

University of Groningen

Postural control during reaching while sitting and general motor behaviour when learning to walk

Boxum, Anke G.; La Bastide-Van Gemert, Sacha; Dijkstra, Linze-Jaap; Furda, Anna; Reinders-Messelink, Heleen A.; Hadders-Algra, Mijna

Published in:
Developmental Medicine and Child Neurology

DOI:
[10.1111/dmcn.13931](https://doi.org/10.1111/dmcn.13931)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Boxum, A. G., La Bastide-Van Gemert, S., Dijkstra, L.-J., Furda, A., Reinders-Messelink, H. A., & Hadders-Algra, M. (2019). Postural control during reaching while sitting and general motor behaviour when learning to walk. *Developmental Medicine and Child Neurology*, 61(5), 555-562. <https://doi.org/10.1111/dmcn.13931>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).



The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Postural control during reaching while sitting and general motor behaviour when learning to walk

ANKE G BOXUM¹ | SACHA LA BASTIDE-VAN GEMERT²  | LINZE-JAAP DIJKSTRA¹ | ANNA FURDA¹ | HELEEN A REINDERS-MESSELINK^{3,4} | MIJNA HADDERS-ALGRA¹ 

1 University of Groningen, University Medical Center Groningen, Department of Paediatrics – Developmental Neurology, Groningen; **2** University of Groningen, University Medical Center Groningen, Department of Epidemiology, Groningen; **3** University of Groningen, University Medical Center Groningen, Department of Rehabilitation Medicine, Center for Rehabilitation, Groningen; **4** Rehabilitation Center 'Revalidatie Friesland', Beetsterzwaag, the Netherlands.

Correspondence to Mijna Hadders-Algra at Developmental Neurology, University Medical Center Groningen, Hanzeplein 1, 9713 GZ Groningen, the Netherlands.
E-mail: m.hadders-algra@umcg.nl

PUBLICATION DATA

Accepted for publication 4th May 2018.
Published online

ABBREVIATIONS

AIMS Alberta Infant Motor Scale
IMP Infant Motor Profile

AIM To study changes in muscular postural strategies and general motor behaviour during the transition to independent walking. Postural control was assessed at its two functional levels: (1) direction specificity, in which dorsal muscles are primarily activated when reaching forward; and (2) fine-tuning of direction specificity.

METHOD In an explorative longitudinal study, surface electromyograms of the arm, trunk, and neck muscles of 28 typically developing infants were recorded during reaching while sitting. Each infant was assessed in three developmental phases: during pull-to-stand (T0), first independent steps (T1), and 1 month after T1 (T2). Motor behaviour was assessed using the Infant Motor Profile (IMP). The effect on developmental outcome measures (postural parameters and IMP) of the developmental phases (T0, T1, T2) was estimated using linear mixed-effects models.

RESULTS None of the postural parameters changed significantly over time. However, individual developmental trajectories showed infant-specific postural reorganizational changes. Total IMP score decreased between T0 and T1 (mean IMP score 95% and 91% respectively; $p < 0.001$); between T1 and T2 IMP scores did not change (91% and 93%; $p = 0.073$).

INTERPRETATION Typically developing infants do not show consistent patterns of postural reorganization but show individual muscular strategies during the transition to independent walking. However, signs of reorganization of general motor behaviour are present.

Postural control is a prerequisite for many daily life activities, especially for motor actions like reaching, sitting, standing, and walking. Hence, the development of postural control and motor behaviour is closely entangled. Both reaching development and the development of gross motor milestones are important for subsequent development of perception, cognition, and social interaction.^{1,2} The important role of posture in reaching was illustrated, for example, by studies that demonstrated that infants who are not able to sit independently reach more frequently, successfully, and unilaterally in a supported sitting position than in supine or a semi-reclined position. Infants able to sit independently are equally successful in all positions and prefer unilateral reaches.^{3,4}

The control of posture is a complex neural task. The central nervous system deals with an interplay between continuous afferent information on body position and orientation from visual, vestibular, or somatosensory input and the subsequent motor commands to the muscles to maintain posture.⁵ To control the many degrees of freedom in a

multi-segmented body, the central nervous system uses a functional organization of postural control into basic muscular synergies that are able to adapt to specific situations.⁶ The basic level of muscular postural control is direction specificity. It means that when the body sways forward, the dorsal muscles are primarily activated to maintain balance.⁷ Direction specificity during goal-directed reaching, which involves an active body sway, slowly improves during infancy. Previous research showed that in a supported sitting position, direction specificity is present during 40% to 50% of reaching movements at 4 months, that is, before infants are able to sit independently. It increases to 60% to 80% of the movements at 18 months,⁸ and reaches adult values (100%) at the age of 2 years.⁹

