Official Journal of the European Paediatric Neurology Society

Original article

Altered arm posture in children with cerebral palsy is related to instability during walking

Pieter Meyns^{a,*}, Kaat Desloovere^{b,c}, Leen Van Gestel^c, Firas Massaad^a,
Bouwien Smits-Engelsman^{a,d}, Jacques Duysens^{a,e}

^a Department of Kinesiology, Faculty of Kinesiology and Rehabilitation Sciences, KU Leuven, Tervuursevest 101 box 1501, B-3001 Heverlee, Belgium

^b Clinical Motion Analysis Laboratory, CERM, University Hospital Leuven, Leuven, Belgium

^c Department of Rehabilitation Sciences, Faculty of Kinesiology and Rehabilitation Sciences, KU Leuven, Heverlee, Belgium

^d Avans+, University for Professionals, Breda, The Netherlands

^e Department of Research, Development and Education, Sint Maartenskliniek, Nijmegen, The Netherlands

ARTICLE INFO

Article history:

Received 23 June 2011

Received in revised form

13 January 2012

Accepted 24 January 2012

Keywords:

Cerebral palsy

Arm posture

Gait

Instability

Guard position

Speed increment

ABSTRACT

Background: Toddlers learning to walk adopt specific 'guard' arm postures to maintain their balance during forward progression. In Cerebral Palsy (CP), the cause of the altered arm postures during walking has not been studied.

Aim: To investigate whether the altered arm posture in children with CP is a compensation for instability during walking.

Methods: Vertical and horizontal hand position, and upper arm elevation angle in the sagittal plane were determined in eleven children with unilateral CP, fifteen children with bilateral CP using 3D gait analysis and compared to twenty-four TD children. A correlation analysis of these measures of arm posture to step width was made to examine the relationship between arm posture and instability.

Results: The hand position of children with CP was more elevated and anterior, and their upper arm was rotated more posterior than TD children. Children with unilateral CP held their most affected hand higher than their least affected. Increasing the speed accentuated the differences between groups for hand elevation. Step width correlated positively with horizontal hand position of the least affected arm in children with CP.

Conclusion: Children with CP appear to rely on 'guard' arm postures as a compensation strategy to maintain balance while walking comparable to newly walking toddlers. Importantly, this pattern is seen on the least affected side. The substantially altered arm posture on the most affected side in children with unilateral CP, however, suggests that spasticity and associated movements are also important contributing factors.

© 2012 European Paediatric Neurology Society. Published by Elsevier Ltd. All rights reserved.

* Corresponding author. Tel.: +32 16 329065; fax: +32 16 329197.

E-mail address: pieter.meyns@faber.kuleuven.be (P. Meyns).

1. Introduction

Currently there is renewed interest in the role of the arm movements during gait since there are indications that these movements are likely the result of activity in spinal locomotor centers.^{1–3} Even in infants, long before independent walking is possible, it was found that the coordination of the leg movements already meets the requirements for independent walking.⁴ This is not true for the reciprocal arm swing during gait because most children only exhibit reciprocal arm swing by the age of one and a half years.⁵ Hence, newly walking children do not adopt the same natural reciprocal arm swing as adults. On the other hand, they do show specific arm postures while walking.⁶ During the first ten weeks of gait children hold their arms in fixed ‘guard’ positions.⁷ While developing gait, they gradually lower the fixed position of the arms from a high guard (external rotation at the shoulder, flexed elbows and hands at shoulder level) to a low guard position (arms extended along the body without noticeable movement). These guard positions in newly walking toddlers have been considered a compensation strategy to maintain balance while walking.^{7,8} Furthermore, similar guard positions of the arms were also described in healthy adults when walking over a slippery surface,⁹ which clearly emphasizes the importance of the arm posture’s contribution in gait stability. In addition, arm movements were found to have a clear biomechanical purpose^{10–12} and an important role in gait.³ Whether this is also true for children with Cerebral Palsy (CP) is the topic of the present study.

