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Are postural adjustments during reaching related to walking development in typically developing infants and infants at risk of cerebral palsy?

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ABSTRACT

Background: In typical development, postural adjustments during reaching change in the second half of infancy, including increasing rates of direction-specific adjustments. These changes are absent or different in infants at risk of cerebral palsy (CP). To discover whether these changes are related to acquisition of independent walking, we studied postural adjustments during reaching in infants before and after they learned to walk.
Methods: Ten typically developing (TD) infants and 11 infants at very high risk (VHR) of CP were assessed before and after they learned to walk. Reaching movements were elicited during supported sitting, while surface electromyography was recorded of arm, neck, and trunk muscles. Percentages of direction-specific adjustments (first level of control), and recruitment patterns and anticipatory activation (second level of control) were calculated.
Results: In both groups, postural adjustments during reaching were similar before and after acquisition of independent walking. Direction-specificity increased with age in typically developing infants but not in VHR-infants.
Conclusion: Increasing age rather than the transition to independent walking is associated with increasing direction-specificity of TD-infants during reaching while sitting, while infants at very high risk of CP show no increase in direction-specificity, suggesting that they gradually grow into a postural deficit.

1. Introduction

Typically, the development of motor skills and development of postural control are closely intertwined. It is therefore expected that changes in motor development be related to changes in postural control and vice versa. This may be true especially for the acquisition of independent walking, which is a posturally demanding skill. Acquisition of independent walking has been associated with changes in postural control. For example, in typically developing (TD) children stabilization of the hip in space appears in the first week of independent walking (Assaiante, Thomachot, & Aurenty, 1993; Assaiante, Thomachot, Aurenty, & Amblard, 1998). In addition, walking experience has been found to facilitate control over postural sway through an increase in sensorimotor integration

(Barela, Jeka, & Clark, 1999; Metcalfe et al., 2005; Sundermier & Woollacott, 1998). The close relationship between postural control and learning to walk is also observed in children with developmental motor disorders, such as cerebral palsy (CP): dynamic postural control during sit-to-stand activity is a predictor of learning to walk in children with CP (Begnoche et al., 2016).

The study of Chen, Metcalfe, Jeka, and Clark, (2007) suggested that learning to walk also affects postural adjustments in a sitting position, as changing postural sway patterns during sitting were observed in infants during the acquisition of independent walking. Also, infants sitting on a moving platform after acquisition of independent walking showed more adult-like anticipatory adjustments to platform movements than before learning to walk (Cignetti, Zedka, Vaugoyeau, & Assaiante, 2013). In our current study, we aimed to investigate the relationship between learning to walk and postural muscle recruitment strategies during reaching, both in typically developing (TD) infants and in infants at risk of CP.

In terms of muscle recruitment strategies, postural control can be considered to consist of two levels. The first or basic level is direction-specificity, meaning e.g., that a forward body sway is counteracted by activation of dorsal muscles. The second level consists of fine-tuning of the postural adjustment, for example in the number of muscles activated, the recruitment order and use of anticipatory adjustments. Our previous studies indicated that in TD-infants aged 4–10 months, direction-specific activation of the trunk muscles is only present in about 60% of reaching movements in a sitting position, but this increases to 88% at the age of 18 months (Van Balen, Dijkstra, & Hadders-Algra, 2012). The studies also showed that the second level of postural control during this age period is characterized by variation, typical of infancy (Hadders-Algra, 2002). Nevertheless, a mild preference for top-down (i.e., cranial-to-caudal) recruitment appeared to be gradually replaced by a mild preference for bottom-up recruitment between 4 and 18 months (Van Balen et al., 2012).

