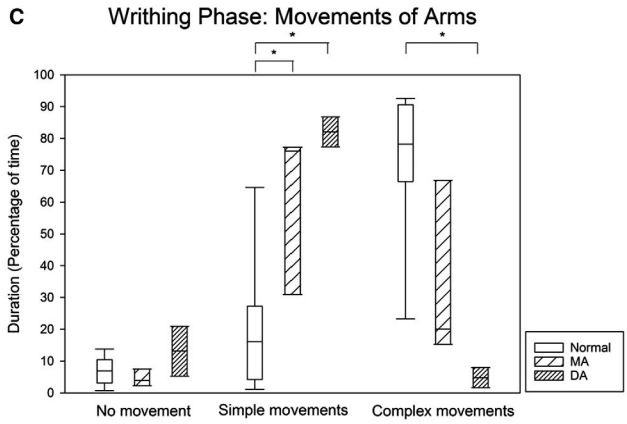
3.3 | Interrelations between GM details

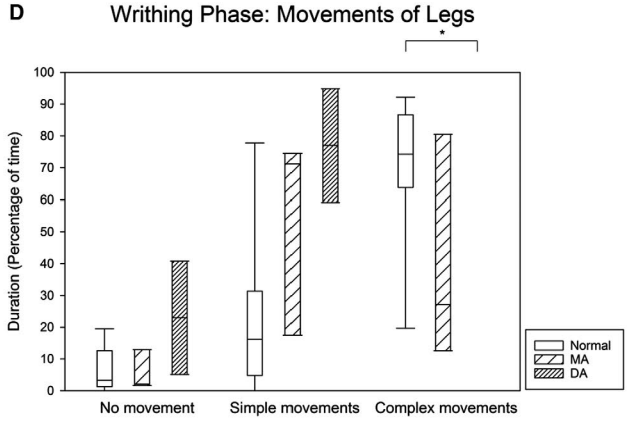
During the writhing phase, position of head was associated with arm and leg movements. A longer duration of head in the midline was associated with a shorter duration of simple movements (Spearman's $\rho = -0.53$, $P = .028$) and a longer duration of complex movements ($\rho = 0.60$, $P = .011$) in arms. Head movements were associated with trunk movements. A higher frequency of change in head position was associated with a longer duration of any movements in trunks ($\rho = 0.58$, $P = .016$), especially varied trunk movements ($\rho = 0.55$,

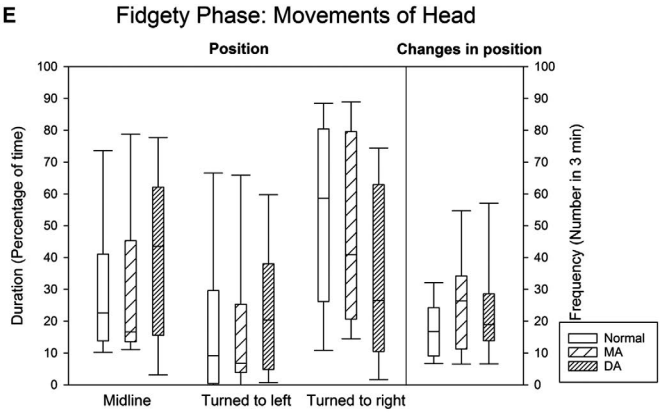
FIGURE 3 Associations between clinical Gestalt and details of general movements (GM). The three groups represent the infants with normal GMs, mildly abnormal (MA) GMs and definitely abnormal (DA) GMs. Figures in left panel show the GMs during the writhing phase (normal: n = 12, MA: n = 3, DA: n = 2); figures in right panel are the GMs during the fidgety phase (normal: n = 19; MA: n = 7, DA: n = 17). Data are presented as median (horizontal bar), interquartile ranges (boxes) and ranges (vertical lines). * indicates $P < .05$ in group comparisons. **Indicates $P < .017$ in group comparisons, adjusted for the multiple testing

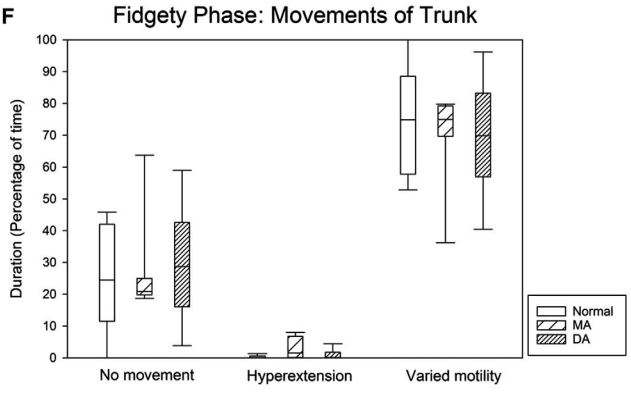

A
Writhing Phase: Movements of Head
Position
Changes in position
Duration (Percentage of time)
Frequency (Number in 3 min)
Normal
MA
DA
Midline
Turned to left
Turned to right