The directionally appropriate adjustments can be adapted to the specifics of the situation using multisensory input.⁷ Modulation can be achieved by, for example, changing the recruitment order of the postural muscles, activating muscles before the start of the movement (anticipatory activation), or adapting the degree of muscle

contraction. At an early age, infants may already use proprioceptive information to adapt their postural muscle activity position to some extent (supine vs supported sitting).¹⁰ Older infants also show minor differences in postural muscle activity between supported and unsupported sitting positions, especially at 18 months and, in particular, in the lumbar extensor muscle (earlier recruitment and higher electromyography [EMG] amplitude in the unsupported condition).¹¹ The adaptation to sensory information is also observed in studies showing that the relation between postural sway parameters and vision or haptic information becomes more apparent with increasing age and increasing motor development.^{12,13}

Our previous research indicated that postural muscle activity during reaching while sitting with support did not change during the development of independent sitting.¹⁴ We suggested that once direction specificity is available, its degree during reaching in a supported sitting position does not influence the emergence of independent sitting. Other studies suggested that postural control might be related to the development of independent standing and walking, considering that the ultimate goal of human postural control is being able to cope with the limited surface support during standing and walking.^{11,15,16} As no longitudinal studies have addressed muscular postural changes, the primary aim of the present observational study was to assess longitudinal postural control during reaching while sitting in the course of the emergence of independent walking. Attention was also paid to head stabilization in space, as providing a stable visual and vestibular reference frame is one of the primary objectives of postural control.¹⁷ Typical individuals are able to stabilize their head in space during walking, despite the abundant movements in the underlying body parts.¹⁸ In infants, major developmental changes in head stability occur during the first 10 to 15 weeks of independent walking,¹⁹ but information on head stability when learning to walk is lacking. A secondary aim is to assess whether the development of independent walking influences general motor behaviour. Corbetta and Bojczyk²⁰ suggested that learning new patterns of muscle coordination while developing the skill to control balance in upright position may be accompanied by changes and regressions in already existing and established motor skills. To assess general motor behaviour, the Infant Motor Profile (IMP) was used.²¹ The IMP is a novel instrument that evaluates spontaneous play behaviour in five domains: variation (size of the repertoire), adaptability (ability to select efficient strategies), symmetry, fluency, and performance (motor milestones).

We hypothesized that the achievement of independent walking might require a reorganization in postural control and in motor behaviour in general. We expect that infants who just mastered their first steps are in the middle of the process of reorganization. Consequently, their postural control and motor development will differ from that in the preceding phase (not able to walk independently) and the following phase (after 1mo of independent walking

What this paper adds

- Infants show signs of reorganization of motor behaviour when learning to walk.
- Infants show individual strategies of postural reorganization when learning to walk.

experience), instead of showing steadily increasing developmental trajectories of the percentages of the different postural parameters and IMP scores. The literature suggests the presence of such transition phases in postural control during the development of a new motor skill. For instance, Chen et al.²² indicated that changes in postural sway parameters when learning to walk are also reflected in the infant's sitting posture, and van der Fits et al.¹⁰ showed that there was a transient dip in postural muscle activity at 6 months – around the age that infants learn to sit independently.

We addressed the following questions: (1) do muscular postural parameters during reaching while sitting show signs of postural reorganization during the transition to independent walking – with a dip in otherwise steadily increasing developmental trajectories? (2) Does motor behaviour, as measured with the IMP, show signs of reorganization during the transition to independent walking? We expected 'dips' in the total IMP score and in the domains of adaptability and performance.²⁰

METHOD

Participants

Twenty-eight typically developing infants were included in the study. Infants were included if born after a gestational age of 37 weeks without prenatal, perinatal, or neonatal complications, and if they were on the verge of independent standing. The latter meant that infants were able to stand with the help of support but not able to stand independently. Exclusion criteria were: (1) admission to a paediatric department; (2) severe congenital abnormalities; (3) birthweight below the tenth centile; (4) neurological abnormalities; (5) parents having insufficient understanding of the Dutch or English language. The medical ethics committee of the University Medical Center Groningen approved the protocol (NL51701.042.14) and parents gave informed consent.

Procedures

The infants were assessed three times: at T0 – being able to pull to stand but not able to stand independently ('Pulls to Stand With Support' item of the Alberta Infant Motor Scale [AIMS]²³); T1 – the infant is just able to walk independently for more than five steps ('Early Stepping' item of the AIMS); and T2 – the infant had some independent walking experience, that is, 1 month after T1 ('Walks Alone' item of the AIMS). Parents contacted the research team if infants were at developmental phase T0 and within a week of achieving T1, which was checked against the AIMS during the laboratory visit. During each session, postural control was assessed and neurodevelopmental condition was evaluated.

Postural assessments

Postural control during reaching was assessed in two conditions: first, while sitting in an infant chair providing trunk support, and, second, during unsupported 'long-leg' sitting on a thin mattress on the floor. If the infant was not cooperating in the supported sitting position, the infant was seated on the parent's lap (three sessions). Care was taken that the position of the infant resembled the position in the chair.⁸ The aim was to elicit at least 10 reaching movements per condition by presenting different toys of about 3cm by 6cm and 40g at arm-length distance.