In infants at high risk (HR) of CP, no increase in direction-specificity was observed between 6 and 18 months (Van Balen, Dijkstra, Bos, Van Den Heuvel, & Hadders-Algra, 2015). Top-down recruitment in these infants was initially lower than that of TD-infants but increased to similar rates at 18 months (Van Balen et al., 2015). As older children with CP do show direction-specificity during reaching (van der Heide et al., 2004), these differences between HR- and TD-infants suggest that development of postural control is delayed in HR-infants. This raises the question of whether development of postural control in infancy depends on age or stage of motor development. During the interval of 4–18 months, in which we found changes in postural control during reaching while sitting (Van Balen et al., 2012; Van Balen et al., 2015), the infants learned to sit, stand and walk. Previously we examined direction-specificity in both typically developing infants and infants at very high risk (VHR) of CP before and after learning to sit independently, but found no differences, either within or between the groups (Boxum et al., 2014). In the current study, we examined postural adjustments during reaching while sitting in both TD- and VHR-infants before and after learning to walk independently. We hypothesized that, if independent walking facilitates direction-specificity during sitting or vice versa, there would be an increase in direction-specificity in both groups after learning to walk independently. Similarly, if the change to a modest preference for bottom-up recruitment in TD-infants reported earlier (Van Balen et al., 2012; Van Balen et al., 2015) is related to walking, then we would expect to replicate this change after learning to walk.

2. Methods

2.1. Participants

Eleven VHR-infants (six boys, five girls), and 10 TD-infants (four boys, six girls) participated in this study. The VHR-infants were included in the LEARN2MOVE 0–2 years (L2M 0–2) project (Hielkema et al., 2010) before 9 months corrected age (CA) based on one of the following criteria: 1) cystic periventricular leukomalacia; 2) parenchymal lesion of the brain (uni- or bilateral); 3) severe asphyxia with brain lesions on magnetic resonance imaging; and 4) neurological dysfunction suspect for CP. Exclusion criteria were the presence of a severe congenital disorder, or 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 walk independently by the age of 21 months CA, and b) they had two postural electromyography (EMG) recordings: one just before and one after learning to walk independently (see Assessment procedure).

Typically developing infants born at term without perinatal complications were recruited from infant public health agencies in Groningen, The Netherlands. Clinical details of the participants are summarized in Table 1. The ethics committee of the University Medical Center Groningen approved the protocols (registration numbers NTR1428 and NL51701.042.14) and informed consent was given by the parents.

2.2. Assessment procedure

The Alberta Infant Motor Scale (AIMS; (Piper & Darrah, 1994)) was used to determine the developmental stages at which the infants were assessed. TD-infants were assessed 1) when they were able to pull up to standing but unable to walk independently (Time A; item 'Pulls to Stand with support' of the AIMS); and 2) when they could walk independently for about one month (Time B; item 'Walks Alone' of the AIMS). Postural control in VHR-infants was assessed at inclusion (T0), 6 months after inclusion (T2), 12 months after inclusion (T3) and at 21 months CA (T4). Two assessments matching the abovementioned developmental criteria of Time A and B were selected for each VHR-infant. Thus, the interval between Time A and B for the VHR-infants resulted from the assessment schedule of the L2 M 0–2 trial, but the developmental stages of the VHR-infants of the selected assessments matched the developmental stages of time A and B, respectively, as determined by the AIMS. This implied for Time B that the infants had walked independently for 1–9 months, i.e., the VHR-infants may have had some months more walking experience at time B than the TD-

Table 1
Group characteristics.

Demographics	VHR-infants ($n = 11$)	TD-infants ($n = 10$)
Sex		
Male, n (%)	6 (55%)	4 (40%)
Female, n (%)	5 (45%)	6 (60%)
Gestational age (weeks)		
Median (range)	29.4 (25.9–40.6)	39.9 (38–41.1)[a]
Birth weight (grams)		
Median (range)	1550 (720–3200)	3587 (3030–4275)[a]
Born preterm (< 37 weeks), n (%)	2 (18%)	0
Corrected age (months)		
Time A, median (range)	14.0 (11.4–16.9)	12.6 (10.3–16.1)
Time B, median (range)	21.1 (17.5–22.2)	15.0 (12.6–18.3)[a]
Interval between time A & B in months, median (range)	7 (4.1–9.9)	2.3 (1.4–4.0)[a]
Type of brain lesion, n (%) [TINE classification]		
Posthaemorrhagic porencephaly	4 (36%) [CP: 1, MND: 3]	
Basal ganglia/thalamic lesion	2 (18%) [MND]	
Cortical infarction	1 (9%) [CP]	
Periventricular leukomalacia	1 (9%) [MND]	
Arachnoidal cyst with hydrocephalus	1 (9%) [Normal]	
No lesions[b]	2 (18%) [MND: 1, Normal: 1]	10 (100%) [Normal]
TINE classification, n(%)		
CP	2 (18%)	
MND	7 (64%)	
Normal	2 (18%)	10 (100%)
AIMS Total Scores		
Time A, median (range)	41 (32–49)	51 (46–52)[a]
Time B, median (range)	53 (45–56)	56.5 (53–58)[a]
Infant Motor Profile Total Scores		
Time A, median (range)	0.82 (0.72–0.88)	0.97 (0.94–0.98)[a]
Time B, median (range)	0.82 (0.76–0.89)	0.94 (0.90–0.96)[a]