Children with Cerebral Palsy (CP) show affected motor control with an associated pathological gait pattern due to injury to the central nervous system in the developing brain.¹³ Poor balance control is known to be an important causative element of the gait problems in these children.¹⁴ Prior studies only paid attention to the lower limb during walking,¹⁵ however, it is increasingly clear that one should not overlook the role of arm movements. Therefore we investigated the arm swing in two types of children with CP in previous studies.^{16,17} It was found that children with CP show differences in arm swing behavior compared to typically developing (TD) children. We suggest that these changes in arm swing in children with CP were partly caused by adopting different arm postures compared to TD children, but this topic was not further explored in these initial studies. Some other studies confirmed that such abnormalities in arm posture may be present in children with bilateral CP¹⁸ as well as unilateral CP.¹⁹ None of these studies, however, investigated the underlying causes of the abnormal postures. In contrast, in toddlers clear support was obtained for a relationship between imbalance and the altered normal arm posture (‘guard’ positions⁷). This was based on the observation that the most pronounced guard positions correlated with the largest step width. The question arises whether a similar association can be found in CP children, which also tend to show ‘guard-like’ arm postures.

Therefore, the aim of the current study was to test whether children with unilateral CP and bilateral CP showed changes in the arm posture during walking, and whether these changes were related to instability during walking (as

seen in toddlers). Additionally, we studied whether an increase in walking speed had an influence on the arm postures.

2. Materials and methods

2.1. Participants

Eleven children with unilateral CP (hemiplegia; age range 4–12 years), fifteen children with bilateral CP (diplegia; age range 4–12 years) and twenty-four TD children (age range 5–12 years) participated in this study. Participant characteristics are presented in Table 1. Children with CP were recruited from the Laboratory of Clinical Movement Analysis of the University Hospital Leuven (U.Z. Leuven). Diagnosis and type of CP was determined by a multidisciplinary team of neuro-pediatricians, pediatric orthopedicians and rehabilitation medicine physicians, and is based on neuropaediatric and neurologic examinations including medical imaging (MRI). CP children were excluded if they were unable to walk without walking aids, were not diagnosed with the predominantly spastic type of CP, did not have sufficient cooperation to follow verbal instructions, underwent Botulinum Toxin A treatment within the past 6 months or previously received lower limb surgical intervention. All experiments were approved by the local ethical committee (“Commissie Medische Ethiek van de Universitaire Ziekenhuizen Leuven”) and were performed with the informed, written consent of the parents of the participants in accordance with the Declaration of Helsinki.

Table 1 – Characteristics of TD children and children with CP.

	TD	Bilateral CP	Unilateral CP
N	24	15	11
Gender (M/F)	12/12	11/4	8/3
GMFCS (I/II/III)	–	8/6/1 ^a	7/4/0
Age (y: years, m: months)	9y 4m ± 2y 1m	9y 11m ± 2y 5m	7y 9m ± 2y 11m
Weight (kg)	31.72 ± 8.64	31.54 ± 13.36	23.87 ± 7.57
Height (m)	1.38 ± 0.14	1.34 ± 0.19	1.22 ± 0.15 ^b
Speed FW (m/s)	1.20 ± 0.16	0.94 ± 0.24 ^c	1.10 ± 0.13
Speed FFW (m/s)	1.95 ± 0.17	1.41 ± 0.41 ^c	1.67 ± 0.18 ^c

Note that age, weight, height and speed are presented as follows: mean ± standard deviation. N = number of subjects, M/F = male/female, GMFCS = Gross Motor Function Classification System, FW = preferred walking speed condition, FFW = as fast as possible walking speed condition.

a One subject with a GMFCS level III was included because this subject was able to complete the walking trials of the experiment without walking aids.

b Significantly different from TD (one way Analysis of Variance: $F = 3.69$, $p = 0.032$; TD vs biCP, $p = 0.025$).

c Significantly different from TD (repeated measures ANOVA: speed × group: $F = 11.45$, $p < 0.001$; TD–FW vs biCP–FW, $p = 0.013$; TD–FFW vs biCP–FFW, $p < 0.001$; TD–FFW vs uniCP–FFW, $p = 0.007$). (Modified from Meyns P. et al. Res Dev Disabil 2011;32:1957–1964).

