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Postural control and reaching throughout infancy

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Postural adjustments in infants at very high risk for cerebral palsy before and after developing the ability to sit independently

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ABSTRACT

Background: Children with cerebral palsy (CP) have impaired postural control. Posture is controlled in two levels: direction-specificity, and fine-tuning of direction-specific adjustments, including recruitment order. Literature suggests that direction-specificity might be a prerequisite for independent sitting.

Aim: To study development of postural adjustments in infants at very high risk for CP (VHR-infants) during developing the ability to sit independently.

Method: In a longitudinal study surface electromyograms of the neck-, trunk- and arm muscles of 11 VHR-infants and 11 typically developing (TD) infants were recorded during reaching in sitting before and after developing the ability to sit unsupported (median ages: VHR 8.0 and 14.9 months; TD 5.7 and 10.4 months). Sessions were video-recorded.

Results: In VHR- and TD-infants the prevalence of direction-specific adjustments and recruitment order did not change when the infant learned to sit independently. In VHR-infants able to sit independently more successful reaching was associated with a higher frequency of bottom-up recruitment (Spearman's $\rho=0.828$, $p=0.006$) and a lower frequency of simultaneous recruitment (Spearman's $\rho=-0.701$, $p=0.035$), but not with more direction-specificity. In TD-infants not able to sit independently, more successful reaching was associated with higher rates of direction-specific adjustments at the neck level (Spearman's $\rho=0.778$, $p=0.014$), but not with recruitment order.

Conclusions: In VHR- and TD-infants postural adjustments during reaching in terms of direction-specificity and recruitment order are not related to development of independent sitting. Postural adjustments are associated with success of reaching, be it in a different way for VHR- and TD-infants.

INTRODUCTION

Infants at high risk (HR) for cerebral palsy (CP), such as infants born preterm or with perinatal asphyxia, often show a delay in the development of motor milestones like sitting, walking, reaching and grasping.¹ These motor activities are highly dependent on postural control.² However, little is known on the organization of postural adjustments in HR-infants.

Postural control is a complex neural task involving activity of many muscles. In terms of muscle activity two levels of control can be distinguished. The first level consists of direction-specificity, implying that if balance is compromised by a forward body sway, the muscles on the dorsal side of the body are primarily activated and in case of a backward sway the muscles on the ventral side. At the second level of control the direction-specific postural pattern is fine-tuned to the specifics of the situation by means of e.g. adaptation of the recruitment order of the direction-specific muscles.^{2,3}

Typically developing (TD) infants aged 1 to 3 months show pre-reaching movements accompanied by postural activity without direction-specificity.⁴ Four-month-olds, who just have mastered the ability to reach for a toy, show direction-specific postural adjustments during 40% of reaching movements.⁵ The study of de Graaf-Peters et al. (2007) showed that infants aged 4 to 6 months, who demonstrated direction-specific adjustments during at least half of their reaches, were more successful in reaching and had reaches with a better kinematic quality than infants whose reaches were less often accompanied by direction-specific postural activity.⁶ This suggests that direction-specificity is not a prerequisite for reaching, but that it is associated with better reaching. During infancy the rate of direction-specific adjustments during reaching gradually increases to about 60% at 18 months⁵ and 100% at 2 years of age.⁷ Throughout infancy direction-specific adjustments are characterized by variation, for instance variation in recruitment order.⁵ Despite the large variation, a developmental trend in recruitment order is observed. At 4 months, a mild preference for top-down recruitment (the neck muscle is activated prior to the trunk muscles) is present, which changes into a preference for bottom-up (trunk muscle activated prior to the neck muscles) at 18 months.⁵

Relatively little is known on the organisation of postural adjustments of infants at high risk for CP. The data of van Balen et al. indicated that the development of direction-specificity during reaching in high risk infants is delayed.⁸ But at preschool age, most children with CP do show consistent direction-specific adjustments during reaching while sitting.⁹ The limited data available suggest that only children with CP functioning at Gross Motor Function Classification System (GMFCS)¹⁰ level V – who do not develop the ability to sit independently – show

a total lack of direction-specificity.^{9,11} This might mean that direction-specificity is a prerequisite for the development of sitting ability. But direction-specificity is not the only factor involved in the development of the ability to sit without support, as the study of Hedberg et al. (2004) showed that one-month-old TD-infants virtually always showed direction-specific postural adjustments in response to external perturbations of balance, while they were unable to sit independently.¹²