VHR: very high risk; TD: typically developing; TINE: Touwen Infant Neurological Examination; MND: minor neurological dysfunction; Time A: assessment when infant was able to pull up to standing but not able to walk independently (item 'Pulls to Stand with support' of the AIMS, see text); Time B: assessment when infant was able to walk independently for about a month (Time B; item 'Walks Alone' of the AIMS, see text).

[a] Mann–Whitney: p < .01.

[b] Infants without brain lesions were included based on neurological dysfunction suspect for CP before 9 months corrected age (CA). Neurological classification of VHR-infants based on the assessment at 21 months CA.

infants, who were assessed one month after learning to walk. Reaching movements were elicited from the infant seated in a supported sitting position (in an infant chair or on their parent's lap) by presenting a small toy at arm's length distance. 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 = 3 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). 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). The entire EMG-session was recorded on video. The video was used to select reaching movements with the preferred arm without evident trunk or head movements not related to the reaching movement, in which the infant was in an alert and calm behavioral state.

On the same or a neighboring day, the infants' neurological status was assessed using the Touwen Infant Neurological Examination (TINE) (Hadders-Algra, Heineman, Bos, & Middelburg, 2010); the VHR-infants were also neurologically assessed at 21 months CA. The assessment resulted in the classification of neurological normal, minor neurological dysfunction or CP. The latter (only diagnosed at 21 months CA) implied the presence of a 'classical' configuration of neurological signs, such as, in the 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.

At the occasion of the TINE assessment, the quality of the infant's motor behavior was assessed with the Infant Motor Profile (IMP; (Heineman, Bos, & Hadders-Algra, 2008; Heineman, Bos, & Hadders-Algra, 2011; Heineman et al., 2013). The IMP evaluates motor behavior in five domains: (1) variation, (2) adaptability (ability to select motor strategies that fit the current situation), (3) movement fluency, (4) movement symmetry, and (5) motor performance.

2.3. Video and EMG analysis

EMG analysis was carried out using the PedEMG software (Developmental Neurology, University Medical Center Groningen, The Netherlands) (Van Balen et al., 2012). PedEMG allows for synchronous analysis of video and EMG data. The software used for EMG analysis includes the model based statistical algorithm of Staude and Wolf (Staude & Wolf, 1999) to determine onsets of phasic EMG-

activity. Before determining the onsets the signal was filtered for 50 Hz noise using a 5th order band Chebyshev filter, when appropriate. Signal artefacts and cardiac activity were identified to take into account when appropriate. Clear signal artefacts were identified manually. Cardiac activity 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 either 1000 ms after activation of the prime mover or the end of the reaching movement, whichever came first (see Van Balen et al. (2012), Boxum et al. (2014)). For each trial, we determined the following parameters: (1) direction-specificity at the neck and/or trunk level; a trial was direction-specific if the dorsal muscle was activated prior to or in the absence of ventral muscle recruitment. The other EMG-parameters were only calculated if direction-specific activity at the trunk level was present: (2) the occurrence of the 'complete pattern', that is the pattern in which all direction-specific muscles were recruited; (3) recruitment order (top-down, bottom-up, or otherwise). If two muscles were activated within an interval of 20 ms, recruitment was considered to be simultaneous; (4) the recruitment latencies of postural muscles, defined as the time interval between the onset of the prime mover and the onset of activity in the postural muscle. For each infant at each age median latency values were calculated; (5) the presence or absence of anticipatory postural activity (i.e. activation starting within 100 ms before the prime mover).