2.2. Protocol

Participants were asked to walk at a preferred and “as fast as possible” (without running) speed along a 10 m walkway. Three-dimensional full-body kinematic data (100 Hz) were recorded with an eight camera Vicon system (Oxford Metrics, Oxford, UK). The total body “PlugInGait” marker set was used. A successful trial included four consecutive foot strikes with full-marker-visibility. Trials were not retained when the participant made excessive movements of the head, arms or trunk unrelated to walking. The participant was granted some practice trials for each condition. Three walking trials for each walking speed were used for further analysis.

2.3. Data processing

The marker coordinates were filtered and smoothed using Woltring’s quintic spline routine with a predicted mean-squared error of 15.²⁰ Workstation (Vicon Workstation 5.2 beta 20, Oxford Metrics, Oxford, UK) and Polygon software (Version 3.1, Oxford Metrics, Oxford, UK) were used to define the gait cycles and to determine the spatio-temporal parameters. The most affected (MA) side in children with CP was determined as the side on which the leg had the highest spasticity measures (Modified Ashworth Scale).

To assess whether children with CP kept the arms systematically in a specific posture three measures were used. Typical examples of each group for the measures are shown in Fig. 1.

Firstly, to check whether an elevated arm position occurred during walking, the mean position of the hand marker over the gait cycle along the vertical axis (“vertical hand position”) was determined (Fig. 1 top panel). Secondly, as a guard position is also characterized by having the hands continuously in front of the body, the average displacement of the hand marker over the gait cycle in the sagittal plane along the horizontal axis (“horizontal hand position”) was calculated (Fig. 1 middle panel). The correction for whole body forward and up and down movements consisted of subtracting the displacement along the horizontal and vertical axis, respectively, of the marker on the spinous process of the fifth lumbar vertebra (L5) from the time-courses of the displacement of the hand. To take into account size differences, both above mentioned variables were normalized by dividing them by the participants height.²¹ Additionally, we calculated the average angular displacement over the gait cycle of the upper arm segment with respect to the vertical (or “upper arm angle”), which gives a clear impression of the position of the upper arm during walking (Fig. 1 bottom panel). Finally, the step width was used as a measure of instability of walking. In order to assess whether the altered hand position arises due to problems in maintaining the balance during walking, correlations of step width and the three measures of arm posture were investigated. Step width was determined as the distance between the foot markers normal to the line of progression and also normalized according to the participants height. All variables were averaged over trials, for each participant at each walking condition.

Fig. 1 – Single trial examples of the most affected/non dominant arm of a typically developing child (TD: left), a child with bilateral CP (biCP: middle) and a child with unilateral CP (uniCP: right) for the three measures used. For the vertical position of the hand (top panel) and the horizontal position of the hand (middle panel) the zero represents the position of L5. A positive value signifies a more elevated position for the vertical position of the hand, and a more forward position for the horizontal position of the hand. For the angle of the upper arm with respect to the vertical (bottom panel), a value of zero would mean that the upper arm and the vertical are parallel while positive values represent a more anteriorly rotated upper arm. Dotted lines are the average over the gait cycle.

2.4. Statistical analysis

Age, weight and height between TD children, children with bilateral CP, and children with unilateral CP were compared using a one way analysis of variance. A repeated measures ANOVA with group and walking condition as factors was used to compare walking speeds between the three groups. To compare the three groups for each variable we used a general linear model with group as a factor, and two repeated measures factors (walking condition, side of the body). Since the walking speeds differed between the groups, we included actual walking speed as a covariate in our analysis. Tukey's post hoc comparisons were systematically applied. To establish the relation between the measures of arm posture and step width, Pearson correlations were determined for the TD group, the total group of CP and the CP subgroups. An $\alpha = 0.05$ was used to establish statistical significance.