Bipolar surface electrodes with an interelectrode distance of approximately 14mm were placed over the following muscles on the preferred side of the body: deltoid, pectoralis major, biceps brachii, triceps brachii, neck flexor, neck extensor, rectus abdominis, thoracic extensor, and lumbar extensor. The preferred side (right in all children) was chosen considering its ecological validity. The EMG signal was continuously recorded by means of an electrophysiological front-end amplifier (Cometa Wireless EMG, Milan, Italy) at a sampling rate of 2000Hz, and resampled to 500Hz for analysis. To assess head stability, two reflective markers were placed on the right side of the head: lateral to the eye and on the mandibular angle. Another marker was placed on the right wrist to assess reaching kinematics. The session was video-recorded by using a dual camera system recording at a sampling rate of 50Hz. When infants started to cry or became fussy, the session was stopped. Only if data on a specific parameter of three reaching movements were present were they included in the analysis.

Clinical neurodevelopmental assessments

At each session, the Touwen Infant Neurological Examination was used to assess the neurological status of the infant. The AIMS was used to classify the standing and walking ability of the infant.²³ To evaluate motor behaviour, the IMP – a video-based assessment of spontaneous and elicited play behaviour – was used. The IMP evaluates variation, adaptability, symmetry, fluency and motor performance in supine, prone, sitting, standing and walking; it pays specific attention to reaching and grasping.²¹ The three assessments have good reliability and validity.^{21,24,25}

Data analysis

The PedEMG program (Developmental Neurology, University Medical Center Groningen, the Netherlands)⁸ was used to analyse the video and EMG signals. Reaching movements with the preferred arm and in a calm behavioural state were selected. To identify reaching-related muscle activity, the EMG signal was synchronized with the video. Significant bursts of activation of the postural muscles were identified between 100ms before activation of the first activated arm muscle and the end (or first 1000ms) of the reaching movement,¹⁴ using the algorithm of Staude

and Wolf.²⁶ Kinematic data on head stability and reaching movements were retrieved using SIMI Motion System Analysis (SIMI Reality Motion Systems, Unterschleißheim, Germany).

Subsequently, direction specificity at the trunk and/or neck level was determined. If the trial was direction specific at trunk level, the parameters of the second level of postural control were calculated: (1) recruitment order, in which a top-down recruitment indicates that the neck muscle is activated before the thoracic and lumbar extensor and a bottom-up recruitment in the reverse direction; (2) anticipatory activity at the trunk or neck level, when postural muscles are activated within 100ms before activation of the first activated arm muscle (prime mover); (3) mean EMG amplitude in three intervals – after subtracting baseline activity: (a) 100ms before activation of the prime mover (anticipatory activity); (b) start prime mover until 100ms; (c) 100ms to 1000ms. The total travelled path of the vector between the two head markers (angle of the head in space) and number of movement units of the marker lateral to the eye were used as measures of head stability. A movement unit is an acceleration and a deceleration in the velocity profile of the marker. The use of one movement unit indicates that the movement is programmed in advance, multiple movement units imply multiple corrections in the trajectory.²⁷

To determine whether infants were able to modulate EMG amplitude to reaching specifics, kinematic parameters of reaching were also retrieved: duration of the reaching movement, average speed, and number of movement units of the wrist.

Statistical analyses

Power calculation was based on our own data on direction specificity of infants aged 10 months to 18 months, of which we calculated means to provide data for the power calculation.⁸ Mean direction specificity occurring both at trunk and neck level increased from 31% (SD 17) at 10 months to 49% (SD 22) at 18 months ($r_{ho} = 0.20$). The calculation revealed that a group size of 26 infants allowed for a power of 0.80 ($\alpha = 0.05$) with Cohen's effect size of 0.59 to detect significant changes in direction specificity.

To assess the effect of developmental phase on postural control and IMP scores, SPSS (version 23.0.0.3; IBM, Armonk, NY, USA) was used to fit mixed-effects models for repeated measurements, which take clustering of data within the infant into account. A linear mixed-effects model was used to quantify the effect of developmental phase on total IMP score and median head sway (given that head sway had a significantly skewed distribution), using restricted maximum likelihood estimation. Thereafter, similar models for the IMP domains were fitted. The fit of the mixed-effects models was inspected by assessing the distribution of the residuals. The effects of developmental phase on the dichotomous dependent variables direction specificity, recruitment order, and anticipatory activity were fitted using generalized linear mixed models

with binomial link function (logit), generalized estimating equation, robust estimator, and exchangeability working correlation matrix. For the count-dependent variable of movement unit we used a similar model with the Poisson loglinear link function. Ratios (number of trials with positive outcome/total number of valid trials) were used to model outcomes to control for the different numbers of reaching movements per infant. All models were corrected for age at the moment of measure, and for sex. As the latter did not alter outcome significantly, only the results of the models without correction for sex are presented. If the mixed model resulted in a significant difference ($p < 0.05$) between the three measurements, post hoc tests with Bonferroni correction were performed.

Spearman's correlation was used to explore associations between EMG amplitude (the degree of muscle contraction) of the direction-specific muscles (neck extensor, thoracic extensor, or lumbar extensor) and kinematic parameters within one infant in one measurement. We classified the infant as being able to modulate the amplitude of the direction-specific muscle to reaching or head stability kinematics if the infant showed a significant correlation ($p < 0.05$) between the kinematic parameter and one of the three amplitude intervals.