Others studied the development of reaching and postural control using the theoretical framework of the dynamic systems theory.¹³ For instance, the longitudinal data of Thelen and Spencer indicated that in typical development stable head control precedes the emergence of reaching.¹⁴ Harbourne and Stergiou¹⁵, who applied non-linear dynamics to study centre of pressure (COP) behavior of sitting infants, reported that infants decreased the degrees of freedom in body motility when the ability to sit emerged, to return to increased levels of degrees of freedom when they could sit properly without help – a flexibility allowing them to adapt to the environment. Kyvelidou et al.¹⁶ noted that COP behavior of infants with CP and infants born preterm with motor delays at the emergence of early sitting differed from that of TD-infants. The data suggested that the infants with CP had a severely limited repertoire of adjustments, those with developmental delay a moderately reduced repertoire, while TD-infants had a large and flexible repertoire.

Non-linear measures, such as used in the above mentioned studies on COP-behavior,^{15,16} do not provide information on the muscular strategy to achieve the stability needed to sit without support. Therefore we wondered whether in infants at very high risk for CP (VHR-infants) and TD-infants the development of the ability to sit without help (requiring active neural control instead of reactive neural control) is related to the development of direction-specific postural adjustments during reaching (also requiring active control). Thus, the aim of this longitudinal study is to increase the understanding of postural development in VHR-infants, during the phase of the development of sitting ability. To this end, postural control during reaching was studied in infants participating in the LEARN2MOVE 0–2 years project (L2M 0–2). L2M 0–2 aims to evaluate whether intervention with the newly developed COPCA-program (Coping with and Caring for infants with special needs – a family centred program [Dirks et al. 2011])¹⁷ results in a better outcome in terms of functional capabilities of the VHR-infant and developmental potential of the family, compared to traditional infant therapy.¹⁸ Similar data on postural control of TD-infants were available from a previous project.⁵

We addressed the following questions: (1) Does postural control in terms of direction-specificity and recruitment order of VHR-infants change when the infant develops the ability to sit independently? (2) Does postural control in terms of direction-specificity and recruitment order of VHR-infants before and after development of the ability to sit independently differ from that of TD-infants? (3) Is postural control in terms of direction-specificity and recruitment order in VHR-infants associated with reaching performance, and with the presence of CP at 21 months corrected age?

METHOD

Participants

This study comprised 11 VHR-infants (nine boys, two girls), and 11 TD-infants born at term without perinatal complications (seven boys, four girls). The VHR-infants were included in the L2M 0–2 project before 9 months corrected age based on one of the following criteria (Hielkema et al. 2010)¹⁸: 1) cystic periventricular leukomalacia; 2) parenchymal lesion of the brain (uni- or bilateral); 3) brain lesions on MRI with Sarnat 2 or 3¹⁹ caused by term/near-term asphyxia; 4) neurological dysfunction which might lead to the development of CP. Infants were excluded in case of presence of a severe congenital disorder, or presence of an inadequate understanding of the Dutch language by caregivers. For the present study, VHR-infants who fulfilled the following additional criteria were included: a) they developed the ability to sit independently, and b) they had two postural electromyography (EMG) recordings: one when they were not able to sit independently (EMG recording 1: E1), the other when they could sit without support as noted during the Touwen Infant Neurological Examination²⁰ (EMG recording 2: E2). Clinical details of the participants are summarized in Table 1. The ethics committee of the University Medical Center Groningen approved the protocol (L2M 0–2 is registered under trial number NTR1428) and informed consent was given by the parents.

Table 1. Participant's characteristics

| | VHR-infants | TD-infants |
|---------------------------------------|------------------|-------------------|
| Gestational age (wk), median (range) | 36.3 (26.3–41.1) | 40.5 (37.6–42.0)* |
| Birth weight (g), median (range) | 2375 (1070–5400) | 3463 (3000–4000)* |
| Corrected age E1 (mo), median (range) | 8.0 (4.7–9.6) | 5.7 (3.8–6.5) |
| Corrected age E2 (mo), median (range) | 14.9 (11.4–22.4) | 10.4 (9.6–11.4)* |
| Type of brain lesion, n (%) | | |
| Posthaemorrhagic porencephaly | 6 (55) | Not applicable |
| Basal ganglia/thalamic lesion | 2 (18) | |
| Cortical infarction | 1 (9) | |
| Other lesions ^o | 2 (18) | |

g: grams, E1: Electromyography recording 1 (not able to sit unsupported), E2: electromyography recording 2 (able to sit unsupported), mo: months corrected age, TD: typically developing, VHR: very high risk, wk: weeks