3. Results

3.1. Do children with bilateral CP and unilateral CP show altered arm postures during walking?

The mean vertical hand position during the gait cycle is depicted in Fig. 2A, averaged for side of the body and walking condition.

In all groups, the hand position was below the zero level (i.e. height of L5) but both CP groups showed a vertical hand position that was more elevated compared to TD children (group: $p = 0.009$; TD: -0.10 ± 0.03 versus biCP: -0.06 ± 0.05 , $p = 0.002$; uniCP: -0.06 ± 0.04 , $p = 0.001$). In uniCP children, the most affected (MA) hand was held higher during walking than the least affected (LA) hand (Fig. 2B; group $\times$ side: $p = 0.006$; MA: -0.03 ± 0.04 versus LA: -0.08 ± 0.03 , $p < 0.001$).

When the participants walked at a higher speed the vertical hand position showed a larger increase in the two CP groups compared to TD children (Fig. 2C; speed $\times$ group: $p = 0.041$; TD – FW: -0.11 ± 0.02 versus FFW: -0.09 ± 0.03 , $p = 0.012$; biCP – FW: -0.08 ± 0.05 versus FFW: -0.04 ± 0.05 , $p < 0.001$; uniCP – FW: -0.08 ± 0.03 versus FFW: -0.04 ± 0.04 , $p < 0.001$). The speed $\times$ side interaction effect showed that when children walked faster, the vertical hand position on MA/non dominant side increased more than the vertical hand position on the LA/dominant side ($p = 0.043$; MA – FW: -0.09 ± 0.03 versus FFW: -0.05 ± 0.05 , $p < 0.001$; LA – FW: -0.10 ± 0.03 versus FFW: -0.08 ± 0.04 , $p < 0.001$). In uniCP children specifically, the vertical hand position on the MA side increased much more when walking speed increased compared to that on the LA side, as shown in Fig. 2D (speed $\times$ side $\times$ group: $p < 0.001$; MA – FW: -0.06 ± 0.03 versus FFW: -0.01 ± 0.05 , $p < 0.001$; LA – FW: -0.09 ± 0.03 versus FFW: -0.07 ± 0.04 , $p < 0.001$).

A guard position is also characterized by the hands being more anterior. We found that children with CP held their arms

Fig. 2 – Comparison of vertical positions of the hand: (A) averaged for side of the body and walking condition of TD children (empty bars), biCP children (diagonally striped bars) and uniCP children (black bars). (B) averaged for walking condition; most affected (or non dominant) side of the body (MA: black bars) and the least affected (or dominant) side of the body (LA: empty bars) for the three groups (TD, biCP and uniCP). (C) averaged over the two sides of the body; FW condition (empty bars) and FFW condition (striped bars) for the three groups (TD, biCP and uniCP). (D) plotted separately for the most affected (or non dominant) (MA) and the least affected (or dominant) side of the body (LA), in the FW condition (empty bars) and FFW condition (striped bars) for the three groups (TD, biCP and uniCP). Bars: Mean. Whiskers: SD. Horizontal lines: statistically significant differences (Tukey's post hoc). Note that the zero position is defined as the height of L5.

more in front of their body during walking compared to TD children (Fig. 3A; group: $p = 0.002$; TD: 0.10 ± 0.03 versus biCP: 0.15 ± 0.04 , $p < 0.001$; uniCP: 0.13 ± 0.04 , $p = 0.021$). The increase in walking speed had no significant effect on the horizontal hand position.