RESULTS

Infant characteristics and the number of EMG trials are displayed in Table I. Table SI (online supporting information) shows reaching characteristics. Of the 28 infants, two dropped out after the first session because they did not tolerate the electrodes. At T1, the data of three infants were not taken into account in the analyses, as the infants did not meet the AIMS criterion of early stepping (scored as 'walking alone' [$n=1$]; unable to produce 'early stepping'

Table I: Infant characteristics

Sex (M:F)	14:14
Median (range) gestational age (wks)	39.9 (37.0–42.0)
Median (range) birthweight (g)	3654.5 (3000–4500)
Neurological classification (TINE)	
Normal or normal-suboptimal	28
MND	0
Clear neurological syndrome	0
Median (range) age at assessment (mo)	
T0	12.5 (9.3–16.1)
T1	14.4 (11.4–19.1)
T2	15.6 (12.6–21.5)
Median (range) age at independent walking (mo)	14.1 (11.1–18.7)
Measurements	
Chair	
T0	28
T1	23
T2	25
Long-leg sitting	
T0	26
T1	19
T2	21

$n=28$. Data are n unless otherwise indicated. F, female; M, male; MND, minor neurological dysfunction; TINE, Touwen Infant Neurological Examination.

during laboratory visit [$n=2$]). Missed sessions in the other infants or positions were a result of technical problems ($n=2$) or crying when the floor part of the measurements started ($n=9$).

Postural control

Figure 1 shows examples of direction-specific and non-direction-specific EMG recordings of an infant at T0, T1, and T2. None of the postural parameters showed a difference between the three measurements, corrected for age at measurement (Table II). This indicates that the children did not show consistent changes in postural muscle activity during sitting while reaching with increasing walking development. This was true for both sitting conditions (with and without support). Only the results without correction for sex are presented in Table II, as correction for sex did not alter outcome significantly. Nevertheless, the individual developmental trajectories of the various postural parameters when learning to walk indicated the presence of infant-specific changes. Figure S1 (online supporting information) shows the individual trajectories of the parameters of each infant during the development of independent walking. For each parameter some children showed a temporary peak, some a temporary dip, some a steady increase, and others a steady decrease. Table III summarizes the individual trajectories in all parameters. It illustrates that the various parameters within one infant do not show consistent patterns of 'dips', 'peaks', increases, or decreases.

The correlations between EMG amplitude and kinematic parameters revealed that most infants did not show statistically significant correlations between EMG amplitude and the kinematic parameters. This indicates that the infants did not modulate EMG amplitude (adapt the degree of muscle contraction) to reaching characteristics or head stability. This was true for both testing conditions (Table SII, online supporting information provides an overview of the correlations between amplitudes and kinematic parameters in the chair at T2.)

Infant motor profile

Table SI shows information on single items on adaptability during walking. The mixed-effects model showed that the total IMP score differed significantly between the three measurements, corrected for age (Table II). Post hoc tests revealed that there was a significant difference between T0 and T1 (mean IMP score T0 95%, T1 91%; $p < 0.001$). A similar difference was absent between T1 and T2 (mean IMP score T1 91%, T2 93%; $p = 0.073$). Secondary analyses indicated that the changes in the IMP scores could partly be attributed to changes in the adaptability domain (mean T0 98%, T1 87%, T2 92%; post hoc: T0–T1 $p < 0.001$, T1–T2 $p = 0.006$) and the fluency domain, which demonstrated a significant difference between T0 and T1 but not between T1 and T2 (mean T0 95%, T1 89%, T2 91%; post hoc T0–T1 $p = 0.040$, T1–T2 $p = 0.809$). The scores on the performance domain did not change between T0 and