* Mann-Whitney: $p < 0.01$

^o Other brain lesions: arachnoid cyst with hydrocephalus and bilateral intraventricular haemorrhage grade 3

Procedure

Postural control in VHR-infants was assessed at inclusion (T0), 6 months after inclusion (T2), 12 months after inclusion (T3) and at the corrected age of 21 months (T4). For this study, two assessments were selected: 1) the first assessment available when the infant was able to reach but unable to sit unsupported (E1); and 2) the first assessment available when the infant could sit unsupported (E2).

Similar data of 11 TD-infants were present at the ages of 4, 6 and 10 months.⁵ According to the Touwen Infant Neurological Examination (TINE)²⁰, six of the TD-infants could not sit independently at 6 months (E1 for the present study); in the remaining five infants who could sit independently at 6 months, the data recorded at 4 months, when the infants could not sit independently were used for E1. All TD-infants were able to sit independently at 10 months; these 10 months data were used for E2.

The infants were examined while seated in an infant chair providing postural support at the back and front or while sitting on the floor with the parent providing back support. The latter occurred in both assessments of one VHR-infant. Reaching was elicited by presenting a small toy at arm length distance. The aim was to elicit at least ten reaching movements with the preferred arm, but if less than ten reaching movements were available – in order to minimize loss of data – data were included if a minimum of three adequate trials were present. The reaching session lasted about 30 minutes. If less than three reaching movements per position were present, the data of this session were excluded from further data

analysis. Data of two sessions could not be used (data of a non-sitting VHR-infant who was interested in the toy but did not reach, and data of a sitting VHR-infant due to technical problems).

EMG recording

EMG of the neck, trunk and arm muscles was continuously recorded on the right side of the body (unless the infant preferred the left arm to reach: $n=2$ VHR-infants) with bipolar surface electrodes (interelectrode distance: 14 mm). The electrodes were placed on postural muscles, i.e., the sternocleidomastoid (neck flexor, NF), neck extensor (NE), rectus abdominis (RA), thoracal extensor (TE), lumbar extensor (LE), and on arm- and shoulder muscles, i.e., the deltoid (DE), pectoralis major (PM), biceps brachii (BB) and triceps brachii (TB). In most infants, an additional electrode was placed on the sternum to facilitate detection of cardiac activity. The EMG signal was recorded at a sampling rate of 500 Hz with the software program Portilab (Twente Medical Systems International, Enschede, The Netherlands).

Video recording

The entire EMG-session was recorded on video. The video was used to select reaching movements with the preferred arm, to classify the success of the movements (percentage of reaching movements resulting in actual grasping of the object) and to select trials in which the infant was in an alert and calm behavioural state. The video was also used to identify and exclude trials with evident trunk or head movements which were not related to the reaching movement.

Data analysis

EMG analysis was carried out using the PedEMG software (Developmental Neurology, University Medical Center Groningen, The Netherlands).⁵ PedEMG allows for synchronous analysis of video and EMG data. The software used for EMG analysis includes the computer algorithm of Staude and Wolf.²¹ This algorithm uses a model based statistical decision method to determine onsets of phasic EMG activity. Before determining the onsets the signal was filtered for 50 Hz noise using 5th order band Chebyshev filter. Signal artifacts and cardiac activity were identified to take

into account when appropriate. Clear signal artifacts were identified manually. Cardiac activity (QRS-complexes) was identified using a pattern recognition algorithm based on a linear derivative approximation of the signal using the combination of the repeating pattern and specific shapes of the QRS-complexes.

The activity of the postural muscles was considered to be related to the arm movement when increased muscle activity was found within a time window starting 100 ms before activation of the prime mover, i.e., the arm muscle that was activated first, until the duration of (or the first 1000 ms of) the reaching movement (for details see van Balen et al.).⁵ The choice of the 100 ms time window instead of the 500 ms window used by Witherington et al.²² to determine postural muscle activity related to a reaching movement was based on a) the video recordings revealing that the longer time window was associated with a high rate of 'false positives', i.e., muscle activity related to other spontaneous movements of the infant and not to reaching; b) a preliminary analysis of the data in which we compared the results of the 100 ms and 500 ms time window. This analysis revealed that the rates of direction-specificity and specific forms of recruitment order were not affected by the duration of the analysis window; and c) the 100 ms window allows for comparison of the infant data with the data of older children in which the 100 ms window was used (van der Heide et al.).^{7,9,23}