A more anterior position of the hand can be due to the upper arm being held in front or behind the vertical axis. Hence it was needed to measure upper arm elevation angles in the sagittal plane (a positive angle meaning that upper arm was rotated anteriorly). As seen in Fig. 3B both TD and CP children rotated their upper arm on average posteriorly with respect to the vertical. However TD children held their arms less backwards (arm angle closer to the vertical) compared to children with CP (Group: $p = 0.001$; TD: $-9.23^\circ \pm 6.94$ versus biCP: $-21.33^\circ \pm 10.88$, $p < 0.001$; uniCP: $-15.82^\circ \pm 6.85$, $p = 0.032$). Furthermore, the arm angle on the non dominant side of TD children was significantly closer to the vertical compared to the MA side of children with CP. This was revealed by an interaction effect of side $\times$ group ($p = 0.033$; TD: $-8.032^\circ \pm 7.702$ versus biCP: $-22.74^\circ \pm 8.56$, $p < 0.001$; uniCP: $-17.40^\circ \pm 7.36$, $p = 0.017$). The arm angle on the dominant (LA) side was also closer to the vertical for TD children compared to biCP children ($-10.43^\circ \pm 6.18$ versus $-19.91^\circ \pm 13.19$, $p = 0.005$).

Fig. 3 – Comparison of (A) the horizontal position of the hand and (B) the upper arm angle of TD (empty bars), biCP (diagonally striped bars) and uniCP children (black bars); averaged for side of the body and walking condition. Bars: Mean. Whiskers: SD. Horizontal lines: statistically significant differences (Tukey's post hoc).

3.2. Is an altered arm position related to instability of walking?

Since it was hypothesized that gait instability, as assessed by step width, could be the basis for the altered arm posture, we investigated the correlations of step width with the measures of arm posture. We also compared the correlations of the difference in step width and the difference in arm posture between the two walking speed conditions.

A positive correlation was found between step width and the horizontal hand position on the LA arm for both walking speed conditions in the total group of CP but not in the TD children (Fig. 4).

It can also be seen in Fig. 4 that the correlation between horizontal hand position and step width was stronger as speed increased (FW: $r = 0.391$, $p = 0.048$; FFW: $r = 0.467$, $p = 0.019$). To check whether individuals who change step width from FW to FFW also alter their arm posture, we examined the correlations between the difference in step width and the difference in measures of arm posture between the two walking conditions for each individual. A positive correlation between the difference in step width and the difference in horizontal hand position between the two walking speed conditions was found for both the MA and LA side of the body in the total group of CP (MA: $r = 0.436$, $p = 0.03$; LA: $r = 0.388$, $p = 0.05$, not illustrated).

For the other arm position measures (vertical hand position and upper arm elevation angle) no significant correlations were found with step width. Correlations were also determined in the subgroups of CP. Some trends were observed, however statistical significance was not reached.

4. Discussion

Since children with CP show reduced stability and they present with altered arm postures while walking, we investigated whether these arm postures are related to the less stable gait as was seen in newly walking toddlers.

From the current results it is clear that children with CP exhibit an altered arm position during walking compared to TD children. Children with CP hold their hands more in front of their body and in elevation compared to the TD children. Additionally, they hold their upper arms more backwardly rotated than TD children, while their hands are positioned more to the front. This can only be achieved when the elbow is more flexed. Our findings indicate that both groups of children with CP keep their elbows flexed during walking, especially in their most affected arm. This is consistent with previous literature on the degree of elbow flexion during walking in children with unilateral CP.¹⁹ An additional finding was that children with bilateral CP also show this flexed position on the least affected side. Romkes and colleagues¹⁸ found similar results in their study that evaluated the upper body movements during gait in children with bilateral CP. They indicated that these children have more shoulder abduction and elbow flexion compared to TD children. These postures of the arm closely resemble the description of the guard positions that toddlers exhibit during the first weeks of walking by Ledebt.⁷ Ledebt distinguished a high, middle and low guard position

Fig. 4 – Scatter plots with Pearson correlation information of the step width and the average horizontal position of the hand on the least affected side for CP (left) and TD children (right) for both walking conditions (FW: preferred speed; FFW: “as fast as possible” walking speed condition).

before children actually move their arms. Toddlers with a high and middle guard position hold the elbows in a flexed position and their hands are positioned higher compared to the reciprocal arm swing. Thus, children with CP exhibit arm postures that are more similar to toddlers compared to the arm postures of their peers.