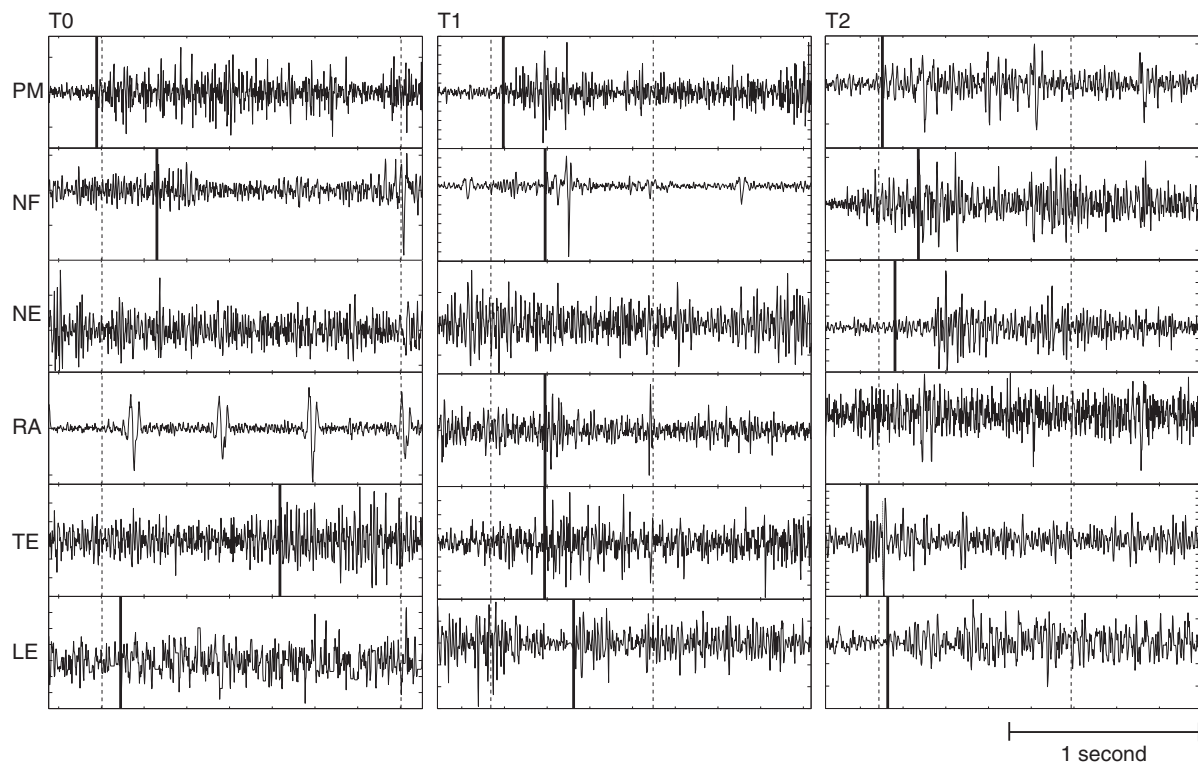


Figure 1: Examples of electromyography signals of the same infant sitting in the infant chair at T0, T1, and T2. Each row represents muscle activity of one muscle. The vertical dotted lines display the start and end of the reaching movement as indicated on video; the bold vertical line indicates a significant increase in muscle activity using the Staude and Wolff algorithm,²⁶ i.e. the start of muscle activation. Amplitude units with intervals of 50 μ V are indicated by the small horizontal lines on the y-axis. Direction specificity means activation of dorsal muscles before (or in absence of) ventral muscle activity. At T0 postural activity during reaching is direction specific at trunk level with lumbar extensor (LE) and thoracal extensor (TE) being activated without (or in other cases before) activation of the rectus abdominis (RA) muscle; postural activity is not direction specific at neck level as neck extensor (NE) is not activated (or in other cases before neck flexor [NF]). At T1 postural activity is not direction specific and at T2 postural activity is direction specific at neck and at trunk level. PM, prime mover, the first activated arm muscle (at T0 triceps brachii, at T1 deltoid, at T2 pectoralis major).

T1 but increased between T1 and T2 (mean T0 87%, T1 86%, T2 90%; post hoc: T0–T1 $p=1.000$, T1–T2 $p<0.001$).

DISCUSSION

The present study indicates that typically developing infants do not show a consistent pattern of reorganization in muscular postural parameters during seated reaching while learning to walk. However, the developmental trajectories of the IMP suggested that signs of a reorganization in general motor behaviour during the transition to independent walking are present.

When learning to walk, the nervous system coordinates the organization of the newly involved muscles into new functional synergies. In addition, the sensorimotor system has to incorporate, for instance, proprioceptive information from the feet into the already existing sensorimotor system.^{12,22} Chen et al.²² demonstrated that this reweighting of sensory information was reflected in postural sway behaviour during sitting. The update of the sensorimotor system presumably also promotes the development of

anticipatory postural adjustments when infants learn to walk.¹⁵ However, contrary to our hypothesis, we did not observe a consistent pattern of transition in our muscular postural parameters – not even in anticipatory activity. The lack of association between the postural parameters and learning to walk, and the similarity in postural adjustments in the two sitting positions suggest that muscular postural control of reaching while sitting is a relatively well-mastered job for the infant, even when the infant is sitting unsupported. This differs for younger infants, where sitting with and without support is associated with different reaching skills and postural muscle activity.^{3,4,10} Our findings suggest that the expression of a possible reorganization is presumably dependent on the testing situation. Possibly, our simple task of reaching while sitting allowed the infants to try and use the different postural strategies, which did not result in one predominant strategy. Our data contrast with those of Hedberg et al.,²⁸ who used a far more challenging test situation. Their longitudinal study showed that infants who learned to stand and walk increased direction specificity with increasing age and

Table II: Mixed-effects model analyses: the change in Infant Motor Profile (IMP) and postural parameters when learning to walk, corrected for age at measurement