For each infant at each assessment the following parameters were calculated: 1) percentage of direction-specific trials at the neck and/or trunk level; direction-specificity means that the direction-specific dorsal muscle is activated prior to or in the absence of ventral muscle recruitment. The other EMG-parameters were only calculated if direction-specific activity at trunk level was present: 2) latencies to recruitment of the direction-specific muscles after onset of the prime mover; and 3) percentage of trials with top-down, bottom-up or a simultaneous recruitment order. Recruitment order was classified as top-down when NE was the direction-specific muscle which was recruited first (or in case the NE signal was missing, TE was recruited first), and as bottom-up when LE was recruited first (or in case that the LE signal was missing, TE was recruited first). If all recruited direction-specific muscles were activated within a time frame of 20 ms, recruitment order was classified as simultaneous.

Neurological assessment

Neurological condition was evaluated a few days before the postural assessment, using the TINE.²⁰ TINE was also video recorded. It resulted in a classification into normal neurological condition, minor neurological dysfunction or a clear neurological syndrome. The TINE has a good reliability and validity.²⁴

TINE was also used to specify sitting ability (each time) and neurological outcome at 21 months corrected age (CA). Sitting ability was scored as 'not being able to sit independently' when the infant was not at all able to sit independently on the floor, or could maintain sitting position less than a few seconds. Sitting ability was scored as 'being able to sit independently' when infants were able to sit on the floor without support from an adult or a chair for at least 10 s. The duration of sitting behaviour was determined on the basis of the time display of the video recording of the TINE assessment. At 21 months CA, TINE was also used to determine the presence of CP. CP is a specific neurological syndrome and implies the presence of a 'classical' configuration of neurological signs, in case of bilateral spastic CP: the combination of a stereotyped posture and motility of the legs, an increased muscle tone and brisk tendon reflexes in the legs and Babinski signs.

Statistical analyses

Data were analyzed with the SPSS computer package (version 20.0). As data did not show a normal distribution, non-parametric tests were used. Differences between the VHR- and TD-infants, between VHR-infants with and without CP and between those with COPCA and traditional intervention were calculated with the Mann-Whitney U test. The paired Wilcoxon test was used to assess differences between E1 and E2. Dependent variables were percentage of direction-specific postural adjustments at the trunk level, at the neck level and at both trunk and neck levels; percentage of trials with top-down, bottom-up, or simultaneous recruitment; latencies to the onset of NF, NE, RA, TE, LE muscles, the percentage of successful reaching and the duration of reaching movements. Independent variables were group (VHR vs. TD), time of EMG-recording (E1 vs. E2), presence of CP (yes vs. no) and intervention (COPCA vs. traditional intervention). To assess the association between postural parameters and success of reaching, Spearman's correlation was used. p-Values <0.05 were considered statistically significant.

RESULTS

Preliminary data analysis indicated that EMG activity of the infant who received postural support from her parent did not differ from that of the infants who received support from the infant chair, at both EMG sessions. Also the data of infants receiving COPCA and those receiving traditional intervention did not differ. Therefore the data of the VHR-infants were pooled.

The corrected age of the VHR-infants at E1 was similar to that of TD-infants (8.0 vs 5.7 months (median values); Mann-Whitney: $p=0.062$), at E2 the corrected age of the VHR-infants was higher than that of the TD-infants (E2: 14.9 vs. 10.4 months (median values); Mann-Whitney: $p<0.001$). Gestational age and birth weight of the VHR-infants were significantly lower than those of TD-infants (Table 1). Five of the 11 VHR-infants developed CP, outcome of one infant was missing, as parents withdrew from the project after E2.

The median numbers of appropriate trials per infant are displayed in Table 2. In these trials direction-specificity at the trunk and neck level was determined. Often, fewer trials were available for the calculation of the other parameters (latencies and recruitment order), as the latter were only determined for trials that were direction-specific at the trunk level.