The two previous studies on arm posture in CP focused mainly on the description of the arm posture, but the possible basis for these postures were not investigated. One way to get some information on this issue is to study the relation to stability. In toddlers the arm posture is thought to be involved in balance control at the onset of independent walking.⁷ Ledebt suggested this because she found a strong correlation between the decrease of step width and the decrease of high and middle guard posture of the arms.⁷ Later Kubo and Ulrich confirmed that the high guard position of the arm in toddlers was a way to accomplish maintaining their upright position and forward progression.⁸ If the currently evaluated children with CP used their altered arm posture for the same purpose as toddlers, one would also expect a correlation between less stable gait and hand position. To answer this question we investigated whether the step width correlated with any of the measures of the hand position. It was found that step width correlated with the horizontal hand position of the least affected side. This means that in the CP group, larger step widths coincided with hand positions of the least affected side that are more forward. Additionally, the difference in step width between the two walking conditions positively correlated with the difference in horizontal hand position for each side. This signifies that the individuals with CP who increased their step width when walking faster also presented a more forward position of the hand on the least and most affected side of the body. These correlation results indicate that children with CP indeed show this ‘guard’ posture strategy as

a compensation for instability of walking, and they mostly use the least affected side for this compensation.

Although the present study shows that instability is probably the main cause of the altered postures, one should not overlook two alternative possibilities, namely spasticity or contractures and the so-called “associated reactions”. First, one has to consider that spasticity could underlie these changed arm postures in CP, especially on the most affected side because CP children often hold the arm in an altered position even in a stable standing position.²² If spasticity played a role in the present results, one would expect the position of the hand to be especially high on the most affected side. This asymmetry in arm posture is exactly what was found in children with unilateral CP. Therefore, the altered arm posture on the most affected side in children with unilateral CP was likely caused by spasticity. It is clear though that spasticity is not able to account for all results. Indeed in children with bilateral CP (diplegia) one would expect no (or very mild) spasticity in the arm muscles, yet they also clearly showed modified arm positions.

A second alternative factor to be considered is the presence of associated reactions. These are involuntary changes in muscle tone²³ (which may result in a movement) that arise from excessive effort needed for a voluntary movement²⁴ or from an involuntary reaction such as sneezing or yawning.²⁵ Recently, associated reactions have been mostly described in the affected arm (in adults with hemiplegia).²⁶ In the 1920s, however, associated reactions have been documented for the non-paretic side as well,²⁷ likely because the non-paretic side might actually also be affected, but to a lesser extent, and therefore changes to muscle tone can be present in this less affected side. Additionally, unintended, symmetrical irradiations of motor activity to the contralateral side (or mirror movements) during a unimanual motor performance are

found in young TD children, and to a much larger extent in children with unilateral CP.²⁸ In the CP group, these mirror movements were more prominent in the non-hemiplegic hand. Furthermore, Bobath described that associated reactions occur also in persons with bilateral CP when a lot of effort is required to overcome the resistance of the spastic muscles, for instance when trying to walk.²⁴ Although, in recent years not much attention has been paid to these reactions, but this does not mean that they should be overlooked. Moreover, the current results indicated that speed clearly increased the abnormalities in posture, which is in line with an explanation in terms of associated reactions, being sensitive to increased motor demands.

The current findings on the arm posture during gait need to be seen in the broader context of these arm movements during gait. Humans start their locomotor behavior as quadrupeds (crawling) and are then faced with the difficult task of balancing on the two legs only.²⁹ The current postural position of the arms can be seen as a transition phase in which the arms play an important role as stabilizers.⁷ Since the stabilization is even more of a problem in children with CP,¹⁴ it is argued that the stabilizing role of the arms is used for a prolonged period.