	Infant chair				Long-leg position				
	Mean estimates (95% CI)				Mean estimates (95% CI)				
	T0	T1	T2	<i>p</i>	T0	T1	T2	<i>p</i>	
DS trunk (%)	77 (69–84)	72 (63–80)	80 (71–87)	0.333	79 (70–86)	81 (71–88)	84 (74–91)	0.665	
DS neck (%)	31 (25–39)	35 (27–44)	38 (31–46)	0.509	37 (29–44)	31 (24–38)	36 (29–44)	0.578	
DS trunk and neck (%)	38 (30–45)	34 (26–43)	47 (40–55)	0.126	37 (29–46)	35 (28–43)	44 (33–55)	0.395	
Top-down (%)	33 (28–39)	27 (19–37)	26 (19–34)	0.445	33 (28–39)	21 (14–31)	28 (21–35)	0.186	
Bottom-up (%)	24 (18–31)	27 (21–34)	29 (22–38)	0.587	22 (17–29)	36 (27–46)	28 (21–36)	0.156	
Anticipatory activity trunk (%)	22 (16–31)	24 (18–30)	25 (18–33)	0.897	27 (19–37)	26 (20–33)	27 (20–35)	0.982	
Anticipatory activity neck (%)	14 (10–19)	12 (7–19)	17 (13–22)	0.392	18 (12–25)	11 (7–19)	11 (6–20)	0.283	
Head sway (°)	15.7 (14.0–17.3)	14.5 (12.8–16.2)	15.0 (13.2–16.8)	0.593	16.7 (14.2–19.1)	16.0 (13.5–18.5)	14.3 (11.6–17.0)	0.478	
MU head (<i>n</i>)	1.9 (1.6–2.3)	1.8 (1.5–2.1)	1.9 (1.7–2.2)	0.615	1.8 (1.5–2.1)	1.7 (1.4–2.1)	2.1 (1.8–2.6)	0.289	
IMP total ^a (%)	95 (94–97)	91 (90–93)	93 (92–95)	<0.001					
Variation ^b (%)	98 (96–100)	96 (94–97)	95 (94–97)	0.121					
Adaptability ^b (%)	98 (96–100)	87 (85–88)	91 (89–93)	<0.001					
Fluency (%)	95 (91–99)	89 (85–92)	91 (88–95)	0.045					
Performance (%)	87 (86–88)	86 (85–87)	90 (89–91)	<0.001					

Bold denotes significant data. ^aAs the domain symmetry suffered from too strong a ceiling effect in the data (i.e. too many children obtaining the maximum score of 100%), no reliable statistical model could be built. This ceiling effect reflects the typically developing nature of the participating infants. ^bThe models for variation and adaptability suffered to a lesser extent from the ceiling effect. Although normality of the residuals was not met in all linear mixed-effect models, similar results were produced using different modelling approaches (i.e. modelling the raw scores as binomial counts using generalized estimating equation with logit link function); therefore, we were willing to trust the outcome of the models here presented. CI, confidence interval; DS, direction specificity; MU, movement unit.

Table III: Individual developmental trajectories of the different postural parameters when learning to walk in supported sitting position

Infant	DS trunk	DS neck	DS trunk and neck	Bottom-up	Top-down	Anticipatory activity trunk	Anticipatory activity neck
1	v						
2	v	–	–				Λ
3	Λ	–	–	–	–	–	–
4	–					v	
5	v	Λ	↑↑				–
6	v	–	v	Λ	–	–	–
7	Λ	–	Λ	Λ	–	↓↓	–
8	–	–	–	↑↑	–	Λ	v
9	↑↑	–	–	–	v	Λ	–
10	–	v	–	–	↓↓	↓↓	↓↓
11	v						
12	–	–	–	–	–	–	v
13	–	–	–				Λ
14	v	↑↑	v	Λ	↑↑	–	–
15	↓↓	–	–	↑↑	v	–	–
16	–	Λ	v				
17	↓↓	–	v				
18	v	v	v	–	–	Λ	–
19	v	v	–				–
20	↓↓	–	↓↓			–	
21	–	v	v				

The cut-off of 10% was arbitrarily chosen, as the postural control literature did not offer information for a scientifically-based alternative. Note that trajectory information is missing in seven infants because of missing data at T1 (*n*=3), at T2 (*n*=2), and drop-out after T0 (*n*=2). A corresponding table with data in the unsupported position was similar. v, 'dip' trajectory consisting of a decrease of ≥10% of the mean of the parameter per session between T0 and T1 followed by an increase of ≥10% between T1 and T2; Λ, 'peak' trajectory consisting of an increase of ≥10% between T0 and T1 followed by a decrease of ≥10% between T1 and T2; ↓↓, 'decreasing' trajectory consisting of a decrease of ≥10%, both between T0 and T1 and between T1 and T2; ↑↑, 'increasing' trajectory consisting of an increase of ≥10% both between T0 and T1 and between T1 and T2; –, no increase or decrease between the measurement moments, or changes <10%; a blank cell indicates that the data of the parameter were missing in one of the sessions, precluding the assignment of a trajectory. DS, direction specificity.

walking experience while being perturbed by a moveable platform in a standing position.²⁸ This suggests that more challenging situations like standing and experiencing

external perturbations from a platform may force the balance-control system to select the most functional strategy, that is, direction specificity.