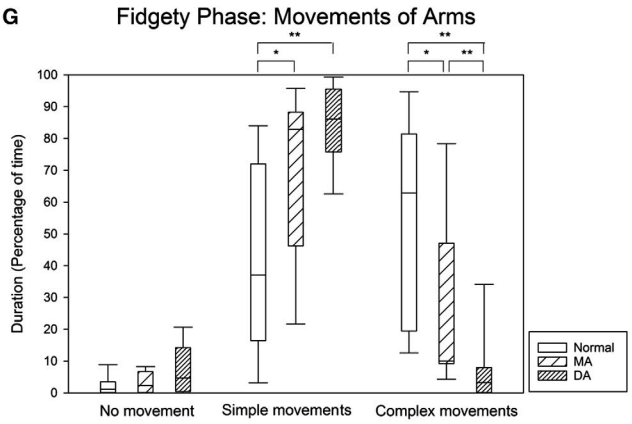

B
Writhing Phase: Movements of Trunk
Duration (Percentage of time)
Normal
MA
DA
No movement
Hyperextension
Varied motility

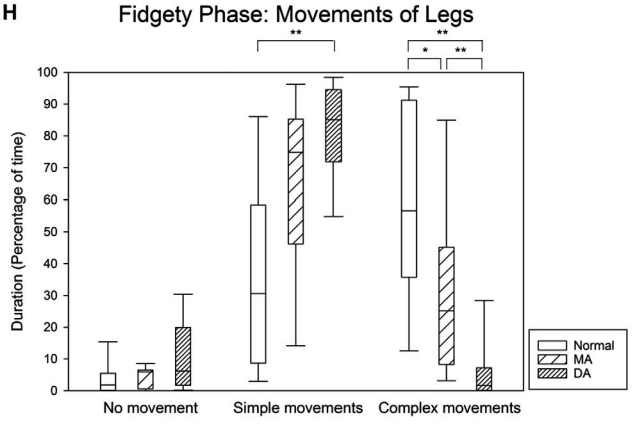

C
Writhing Phase: Movements of Arms
Duration (Percentage of time)
Normal
MA
DA
No movement
Simple movements
Complex movements


D
Writhing Phase: Movements of Legs
Duration (Percentage of time)
Normal
MA
DA
No movement
Simple movements
Complex movements


E
Fidgety Phase: Movements of Head
Position
Changes in position
Duration (Percentage of time)
Frequency (Number in 3 min)
Normal
MA
DA
Midline
Turned to left
Turned to right


F
Fidgety Phase: Movements of Trunk
Duration (Percentage of time)
Normal
MA
DA
No movement
Hyperextension
Varied motility


G
Fidgety Phase: Movements of Arms
Duration (Percentage of time)
Normal
MA
DA
No movement
Simple movements
Complex movements


H
Fidgety Phase: Movements of Legs
Duration (Percentage of time)
Normal
MA
DA
No movement
Simple movements
Complex movements

P = .022) (Table 2). Furthermore, movements of trunk were associated with the movements of arms and legs. A longer duration of varied trunk movements was associated with a longer duration of complex leg movements (ρ = 0.54, P = .027). In addition, infants who spent more time on hyperextension of the trunk had longer durations of simple movements in arms (ρ = 0.63, P = .007) and legs (ρ = 0.71, P = .001), and shorter durations of complex movements in arms (ρ = −0.60, P = .012) and legs (ρ = −0.61, P = .009) (Table 2).

The GM characteristics of arm and leg movements in the writhing phase were interrelated. Infants who spent more time on simple movements in arms had longer duration of simple movements and shorter duration of complex movements in legs (ρ = 0.73 and ρ = −0.74, respectively, both P = .001). Likewise, infants spent more time on complex arm movements had longer duration of complex leg movements (ρ = 0.69, P = .002) and short duration of simple leg movements (ρ = −0.64, P = .006) (Table 2).