2.4. Statistics

Statistical modelling was carried out using SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, NY, USA) and the Statistical Analytics Software 9.3 (SAS Institute Inc., Cary, NC, USA). For the dichotomous parameters (the presence or absence of direction-specificity, the complete pattern, top-down and bottom-up recruitment, and anticipatory activation), a binomial generalized estimating equations model with repeated measurements and robust estimators was fitted using predictor variables Group and Time or Group and Corrected Age (CA). Continuous variables (the median latencies) were modelled in SAS with a linear mixed model with repeated measurements.

3. Results

Group characteristics are shown in Table 1. Birth weight and gestational age differed between the groups, which is inherent to differences in group definitions. At the first assessment (time A), corrected age was not statistically different between the groups: 14.0 months (median; range: 11.4–16.9) for the VHR-infants and 12.6 months (10.3–16.1) for the TD-infants. At the second assessment, the groups did significantly differ with respect to corrected age: 21.1 months (median; range: 17.5–22.2) for the VHR-infants and 15.0 months (12.6–18.3) for the TD-infants. However, there was considerable overlap between the variables of assessment time (A and B) and corrected age. Therefore, we did not add corrected age to the models but compared models with corrected age as predictor to those with assessment time as predictor when scatter plots indicated a possible effect of corrected age within (one of) the groups.

At the second assessment, two of the 11 VHR-infants were diagnosed with unilateral spastic CP at GMFCS-level I, while seven had minor neurological dysfunction (MND) and two were neurologically normal. All TD-infants were neurologically normal. The Infant Motor Profile (IMP) scores are shown in Table 1. At both time A and B, the VHR-infants had lower IMP-scores than the TD-infants (time A: median 0.82 (range: 0.72–0.88) for the VHR-infants vs. 0.97 (0.94–0.98) for the TD-infants; Mann-Whitney p < .001; time B: median 0.82 (range: 0.76–0.89) for the VHR-infants vs. 0.94 (0.90–0.96) for the TD-infants; Mann-Whitney p < .001). The VHR-infants' scores were particularly lower in the domains of variation, symmetry and motor performance (data not shown).

3.1. The effect of learning to walk and the effect of age

Results are shown as estimated marginal means (EMM) or estimated mean differences (EMD) followed by 95%-confidence intervals in square brackets.

3.1.1. Direction-specificity

In both groups and measurements, direction-specificity was higher at trunk level (45–83%) than at neck level (15–43%). Direction-specificity at the trunk level was lower in VHR-infants than in TD-infants (estimated mean difference: 16%, 95% confidence interval: [5–27], p = .006; Fig. 1). This was particularly due to lower values in walking infants (VHR 60% [46–72], TD 81% [70–89], p = .011); the difference between groups in non-walking infants was not significant at this n (VHR 61% [52–69]), TD 70% [60–78], p = .147). Direction-specificity seemed to increase after learning to walk in TD-infants and to decrease after learning to walk in VHR-infants, but neither difference was statistically significant. When using corrected age as predictor instead of assessment time, the probability of a direction-specific adjustment at the trunk level increased with increasing age in TD-infants (p = .042) but not in VHR-infants.

Direction-specificity at the neck level after learning to walk was also lower in VHR-infants than in TD-infants (VHR 25% [17–34], TD 41% [33–50], p = .009; Fig. 1). This resulted mainly from a decrease between the two measurements in VHR-infants from 41% [32–50] to 25% [17–34] (p = .016). Corrected age was also a good predictor of this finding: the probability of a direction-specific adjustment at the neck level decreased with increasing age in VHR-infants (p = .001) but not in TD-infants.