Despite the contribution of some alternative explanations, the altered arm position in children with CP seems to be primarily part of a compensation strategy to increase stability during walking, especially when considering the least affected side. These findings are comparable to those seen in newly walking toddlers, with the difference that in children with CP additionally abnormal muscle tone adds to the altered arm posture. Since holding the arms in a guard-like position is a compensation for instability, these abnormal arm postures should not be considered as mere symptoms of their affliction. However, they should be recognized as an adaptive strategy to beneficially influence balance during forward progression, and therefore it may be better not to discourage or unlearn them during gait rehabilitation (as is often the case in robotic-assisted treadmill training).³⁰ When balance during walking improves, arm guard positions are expected to decrease.

Finally, when interpreting the results one should take into account some limitations. Most of the evaluated children with CP had a GMFCS level 1, therefore the CP group is quite mildly affected. Hence the present results may underestimate the effects seen in a more general population of CP. In the current study the radiographic tools (MRI images) were used only for the diagnosis and the allocation of the participant to one of the groups, for future studies it would be of interest to have a more precise description of the anatomical lesions in the CP brain (for example using DTI) to be able to explore the relation between brain pathology and arm posture, and stability. In this study the posture of the arms was determined as the average vertical and horizontal hand position over the gait cycle in the sagittal plane. This was based upon the description of the 'guard' positions used by toddlers. Arm movements are often described in terms of joint angles. However, at present we opted for a simplified kinematics approach, which could provide sufficient information about the arm posture during walking. Clear significant correlations were only found between step width and one of the calculated parameters of arm posture, however, this parameter, namely horizontal hand position, is regarded a very representative measure of

'guard' position. It is proposed that these simplified techniques, as used in the present study, were sufficient to show that the altered arm posture in children with CP is related to balance control during walking.

Declaration of conflicting interests

The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Acknowledgments

This project was supported by a grant from 'bijzonder onderzoeksfonds' KU Leuven (OT/08/034). LVG received a PhD fellowship of the Research Foundation Flanders (FWO). FM was supported by an F+ fellowship from KU Leuven, a Post-doctoral fellowship of the Research Foundation – Flanders (FWO) and a scientific prize of the Foundation Van Goethem-Brichant. JD was also supported by FWO (grant G.0901.11). We thank the physical therapists of the Laboratory of Clinical Movement Analysis of the University Hospital Leuven (U.Z. Leuven) for their aid and experience during the measurements.

REFERENCES

1. Wannier T, Bastiaanse C, Colombo G, Dietz V. Arm to leg coordination in humans during walking, creeping and swimming activities. *Exp Brain Res* 2001;**141**:375–9.
2. Dietz V. Do human bipeds use quadrupedal coordination? *Trends Neurosci* 2002;**25**:462–7.
3. Zehr EP, Duysens J. Regulation of arm and leg movement during human locomotion. *Neuroscientist* 2004;**10**:347–61.
4. Pang MYC, Yang JF. Interlimb co-ordination in human infant stepping. *J Physiol* 2001;**533**:617–25.
5. Sutherland DH, Olshen R, Cooper L, Woo SLY. The development of mature gait. *J Bone Jt Surg Am* 1980;**62**:336–53.
6. Statham L, Murray MP. Early walking patterns of normal children. *Clin Orthop Relat Res* 1971;**79**:8–24.
7. Ledebt A. Changes in arm posture during the early acquisition of walking. *Infant Behav Dev* 2000;**23**:79–89.
8. Kubo M, Ulrich B. A biomechanical analysis of the 'high guard' position of arms during walking in toddlers. *Infant Behav Dev* 2006;**29**:509–17.
9. Cappellini G, Ivanenko YP, Dominici N, Poppele RE, Lacquaniti F. Motor patterns during walking on a slippery walkway. *J Neurophysiol* 2010;**103**:746–60.
10. Elftman H. The function of the arms in walking. *Hum Biol* 1939;**11**:529–35.
11. Park J. Synthesis of natural arm swing motion in human bipedal walking. *J Biomech* 2008;**41**:1417–26.
12. Ortega JD, Fehlmann LA, Farley CT. Effects of aging and arm swing on the metabolic cost of stability in human walking. *J Biomech* 2008;**41**:3303–8.
13. Dabney KW, Lipton GE, Miller F. Cerebral palsy. *Curr Opin Pediatr* 1997;**9**:81–8.
14. Woollacott MH, Shumway-Cook A. Postural dysfunction during standing and walking in children with cerebral palsy: what are the underlying problems and what new therapies might improve balance? *Neural Plast* 2005;**12**:211–9.