Table 2. Number of reaching trials per infant included in the analyses.

| | VHR-infants | TD-infants |
|----|-------------|------------|
| E1 | 11 (3–17) | 18 (13–31) |
| E2 | 19.5 (5–35) | 17 (10–19) |

Results are displayed as median (range). E1: Electromyography recording 1 (not able to sit unsupported), E2: electromyography recording 2 (able to sit unsupported)

First level of postural control in VHR- and TD-infants

The postural adjustments of VHR- and TD-infants were characterized by variation, see Figure 1. In VHR-infants, direction-specific activity in the trunk was present in 60% of the trials at E1 (median value). This rate did not change significantly with the development of the ability to sit independently (E2 67%; Wilcoxon: $p=0.735$; Figure 2). In TD-infants, direction-specific activity in the trunk occurred in similar frequencies (E1 and E2 56%, Mann-Whitney: $p=0.962$ and $p=1.000$ resp.), without a significant change between E1 and E2 (Wilcoxon: $p=0.715$; Figure 2).

In VHR-infants, 38% of the trials at E1 were accompanied by postural adjustments which were direction-specific at the neck level. The rate of direction-specific activity in the neck of VHR-infants at E1 did not differ significantly from the rate at

E2 (25%; Wilcoxon: $p=0.893$; Figure 2), nor did these rates differ from those of the TD-infants (E1 46%, E2 38%, Mann-Whitney: $p=0.658$ and $p=0.371$ respectively). Also in the TD-infants the prevalence of direction-specificity in the neck did not change significantly between E1 and E2 (Wilcoxon: $p=0.345$; Figure 2).

Direction-specific postural activity in both neck and trunk occurred in 26% of the trials of the VHR-infants at E1 and E2 (Wilcoxon: $p=0.866$; Figure 2). These rates were similar to those of the TD-infants (E1 48%, E2 35%; Mann-Whitney: $p=0.438$ and $p=0.375$, resp.), in whom they also did not change with age (Wilcoxon: $p=0.500$; Figure 2).

Second level of postural control

Throughout infancy, the latencies to the recruitment of the postural muscles were largely variable. In VHR-infants the median latencies of activation of the postural muscles varied between 125 and 582 ms, in TD-infants between 43 and 341 ms. In both groups the latencies of the postural muscles at E1 did not differ significantly from those at E2 (Table 3). Neither did the latencies of the VHR-infants differ from those of TD-infants.

Also recruitment order of the direction-specific muscles of both VHR- and TD-infants was characterized by variation (see Table 4). At E1 simultaneous recruitment was infrequently observed. However, at E2, VHR-infants used a simultaneous recruitment order significantly more often than the TD-infants (VHR 12% vs. TD 0% (median values); Mann-Whitney: $p=0.044$). Recruitment order in both groups did not differ significantly between E1 and E2. (Table 4).