In direction-specificity at both levels simultaneously there were no significant differences between groups or measurements (VHR 33% [25–44] before walking and 32% [18–49] after, TD 41% [34–47] before walking and 45% [36–55] after; EMD between VHR and
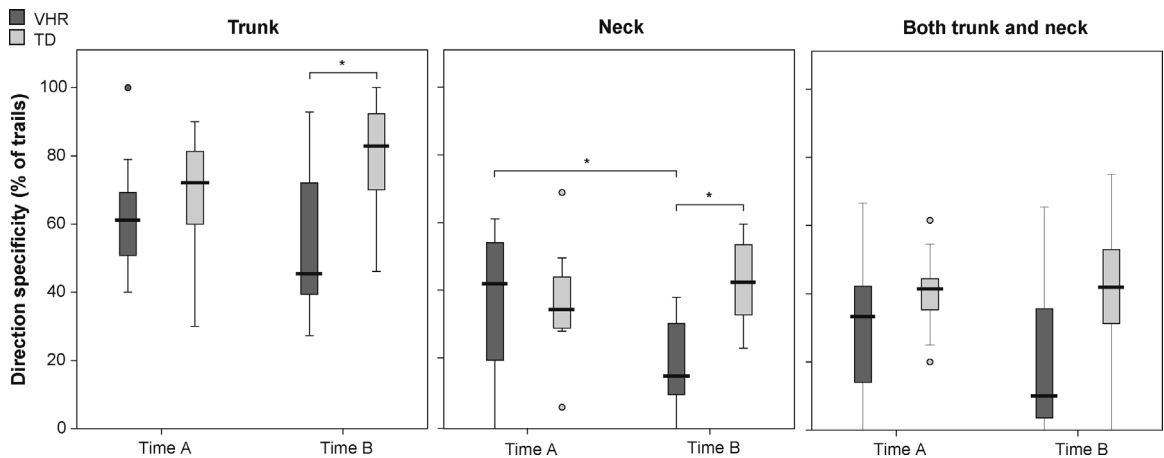
Fig. 1. Percentage of direction-specific trials (first level of control) of VHR-infants and TD-infants before (Time A) and after learning to walk independently (Time B). Left panel: direction-specificity in the trunk muscles. Middle panel: direction-specificity in the neck muscles. Right panel: direction-specificity in both the trunk and neck muscles. *Significant at p < .05.

TD: 10% [–1,22], p = .077). Corrected age was not a significant predictor.

3.1.2. Muscle recruitment strategies

Average usage of the complete pattern differed between 42% and 56% and was not statistically different between groups or measurements (data not shown). Thoracal and lumbar extensor activity was present in the majority of trials (median values 71–88%), while neck extensor activation varied (median values 57–82%). Notably, in both groups neck flexor activation (with or without neck extensor activation) was present in more than 80% of trials (median values 82–88%). VHR-infants activated their rectus abdominis muscle more often than TD-infants (estimated mean difference of 18% [2–33], p = .029).

Recruitment order of the direction-specific postural muscles was different between groups: top-down recruitment before learning to walk was lower in VHR-infants than in TD-infants (VHR 25% [16–36], TD 38% [30–48], p = .043; Fig. 2). Bottom-up recruitment seemed higher in VHR-infants at time A, but this was not statistically significant (VHR 34% [24–47], TD 19% [10–34], p = .080). Recruitment order did not change significantly within groups during acquisition of independent walking or with increasing age.

3.1.3. Latencies and anticipatory postural muscle activation

Anticipatory activation of any of the neck or trunk muscles was seen in 36% to 49% of trials and was not statistically different between groups or measurements. Recruitment latencies of the postural muscles are shown in Fig. 3. Recruitment of the lumbar extensor was faster in VHR-infants than in TD-infants (estimated difference: 84 ms [7–160], p = .032, before learning to walk and
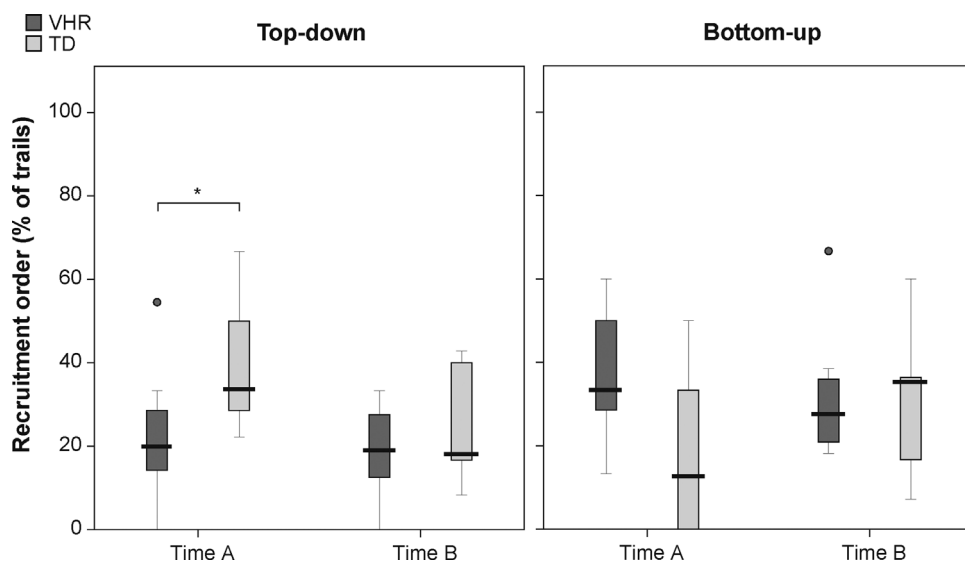