Nevertheless, Figure S1 and Table III suggest that learning to walk may be accompanied by changes in postural control during seated reaching, although a different way for each infant. The latter suggestion fits the idea that motor development is characterized by variation, and that each infant uses different motor strategies to discover new skills and the best adaptations to environmental constraints.²⁹ Our findings correspond to those of Woollacott et al.'s³⁰ study of children with cerebral palsy, where improvement of postural control after training was achieved in a different way in each child. Perhaps the influence of learning to walk at group level is only observable in the net postural outcome reflected, for instance, in sway parameters,^{12,22} whereas this is achieved with different muscular strategies in the individual infant.

Our IMP data underscore the notion of reorganization of motor behaviour during the development of independent walking; the total IMP score and the fluency score decreased and the scores of the domain adaptability showed a dip at the time when the infants were able to produce their first independent steps, after which the performance scores improved. This result corroborates the findings of Corbetta et al. and the suggestions of Chen et al.^{12,20,22} We propose that when learning a new skill, the infant should learn anew how to adapt the new behaviour to different situations, by controlling newly involved muscles and integrating different sensory information.

Most of the infants did not modulate EMG amplitude to reaching and head stability characteristics, not before, during, or after the development of independent walking. This is in line with the results of van der Fits et al.,¹¹ who indicated that modulation of EMG amplitude during reaching in sitting position emerges from 18 months onwards. Presumably, the modulation of postural EMG activity is dependent on the situation or challenge during testing. Apparently, modulation of EMG activity during reaching in sitting position is not affected by learning to walk, but, for example, Hadders-Algra et al.³¹ suggest that the capacity to modulate EMG activity during external perturbations of a moveable platform was promoted by daily balance practice.

Both our head stability parameters remained stable during the development of independent walking. Conceivably, the infants experienced no difficulties with head balance in our sitting position, and a possible reorganization of postural control does not influence head balance in an unchallenging position.

Two strengths of the study are the longitudinal data collection during the development of independent walking and the use of the mixed-effects models; it allowed us to calculate individual trajectories over time, while taking repeated measures at different ages into account. Additionally, by correcting for age we could focus on the effect of the development of independent walking. However, interpretation of the data is limited owing to data loss, reducing our sample to a size that just lacked sufficient power. This

occurred especially at T1 and in the long-leg position. Although parents were instructed very carefully, it appeared difficult to get the parents to contact the research team at the correct time, allowing scheduling of the T1 assessment within a week of the infants' first independent steps. What may be considered another limitation is the assessment of postural activity on one side of the body. However, previous research indicated that the postural muscles on the side contralateral to the reaching arm are less frequently activated than the muscles on the ipsilateral side.¹¹ This suggests that we adequately covered the infant's postural muscle activity.

In conclusion, this study demonstrated that while learning to walk independently, infants show signs of reorganization of their motor behaviour. However, they do not show consistent signs of a reorganization of their muscular postural control strategies during reaching in sitting position. Rather, the data suggest that every infant uses its own muscular postural control strategy during reaching while sitting in the transition period to independent walking. As we have suggested that our testing situation may have been an unchallenging situation for infants, we propose to further explore postural development during walking by assessing muscular postural control strategies in a similar way to the current study but in reaching while standing. Another option would be the evaluation of postural muscles strategies during the development of independent walking in larger groups of infants as this would allow for the exploration of possible latent clusters of specific patterns of development by, for example, factor analysis or latent class analyses. The existence of latent clusters may show that development of specific infants may be similar or that combinations of specific postural parameters develop following a certain track.

ACKNOWLEDGEMENTS

We are thankful for the help of Saskia Dijkstra, Patricia Pekel, Johan Tiems, Siebrigje Hooijsma, and Anneke Kracht in the data collection and/or analysis. AGB received financial support from the Junior Scientific Masterclass. The funder was not involved in the design of the study, data collection, data analysis, manuscript preparation, or publication decisions. The authors have stated that they had no interests which might be perceived as posing a conflict or bias.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1: Individual trajectories of postural parameters before, just after, and a month after independent walking.

Table SI: Reaching characteristics and adaptability items of the Infant Motor Profile during walking

Table SII: Correlation between kinematic parameters and electromyography amplitude of direction-specific postural muscles at T2 in supported sitting position