During the fidgety phase, head position and head movement were not associated with the movements of trunk, arms and legs. Characteristics of trunk movements were associated with characteristics of arm and leg movements. More time on any trunk movements was associated with more time on any movements in arms and legs (ρ = 0.42, P = .005, ρ = 0.50, P = .001, respectively) and simple movements in arms (ρ = 0.34, P = .024) but less time on complex movements in arms and legs (ρ = −0.37, P = .014, ρ = −0.38,

TABLE 2 Relations of general movement characteristics in different body parts

	Writhing phase (n = 17)				Fidgety phase (n = 43)			
	Head position and movement							
	Midline	To left	To right	Change	Midline	To left	To right	Change
Trunk movement								
No movement	−0.10	−0.37	0.14	−0.58*	−0.18	−0.01	0.11	0.08
Hyperextension	−0.04	0.20	−0.19	0.08	−0.03	0.19	0.05	0.17
Varied motility	0.06	0.32	−0.06	0.55*	0.16	−0.00	−0.13	−0.06
Arm movements								
No movement	−0.21	−0.22	0.22	−0.16	−0.13	−0.03	0.04	−0.11
Simple movements	−0.53*	0.02	0.25	−0.22	0.01	0.07	−0.04	0.02
Complex movements	0.60*	0.06	−0.34	0.22	−0.12	−0.05	0.10	−0.02
Leg movements								
No movement	−0.08	−0.71*	0.50*	−0.38	−0.01	0.19	−0.10	0.20
Simple movements	−0.16	0.22	−0.14	−0.07	0.13	0.26	−0.30	0.02
Complex movements	0.25	0.03	−0.01	0.26	−0.10	−0.30	0.27	−0.05

	Trunk movement					
	No	Hyperextension	Varied	No	Hyperextension	Varied
Arm movements						
No movement	0.23	0.29	−0.22	0.42*	0.17	−0.42*
Simple movements	0.11	0.63*	−0.19	0.34*	0.24	−0.38*
Complex movements	−0.06	−0.60*	0.13	−0.37*	−0.28	0.41*
Leg movements						
No movement	0.31	−0.05	−0.33	0.50*	0.17	−0.50*
Simple movements	0.29	0.71*	−0.37	0.25	0.20	−0.27
Complex movements	−0.45	−0.61*	0.54*	−0.38*	−0.32*	0.41*

	Arm Movements					
	No	Simple	Complex	No	Simple	Complex
Leg Movements						
No movement	0.16	0.11	−0.16	0.54*	0.19	−0.29
Simple movements	0.08	0.73*	−0.64*	0.26	0.79*	−0.77*
Complex movements	−0.21	−0.74*	0.69*	−0.43*	−0.77*	0.84*

Note: Data are presented as Spearman's correlation coefficient.

*Indicates P < .05. 'Complex movements' denotes complex and varied movements.

P = .013, respectively). In contrast, a higher prevalence of varied trunk movements was associated with a higher prevalence of complex movements in arms and legs (both ρ = 0.41, P = .006) and a lower prevalence of simple movements in arms (ρ = −0.38, P = .012). A longer duration of hyperextension was associated with a shorter duration of complex leg movements (ρ = −0.32, P = .037).

In the fidgety phase the GM characteristics of the arms were strongly associated with the GM characteristics of the legs. Recordings with longer durations of no movement, simple movements or complex movements in the arms had longer durations of no movement (ρ = 0.54, P < .001), simple movements (ρ = 0.79, P < .001) or complex movements (ρ = 0.84, P < .001) in the legs, respectively. In addition, a longer duration of simple arm movements was associated with a shorter duration of complex leg movements (ρ = −0.77, P < .001), whereas a longer duration of complex arm movements was associated with a shorter duration of simple leg movements (ρ = −0.77, P < .001) (Table 2).

4 | DISCUSSION

Our results indicated that infants show both simple and complex movements within one GM assessment. Presumably, this is one of the reasons why GMA is difficult and requires ample training.[5,6] Nevertheless, our data also demonstrated that the degree of complexity and variation in trunk, arms and legs were interrelated during the writhing and fidgety phases: the more simple movements in one of these three body parts, the more simple movements in the other parts. In addition, we showed that the clinical GMA-Gestalt was associated with the relative time spent on simple movements and complex movements in arms and legs. Normal GMs comprised more time on complex and varied movements and less time on simple movements than mildly or definitely abnormal GMs. During definitely abnormal GMs complex and varied limb movements were infrequently observed.

In the writhing phase, head position was associated with the movements of the extremities, especially of the arms. A longer duration with the head in midline was associated with more complex movements in the arms. This finding was in line with the clinical experience that arms movements in young infants with neurological dysfunction are easily affected by the asymmetrical tonic neck reflex.[21] Head movements were also associated with the trunk movements in the writhing phase. The association, however, dissolved during the fidgety phase. The disappearance of this interrelation may be attributed to head control developing prior to the control of other body parts.[22] The voluntary control of the head improves remarkably in the first 3 months post-term, which is reflected by the stabilisation of the head in the midline.[23,24] It might be that during the fidgety phase, head movements are mainly controlled by postural control mechanisms. The explanation of early development of voluntary head control was furthermore supported by the lack of significant associations of the head movements with the movements in the extremities and GMA-Gestalt in our study.