Fig. 2. Recruitment order (second level of control) of direction-specific trials. Percentage of trials with top-down (left panel) and bottom-up recruitment (right panel) of VHR-infants and TD-infants, before (Time A) and after learning to walk independently (Time B). *Significant at p < .05.
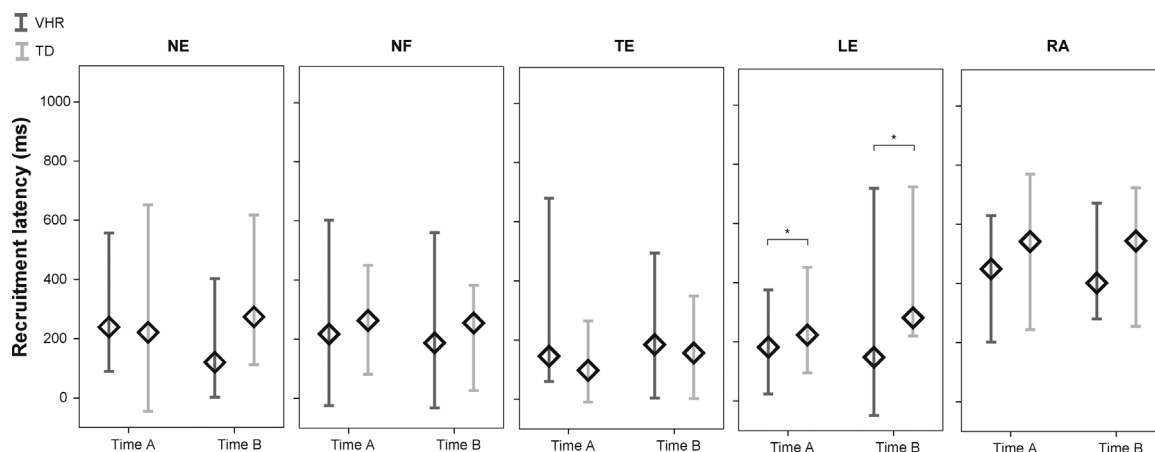
Fig. 3. Recruitment latencies of postural muscles. Diamonds show medians, whiskers show ranges.

111 ms [17–204], p = .021, after learning to walk). After learning to walk, recruitment of the neck extensor also seemed faster in VHR-infants than in TD-infants, but this was not statistically significant (estimated difference: 121 ms [−13; 255], p = .077). Age and learning to walk were not significant predictors of recruitment latencies.

3.2. VHR-infants: associations between postural adjustments and neurological condition

The postural parameters of the two infants with CP differed in some aspects from those of VHR-infants without CP. Direction-specificity at the trunk level was lower, both before learning to walk (CP 46% [37–56] vs. no CP 64% [54–72], p = .009) and after learning to walk (CP 41% [37–45] vs no CP 64% [49–77], p = .003). This may have been due to less frequent LE-recruitment before learning to walk (CP 69% [66–72] vs. no CP 84% [70–92], p = .012) and more frequent RA-recruitment after learning to walk (CP 78% [75–80] vs. no CP 47% [36–59], p < .001). After learning to walk, the two infants with CP had more frequent top-down recruitment than VHR-infants without CP (CP 26% [21–32], no CP 15% [10–23]; p = .043). This may be related to faster recruitment of NE after learning to walk (CP 128 [112–144], no CP 239 ms [139–339]; p = .031).