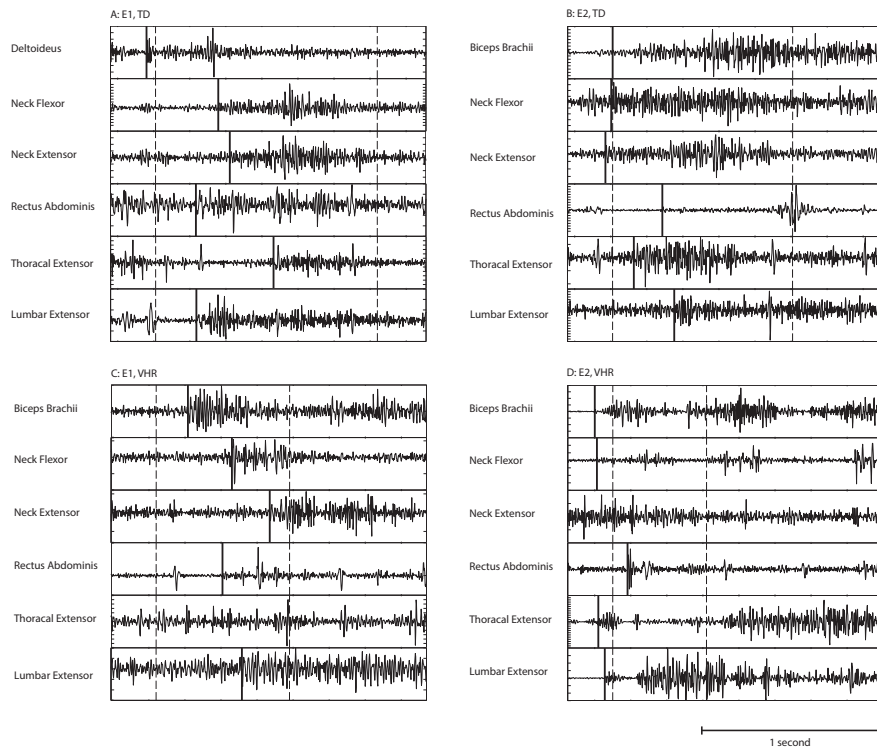


Figure 1: Variation in direction-specificity. EMG-signals of the prime mover and postural muscles. The vertical dotted lines indicate the start and the stop of the reaching movement as observed on the video. The bold vertical lines indicate the moments of significant increase in EMG activity, i.e., they indicate the start of muscle activation. Direction-specificity means that the dorsal muscle is activated prior to the ventral muscle, i.e., the neck extensor is activated before the neck flexor (neck-level), and the thoracal and/or lumbar extensor prior to the rectus abdominis (trunk-level). Panel A: TD-infant at E1; no direction-specific activity. Panel B: the same TD-infant at E2 with direction-specific activity at neck and trunk levels. Panel C: VHR-infant at E1; no direction-specific activity. Panel D: the same VHR-infant at E2; direction-specific at trunk level.

The bold horizontal line below the panels represents the duration of 1 s. The amplitude units are indicated on the Y-axes: the intervals between the small horizontal markers represent 50 μ V.

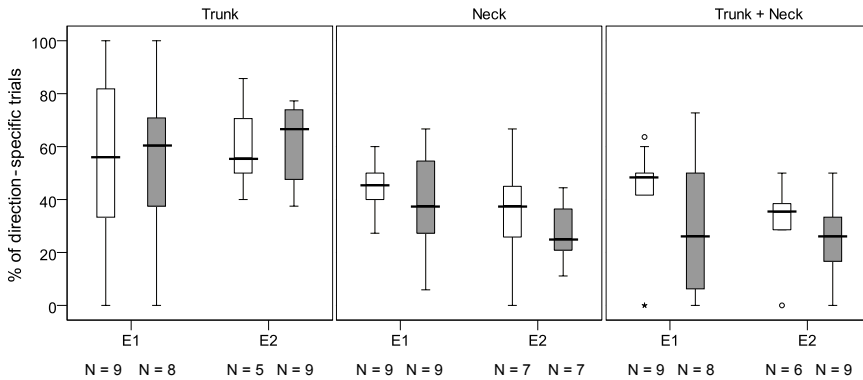


Figure 2: Percentage of direction-specific postural adjustments in infants at very high risk for CP (VHR) and in typically developing (TD) infants, before (E1) and after (E2) developing the ability to sit independently. TD-infants are displayed in the white bars, VHR in the grey bars. Mann-Whitney VHR vs. TD:

E1: trunk level $p=0.962$, neck level $p=0.658$, trunk and neck level $p=0.438$.

E2: trunk level $p=1.000$, neck level $p=0.371$, trunk and neck level $p=0.375$.

Table 3. Latencies (ms) to the recruitment of postural muscles

| | NF | NE | RA | TE | LE |
|-----------|---------------|---------------|---------------|---------------|---------------|
| E1 | | | | | |
| VHR | 132 (-80-420) | 582 (3-786) | 549 (249-746) | 125 (-33-282) | 174 (116-286) |
| TD | 189 (0-510) | 145 (20-220) | 341 (174-514) | 122 (-30-260) | 136 (-13-384) |
| E2 | | | | | |
| VHR | 215 (34-510) | 177 (32-557) | 473 (257-666) | 145 (-3-476) | 172 (-4-401) |
| TD | 117 (70-190) | 182 (-20-350) | 256 (125-473) | 43 (10-260) | 54 (28-460) |

Results are displayed as median (range). E1: Electromyography recording 1 (not able to sit unsupported), E2: electromyography recording 2 (able to sit unsupported), LE: lumbar extensor, NE: neck extensor, NF: neck flexor; RA: rectus abdominis, TE: thoracal extensor.

Table 4. Percentage of top-down, bottom-up or simultaneous recruitment

| | | VHR-infants | | TD-infants | |
|-----------|--------------|-------------|------------|------------|------------|
| E1 | | | | | |
| | Top-down | n = 5 | 43 (0–45) | n = 9 | 43 (23–50) |
| | Bottom-up | n = 5 | 25 (0–36) | n = 9 | 33 (0–55) |
| | Simultaneous | n = 5 | 0 (0–9) | n = 9 | 0 (0–25) |
| E2 | | | | | |
| | Top-down | n = 9 | 33 (0–45) | n = 4 | 19 (13–50) |
| | Bottom-up | n = 9 | 38 (12–75) | n = 4 | 50 (8–88) |
| | Simultaneous | n = 9 | 12 (0–18) | n = 4 | 0 (0–0) |

Results are expressed as median (range). E1: Electromyography recording 1 (not able to sit unsupported), E2: electromyography recording 2 (able to sit unsupported). n displays the number of infants which had a sufficient number of trials allowing for the determination of recruitment order.