15. Van den Broeck C, De Cat J, Molenaers G, Franki I, Himpens E, Severijns D, et al. The effect of individually defined physiotherapy in children with cerebral palsy (CP). *Eur J Paediatr Neurol* 2010;14:519–25.
16. Meyns P, Van Gestel L, Massaad F, Desloovere K, Molenaers G, Duysens J. Arm swing during walking at different speeds in children with cerebral palsy and typically developing children. *Res Dev Disabil* 2011;32:1957–64.
17. Bruijn SM, Meyns P, Jonkers I, Kaat D, Duysens J. Control of angular momentum during walking in children with cerebral palsy. *Res Dev Disabil* 2011;32:2860–6.
18. Romkes J, Peeters W, Oosterom AM, Molenaar S, Bakels I, Brunner R. Evaluating upper body movements during gait in healthy children and children with diplegic cerebral palsy. *J Pediatr Orthop B* 2007;16:175–80.
19. Riad J, Coleman S, Miller F. Arm posturing during walking in children with spastic hemiplegic cerebral palsy. *J Pediatr Orthop* 2007;27:137–41.
20. Woltring HJ. A FORTRAN package for generalized, cross-validatory spline smoothing and differentiation. *Adv Eng Softw* 1986;8:104–13.
21. Hof AL. Scaling gait data to body size. *Gait Posture* 1996;4:222–3.
22. Chin TYP, Duncan JA, Johnstone BR, Graham HK. Management of the upper limb in cerebral palsy. *J Pediatr Orthop B* 2005;14:389–404.
23. Walshe FMR. On certain tonic or postural reflexes in hemiplegia, with special reference to the so-called 'associated movements'. *Brain* 1923;46:1–37.
24. Bobath B. *Abnormal postural reflex activity caused by brain lesions*. Rockville: Md: Aspen Publishers Inc; 1985.
25. Mulley G. Associated reactions in the hemiplegic arm. *Scand J Rehabil Med* 1982;14:117–20.
26. Macfarlane A, Turner-Stokes L, De SL. The associated reaction rating scale: a clinical tool to measure associated reactions in the hemiplegic upper limb. *Clin Rehabil* 2002;16:726–35.
27. Riddoch G, Buzzard F. Reflex movements and postural reactions in quadriplegia and hemiplegia, with especial reference to those of the upper limb. *Brain* 1921;44:397–489.
28. Kuhtz-Buschbeck JP, Sundholm LK, Eliasson AC, Forssberg H. Quantitative assessment of mirror movements in children and adolescents with hemiplegic cerebral palsy. *Dev Med Child Neurol* 2000;42:728–36.
29. Adolph KE, Berger SE. Motor development. In: Kuhn D, Siegler RS, editors. *Handbook of child psychology. Cognition, perception, and language*. 6th ed., vol. 2. New York: Wiley; 2006. p. 161–213.
30. Borggraefe I, Schaefer JS, Klaiber M, Dabrowski E, Ammann-Reiffer C, Knecht B, et al. Robotic-assisted treadmill therapy improves walking and standing performance in children and adolescents with cerebral palsy. *Eur J Paediatr Neurol* 2010;14:519–25.