4. Discussion

In both groups, postural adjustments after learning to walk independently were similar to those before acquiring this ability. Direction-specificity of the two groups differed increasingly with increasing age.

4.1. Typically developing infants

In typically developing infants, we found an increase with age in direction-specificity at the trunk level. This is in line with our earlier study (in other TD-infants) in which we also found an increase between 10 and 18 months (Van Balen et al., 2012). An effect of the experience of learning to walk may be present, but if so, it is limited, i.e., below the detection threshold of the current study. This may be because posturally less demanding tasks such as supported sitting allow the infant to be 'sloppy' with postural adjustments, while more demanding tasks do not. Indeed, during platform perturbations that constitute a bigger postural challenge, infants as young as one month show very consistent direction-specificity (Hedberg, Forssberg, & Hadders-Algra, 2004).

Direction-specificity at the neck level was lower than at the trunk level, consistent with our earlier findings (Van Balen et al., 2012; Van Balen et al., 2015). Neck muscle responses in adults during forward translations in a study by Keshner were also not direction-specific (Keshner, 2003), suggesting that this is a typical finding not related to infancy. It probably reflects the multiple roles of the neck muscles: stabilizing the position of the head in space, moving the head along with the reaching movement, and maintaining its position relative to the trunk (Sveistrup, Schneiberg, McKinley, McFadyen, & Levin, 2008).

The parameters of the second level of postural control did not change with learning to walk or age: recruitment order showed the also earlier found characteristic variation (Van Balen et al., 2012; Van Balen et al., 2015), and anticipatory activation was present in one third up to half of the trials, similar to our earlier results.

4.2. Very high-risk infants

Direction-specificity was lower in VHR-infants than in TD-infants and did not increase with age or learning to walk, confirming our observation that direction-specificity in HR-infants changes little in the second half of infancy despite increasing age and despite increasing walking experience (Van Balen et al., 2015). Compared to the TD-infants, the VHR-infants were older and had more experience because of the longer interval between time A and B, but still this did not result in increased direction-specificity in the

VHR-infants. The fewest direction-specific adjustments were seen in the two infants with CP. Apparently, during development of independent walking, TD-infants get into the habit of consistently applying appropriate (direction-specific) postural adjustments even in less demanding postural tasks such as reaching while sitting supported, while VHR-infants fail to do so. This suggests that the VHR-infants, in particular the children diagnosed with CP, in terms of direction-specific postural adjustments during reaching, may gradually grow into their postural deficit.

The IMP-scores, which evaluated the infant's motor behavior during walking, standing, sitting, reaching and grasping, indicated that the VHR-infants' motor behavior in general was less well organized than that of the TD-infants. Since high-risk infants have both impaired reaching movements (Fallang, Saugstad, Grøgaard, & Hadders-Algra, 2003) and lower-direction-specificity, it could be surmised that high-risk infants exhibit postural adjustments that interfere with reaching. This may be the case, but the relationship is complex. Infants learn to reach long before they consistently use direction-specific postural adjustments (Van Balen et al., 2012), so consistent use of direction-specificity during reaching is not a prerequisite for reaching. Nevertheless, impaired postural adjustment may influence the quality of reaching. In our previous study, we found that postural adjustments were related to success of reaching in both TD-infants and VHR-infants, albeit in a different way in each group. In VHR-infants, top-down recruitment was related with success of reaching, while in TD-infants direction-specificity was related to success of reaching, but only at a young age (Boxum et al., 2014).

Two other possible explanations for lower direction-specificity may be 1) movement of the trunk towards the toy during the reaching movement (as a compensatory mechanism to facilitate reaching in an infant with impaired reaching ability), or 2) more simultaneous antagonistic co-activation. Indeed, in our data, lower direction-specificity was in part due to earlier or co-activation of the rectus abdominis muscle. Excessive muscle activation has been described in early walkers with CP (Prosser, Lee, Barbe, VanSant, & Lauer, 2010; Prosser, Lee, VanSant, Barbe, & Lauer, 2010). In addition, Burtner et al. (1998) also found increased antagonist muscle activation and decreased paraspinal muscle activation.