We also did not find a significant association between trunk movements and GMA-Gestalt. This does not automatically imply that trunk movements have nothing to do with the GMs. Three arguments support the involvement of the trunk in GMs. First, the active control of the trunk for specific goal-directed movements emerges at 4 months.[22] Second, we did find that a longer duration of simple trunk movements, that is hyperextension in the writhing phase, was associated with a longer duration of simple extremity movements, whereas a longer duration of complex trunk movements, that is varied motility in the fidgety phase, was associated with a longer duration of complex extremity movements. However, the difference in trunk movements between the normal, MA and DA GMs may be too small to be captured easily by Gestalt perception. Even the infants with DA GMs spent <10% of the time on hyperextension at writhing age and more than half of the time on varied motility at fidgety age. Third, it has been reported that cramped-synchronised movements are observed more often in infants with MA and DA GMs.[19] Another reason for our failure to find a significant association between trunk movements and GMA-Gestalt probably is the rare occurrence of cramped-synchronised movements and hyperextension in our study sample, even in the VHR infants. The low prevalence of these features resulted in an insufficient statistical power to demonstrate all potential associations between the trunk movements and other movement characteristics. We hypothesise that trunk movements and GMA-Gestalt are associated, when assessed in a larger sample of VHR infants.

The features of fidgety movements were associated with GMA-Gestalt. Infants with DA GMs had significantly more often atypical fidgety movements, that is sporadic or absent fidgety movements, and exaggerated fidgety movements were observed only during MA and DA GMs. However, the data also illustrate that atypical fidgety activity does not automatically imply the presence of definitely abnormal GMs. Vice versa, infants with DA GMs may show quite some fidgety movements.[25] It has been suggested that movement complexity and variation on the one hand and fidgety movements on the other hand are based upon different but overlapping neurobiological mechanisms.[26] Infants who show impairments in both aspects of the GMs have the highest risk of CP.[25,26]

It may be considered a limitation of the study that we studied a selective group of infants, that is TD and VHR infants. This would have been a major limitation if we would have used the sample to predict the infants' developmental outcome. However, the study's aim was not prediction, but a detailed description of normal and abnormal movements. Our selective sample served this goal well. The limited sample size with its logical but imbalanced distribution of GM quality in the two groups is certainly a study limitation. It precluded statistical analyses separately for TD or VHR infants. Another limitation related to our small sample of VHR infants is that the results of our study cannot be generalised to all populations of high-risk infants—the infrequent occurring cramped-synchronised movements being a point in case. The low prevalence of the cramped-synchronised movements has

been described more frequently in high-risk groups in Western Europe,[25,27] but studies in other parts of the world report higher prevalences.[28,29] We recommend that future research evaluates GM details in a larger and representative sample of high-risk infants. It may be considered also a limitation that we assessed the complexity and variation of arm and leg movements in the limbs of both sides simultaneously, as infants later diagnosed with unilateral CP may show minor asymmetries in movements across the distal joints.[30] However, in general most movement asymmetries in early infancy are related to a head preference posture and not to the presence of a brain lesion.[31] Therefore we decided to assess head position as a specific parameter and to assess movement complexity and variation in the arms and legs on both sides of the body simultaneously. Finally, it is possible that the assessor of the GM details was influenced by a GM-Gestalt perceived by seeing the entire infant on the video screen. This bias may have facilitated the associations between GMA-Gestalt and GM details. Nevertheless, the finding of substantial heterogeneity in GM details within a GM-Gestalt classification suggests that this bias was not strong.

5 | CONCLUSIONS

Our results correspond to the clinical experience of GMA: infants who show normal GMs predominantly but not consistently produce complex and varied movements—their complex movements may be interchanged with movements with less complexity and variation. Likewise, infants with abnormal GMs mostly show rather simple and stereotyped movements, but they also may produce sequences with more complexity and variation. This underlines how difficult it is to assess GMs by Gestalt perception. Nevertheless, the degree of complexity and variation of movements of trunk, arms and legs are interrelated, and especially the latter two are associated with clinical GMA-Gestalt.

Our study also demonstrated that it is possible to annotate and describe the quality of GMs in detail. This analysis of GM details is not the direct solution to an objective assessment of GMs, but such detailed information is an essential building block in the development of computer-based analysis of GMA and in further understanding of the neural basis of GMs—and therewith, widespread clinical use of GMA.

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CONFLICT OF INTEREST

Prof. dr Mijna Hadders-Algra has provided courses on the assessment of GMs since 1993. The honorarium of the courses flows into the Research Fund of Developmental Neurology. She did not get a honorarium, grant or other form of payment to produce the manuscript. Other authors declare no conflict of interest.

ORCID

Ying-Chin Wu https://orcid.org/0000-0003-3582-1530
Mijna Hadders-Algra https://orcid.org/0000-0001-6845-5114

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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