Postural control, reaching and CP

At E1, the median percentage of successful reaching, i.e. the percentage of reaches that ended in grasping of the object, was 85% (range: 0–100%) in VHR-infants and 57% (range: 11–100%) in TD-infants (Mann-Whitney: $p=0.205$). At E2, 87% of the trials (range: 40–100%) were successful in VHR-infants and 96% (43–100%) in TD-infants (Mann-Whitney: $p=0.148$). In VHR-infants the rate of successful reaching was not related to the rate of direction-specificity at the neck or trunk level. However, it was associated with the recruitment order of the direction-specific muscles at E2: a higher frequency of bottom-up recruitment and a lower frequency of simultaneous recruitment were associated with more successful grasping (bottom-up: Spearman's $\rho=0.828$, $p=0.006$; simultaneous: Spearman's $\rho=-0.701$, $p=0.035$). In TD-infants, a higher frequency of successful reaching was associated with a higher rate of direction-specific adjustments at the neck level at E1 (Spearman's $\rho=0.778$, $p=0.014$), but not at E2 (Spearman's $\rho=-0.111$, $p=0.812$). Success of reaching in TD-infants was not associated with recruitment order.

The duration of the reaching movement of VHR-infants at E1 was similar to that of TD-infants (1.48 vs. 1.79 s; Mann-Whitney: $p=0.210$). At E2 reaching duration of VHR-infants was shorter than that of TD-infants (1.04 vs. 1.18 s; Mann-Whitney: $p=0.021$).

At this age reaching duration was associated with corrected age: reaches of older infants took less time (Spearman's $\rho=-0.507$, $p=0.032$). A similar correlation was absent at E1. In both groups the duration of reaching was not related to direction-specificity. However, in TD-infants at E1 reaching duration was associated with recruitment order: a higher rate of top-down recruitment was associated with

a shorter duration of reaching (Spearman's $\rho = -0.786$, $p=0.036$). In TD-infants at E2 and in VHR-infants during both assessments recruitment order was not associated with the duration of reaching.

At both assessments the rates of direction-specificity at the neck and trunk levels of the VHR-infants who were diagnosed with CP at 21 months ($n=5$) did not differ significantly from those of infants who did not develop CP ($n=5$) (E1: neck: 27% vs. 50%, Mann-Whitney: $p=0.177$; trunk: CP: 64%, no CP: 38%; Mann-Whitney: $p=0.157$; E2: neck: 23% vs. 43%, Mann-Whitney: $p=0.157$; trunk: CP: 70%, no CP: 61%; Mann-Whitney: $p=0.655$). Recruitment order did not differ between infants diagnosed with CP and infants who did not develop CP.

DISCUSSION

The present study suggested that postural control in terms of direction-specificity and recruitment order in infants at very high risk for CP does not change when the infant develops the ability to sit independently, and does not differ from that in TD-infants. In VHR- and TD-infants postural adjustments were related to success of reaching, be it in a different way.

In motor development the contribution of genetic instruction, environment and experience is still debated.^{13,25-27} Scientists who acknowledge the relatively large contribution of interaction with the environment, generally study the development of postural control in groups of children formed on the basis of functional performance.^{14-16,28} Our results showed that postural control in terms of direction-specificity and recruitment order did not change during the transition from being unable to sit without help to being able to sit independently. This supports the view of other scientists who study postural development generally in an age-based way, therewith implying an implicit recognition of endogenous maturational processes.^{3,5,29} Our data indicate that once direction-specificity is available, the development of independent sitting does not depend on the degree to which the infant exhibits direction-specific adjustments during reaching. This implies that other factors determine the emergence of the skill to sit without help. It is possible that during this transition infants improve their ability to cope with the inertial forces of the body while showing similar degrees of direction-specificity. The data of Harbourne and Stergiou suggested that infants express this ability by freezing the degrees of freedom of the body.¹⁵

As the ultimate goal of human postural control is the ability to cope with balance in standing and walking – conditions with a limited support surface – we

suggest that the development of direction-specific adjustments during reaching might rather be related to the development of the ability to stand than the ability to sit. Other studies indicated that the emergence of independent walking is related to the development of anticipatory postural adjustments.^{30,31} This could imply that the emergence of independent walking requires a firm basis of postural control, i.e., full blown direction-specificity, or it could mean that it requires in particular specific forms of fine-tuning of postural adjustments at the second level of control, such as anticipatory adjustments.