Top-down recruitment before learning to walk was less frequent in VHR-infants than in TD-infants, consistent with our earlier findings (Van Balen et al., 2015). However, the increase in top-down recruitment of HR-infants at 18 months (Van Balen et al., 2015) was not present in the current group of VHR-infants. It could be hypothesized that this preference for top-down recruitment in VHR-infants takes more time to develop, i.e., more than 21 months, since Van der Heide showed stereotyped top-down recruitment in older children with CP (12). The two infants with CP showed more frequent top-down recruitment after learning to walk than VHR-infants without CP. An alternative explanation is that the VHR-infants with least frequent (direction-specific) top-down recruitment showed almost universal neck flexor activation and low direction-specificity, so their responses may have been top-down but not direction-specific (a prerequisite for our definition of top-down recruitment).

Recruitment latencies of VHR-infants were also slightly different from those of the HR-infants reported earlier. While in HR-infants responses were slower than those of TD-infants at 18 months (with less anticipatory activation in HR-infants than TD-infants), VHR-responses of the lumbar extensor were faster than those of TD-infants (with similar anticipatory activation). Shorter latencies are unusual in infants at risk for CP but have been reported before in a specific subgroup of children with periventricular white matter lesions (Hadders-Algra, Brogren, Katz-Salamon, & Forssberg, 1999). Indeed, a major difference between the HR-infants of our previous study and the current VHR-infants is the presence of brain lesions in the latter group. The neuronal reorganization that takes place after the occurrence of an early brain lesion may result in simplified neural circuitries with fewer interneuronal connections, resulting in relatively fast responses (Hadders-Algra et al., 1999). With only two VHR-infants without lesions, we were unfortunately unable to properly test this hypothesis.

4.3. Methodological considerations

Our study has some limitations. First, the external validity of our results is limited by the small group size, which is especially true for the results of the two infants with CP. However, the results of the two infants with CP were consistent with earlier findings. Second, the VHR-infants in this study are a distinct selection of the VHR-infants of the L2M-project: all infants in this study by definition learned to walk before the age of 21 months, and thus are a subgroup with relatively better postural control. Postural parameters of the other VHR-infants may be different.

Third, the TD-infants were assessed just before and after learning to walk, while the VHR-infants were assessed according to the LEARN2MOVE 0–2 study protocol. As a result, the interval between the two measurements was longer in VHR-infants than in TD-infants (see Table 1), and may have included more time during which the VHR-infants either could not walk or had already mastered walking. So, although their inclusion was based on the same developmental stage when compared to TD-infants, the children had an experience advantage over the TD-children. Of note, our main finding is an increase in trunk direction-specificity with age in TD-infants, which was absent in VHR-infants. The difference in timing of the measurements between the groups only serves to emphasize this difference between groups, since the VHR-infants had more time and more trial-and-error experience available between measurements to increase their direction-specificity, and still did not.

Fourth, the effect of learning to walk was confounded by age, as the infants were two to ten months older at the second assessment than at the first assessment and the VHR-infants were older at time B than the TD-infants. Unfortunately, the study was underpowered to include both variables in a single model. They were therefore tested separately. As age was a good predictor of some of the changes we found, it is possible that age rather than developmental stage had the largest effect on the changes in postural control. We cannot completely discard the possibility of an effect of learning to walk, however, since dichotomizing a variable (in this case: developmental stage) results in lower statistical power (Altman and Royston, 2006), which may have been an advantage of the variable 'Age' over the variable 'Walking'. Burtner, Woollacott, Craft, and Roncesvalles (2007) reported that differences in postural responses to

platform perturbations in older children with CP were due to differences in developmental stage rather than differences in age (Burtner et al., 2007). Another possibility is that changing body dimensions trigger changes in postural adjustments, as with locomotion development (Adolph & Avolio, 2000).

In conclusion, postural responses during reaching in a sitting position do not change significantly while learning to walk independently. Direction-specificity increases with age in typically developing infants, but not in infants at very high risk for cerebral palsy suggesting that they gradually grow into a postural deficit. Recruitment patterns of very high-risk infants, i.e., infants with a lesion of the brain, may be different from at-risk infants without a brain lesion.

Disclosure statement

The authors have stated that they had no interests which might be perceived as posing a conflict or bias.

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