REFERENCES

- Soska KC, Adolph KE, Johnson SP. Systems in development: motor skill acquisition facilitates three-dimensional object completion. *Dev Psychol* 2010; **46**: 129–38.
- Sommerville JA, Decety J. Weaving the fabric of social interaction: articulating developmental psychology and cognitive neuroscience in the domain of motor cognition. *Psychon Bull Rev* 2006; **13**: 179–200.
- Rochat P. Self-sitting and reaching in 5- to 8-month-old infants: the impact of posture and its development on early eye-hand coordination. *J Mot Behav* 1992; **24**: 210–20.
- Out L, Van Soest AJ, Savelsbergh GJ, Hopkins B. The effect of posture on early reaching movements. *J Mot Behav* 1998; **30**: 260–72.
- van der Kooij H, Jacobs R, Koopman B, van der Helm F. An adaptive model of sensory integration in a dynamic environment applied to human stance control. *Biol Cybern* 2001; **84**: 103–15.
- Hadders-Algra M. The development of postural control. In: Hadders-Algra M, Brogren-Carlberg E, editors. Postural control: A Key Issue in Developmental Disorders. London: Mac Keith Press, 2008: 22–73.
- Forssberg H, Hirschfeld H. Postural adjustments in sitting humans following external perturbations: muscle activity and kinematics. *Exp Brain Res* 1994; **97**: 515–27.
- van Balen LC, Dijkstra LJ, Hadders-Algra M. Development of postural adjustments during reaching in typically developing infants from 4 to 18 months. *Exp Brain Res* 2012; **220**: 109–19.
- van der Heide JC, Otten B, van Eykern LA, Hadders-Algra M. Development of postural adjustments during reaching in sitting children. *Exp Brain Res* 2003; **151**: 32–45.
- van der Fits IB, Klip AW, van Eykern LA, Hadders-Algra M. Postural adjustments during spontaneous and goal-directed arm movements in the first half year of life. *Behav Brain Res* 1999; **106**: 75–90.
- van der Fits IB, Otten E, Klip AW, Van Eykern LA, Hadders-Algra M. The development of postural adjustments during reaching in 6- to 18-month-old infants. Evidence for two transitions. *Exp Brain Res* 1999; **126**: 517–28.
- Chen LC, Jeka J, Clark JE. Development of adaptive sensorimotor control in infant sitting posture. *Gait Posture* 2016; **45**: 157–63.
- Barela J, Jeka JJ, Clark JE. The use of somatosensory information during the acquisition of independent upright stance. *Infant Behav Dev* 1999; **22**: 87–102.
- Boxum AG, van Balen LC, Dijkstra LJ, et al. Postural adjustments in infants at very high risk for cerebral palsy before and after developing the ability to sit independently. *Early Hum Dev* 2014; **90**: 435–41.
- Cignetti F, Zedka M, Vaugoyeau M, Assaiante C. Independent walking as a major skill for the development of anticipatory postural control: evidence from adjustments to predictable perturbations. *PLoS ONE* 2013; **8**: e56313.
- Assaiante C, Woollacott M, Amblard B. Development of postural adjustment during gait initiation: kinematic and EMG analysis. *J Mot Behav* 2000; **32**: 211–26.
- Pozzo T, Berthoz A, Lefort L. Head stabilization during various locomotor tasks in humans. *I. Normal subjects. Exp Brain Res* 1990; **82**: 97–106.
- Cromwell RL, Newton RA, Carlton LG. Horizontal plane head stabilization during locomotor tasks. *J Mot Behav* 2001; **33**: 49–58.
- Ledeht A, Bril B, Wiener-Vacher S. Trunk and head stabilization during the first months of independent walking. *NeuroReport* 1995; **6**: 1737–40.
- Corbetta D, Bojczyk KE. Infants return to two-handed reaching when they are learning to walk. *J Mot Behav* 2002; **34**: 83–95.
- Heineman KR, Middelburg KJ, Bos AF, et al. Reliability and concurrent validity of the Infant Motor Profile. *Dev Med Child Neurol* 2013; **55**: 539–45.
- Chen LC, Metcalfe JS, Jeka JJ, Clark JE. Two steps forward and one back: learning to walk affects infants' sitting posture. *Infant Behav Dev* 2007; **30**: 16–25.
- Piper MC, Darrah J. Motor Assessment of the Developing Infant. Philadelphia, PA: Saunders, 1994.
- Hadders-Algra M, Heineman KR, Bos AF, Middelburg KJ. The assessment of minor neurological dysfunction in infancy using the Touwen Infant Neurological Examination: strengths and limitations. *Dev Med Child Neurol* 2010; **52**: 87–92.
- Piper MC, Pinnell LE, Darrah J, Maguire T, Byrne PJ. Construction and validation of the Alberta Infant Motor Scale (AIMS). *Can J Public Health*; 1992; **83**(Suppl. 2): S46–50.
- Stauder G, Wolf W. Objective motor response onset detection in surface myoelectric signals. *Med Eng Phys*; 1999; **21**: 449–67.
- von Hofsten C. Structuring of early reaching movements: a longitudinal study. *J Mot Behav* 1991; **23**: 280–92.
- Hedberg A, Schmitz C, Forssberg H, Hadders-Algra M. Early development of postural adjustments in standing with and without support. *Exp Brain Res* 2007; **178**: 439–49.
- Hadders-Algra M. Variation and variability: key words in human motor development. *Phys Ther* 2010; **90**: 1823–37.
- Woollacott M, Shumway-Cook A, Hutchinson S, Ciol M, Price R, Kartin D. Effect of balance training on muscle activity used in recovery of stability in children with cerebral palsy: a pilot study. *Dev Med Child Neurol* 2005; **47**: 455–61.
- Hadders-Algra M, Brogren E, Forssberg H. Training affects the development of postural adjustments in sitting infants. *J Physiol* 1996; **493**(Pt 1): 289–98.