Our data indicated that direction-specificity and recruitment order were not associated with the development of the ability to sit independently. Yet, these postural parameters were associated with functional performance during sitting, i.e., the success and duration of reaching. In TD-infants who were not able to sit independently a higher frequency of successful grasping was associated with more direction-specificity at the neck level. This finding is in line with that of de Graaf-Peters et al., who found that success of reaching was associated with the rate of direction-specificity at the trunk and neck levels during sitting, but not with direction-specificity in supine position.⁶ In our TD-infants who were able to sit independently, direction-specificity and success of reaching were no longer associated. We also found that in TD-infants at E1 top-down recruitment was associated with a shorter duration of reaching. These findings support the notion of Thelen and Spencer that infants primarily stabilize their head to provide a basis to reach, and secondarily adapt postural muscle strategies to the situation.¹⁴

In the VHR-infants success of reaching was not related to the rate of direction-specificity. It was however associated with recruitment order: more bottom-up recruitment was associated with more success of reaching. This is in line with the finding of van der Heide et al., that top-down recruitment (and not bottom-up recruitment) is associated with CP.⁹ It is debated whether the stereotyped top-down recruitment in children with CP is a sign of dysfunction or an adaptation,^{9,32} as the use of the top-down recruitment could be a strategy to attain head stability and therewith provide a stable reference frame on which postural control is based. Stabilizing the head in space to allow clear vision and a better visual and vestibular processing is a primary goal of postural control.^{33,34} It is well known that children with CP have difficulties with head stability during dynamic tasks^{35,36} and even during quiet sitting.³⁷ Thus, our finding of an association between more bottom-up recruitment and more success of reaching corresponds to stereotyped top-down recruitment (as the opposite of bottom-up recruitment) of children with CP, irrespective the underlying mechanism (adaptation of dysfunction). In VHR-infants at E2 simultaneous recruitment was associated with a lower frequency of successful

reaching. The simultaneous recruitment may correspond to the limited repertoire of postural adjustments of infants with CP or motor delay reported by Kyvelidou et al.¹⁶ Interestingly, the reaching movements of the VHR-infants at E2 took less time than those of the TD-infants – a finding which may be explained by the older age of the VHR-infants.

A strength of the study is the longitudinal design to monitor the development of postural control in terms of direction-specificity and recruitment order in infants at very high risk for CP, based on evident brain lesions or based on neurological dysfunction suggestive for the development of CP. Another strength is the use of the PedEMG program, which allows for a combined analysis of EMG- and video recordings and copes with the variation at trial level characteristic for infant EMGs. It may be regarded a limitation of the study that the data were collected in a randomized controlled trial on the effect of early intervention. The intervention could have affected postural development. However, preliminary data analysis suggested that the postural adjustments in the two intervention groups did not differ. This is in line with previous reports comparing developmental outcome between infants receiving COPCA and those receiving traditional infant physiotherapy, indicating that virtually no differences were present between the two groups.^{38,39} Also the small sample size could be considered a limitation, and in particular the small size of the group of children with CP. The latter is inherent to studies of infants at high risk of CP: not all infants will develop CP.⁴⁰ Another limitation is the possibility of false positive activation of the sternocleidomastoid muscle, as it quickly activates with head turns. To control false positives, we used the video to identify and exclude trials with evident head- or trunk movement not related to the reaching movement. Finally, it may be regarded a limitation that we only studied infants who developed the ability to sit independently. This means that our data cannot be generalized to all infants at very high risk for CP, as the most severe cases were not included.

In conclusion, this study illustrated that in VHR- and TD-infants direction-specificity and recruitment order are not relevant parameters for the change in postural control during the development of the ability to sit independently. The postural adjustments were however associated with the success and duration of reaching, in TD-infants with direction-specificity and recruitment order and in VHR-infants with recruitment order only. In terms of early intervention our data may imply that practice of postural adjustments has a larger effect on reaching than on sitting ability. Finally, our hypothesis that the development of direction-specificity during reaching is rather related to the development of independent standing and walking than to the development of independent sitting deserves testing in future studies.

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