Kinematic analysis of upper limb during walking in diplegic children with Cerebral Palsy

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1. Introduction

Most clinical studies using quantitative analysis of walking (Gait Analysis-GA) generally focus on lower limb strategy and tend to ignore arm swing, head and trunk movement during deambulation, assuming that this unit moves as one mass. However, the first studies on gait also included detailed descriptions of arm movement during gait and some authors concluded that the arm swing during gait is not passive and driven by muscle activity.[1–4] Later studies, however, reasoned that active shoulder torques are only small, and suggested that arm swinging may be largely passive.[5,6] At the moment, however, there is consensus on the role of arm swing to reduce energetic cost during walking as much as 8%, to maintain balance (to avoid falls and postural problems), to reduce the mechanical loads on tissue (to avoid pain) and energy efficacy to improve endurance.[7,8] In addition, the efficacy of body movement in normal walking depends on upper limb swing.[9]

Several pathologies, such as for example stroke, Parkinson's disease, Cerebral Palsy and spinal cord injury, may lead to various abnormalities in arm movements during walking. It

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Table 1 – Upper limb kinematic parameters and descriptors (IC: Initial Contact).

Parameters	Description
IC T Tilt	The value of trunk angle respect to the lab reference system on the sagittal plane (Trunk Tilt plot) at IC
ROM T Tilt	The range of motion of trunk angle respect to the lab reference system on the sagittal plane (Trunk Tilt plot) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
IC T Obl	The value of trunk angle respect to the lab reference system on the frontal plane (Trunk Obliquity plot) at IC
ROM T Obl	The range of motion of trunk angle respect to the lab reference system on the frontal plane (Trunk Obliquity plot) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
IC T Rot	The value of trunk angle respect to the lab reference system on the transversal plane (Trunk Rotation plot) at IC
ROM T Rot	The range of motion of trunk angle respect to the lab reference system on the transversal plane (Trunk Rotation plot) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
IC S Fl–Ex	The value of shoulder angle on the sagittal plane (Shoulder Flex–Extension plot) at IC
ROM S Fl–Ex	The range of motion at shoulder on the sagittal plane (Shoulder Flex–Extension plot) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
IC S Ab–Ad	The value of shoulder angle on the frontal plane (Shoulder Abd–Adduction plot) at IC
ROM S Ab–Ad	The range of motion at shoulder on the frontal plane (Shoulder Abd–Adduction plot) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
IC S Rot	The value of shoulder angle on the transversal plane (Shoulder Rotation plot) at IC
ROM S Rot	The range of motion at shoulder on the transversal plane (Shoulder Rotation plot) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
IC E Fl–Ex	The value of elbow angle on the sagittal plane (Elbow Flex–Extension plot at IC)
ROM E Fl–Ex	The range of motion at elbow on the sagittal plane (Elbow Flex–Extension plot) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot

may therefore be expected that pathological gait is energetically more demanding not only because of the pathology with the altered function of the leg but also because of affected arm movements. Patients with Cerebral Palsy (CP) are known to experience weakness, motor control abnormalities and spasticity in the muscles of the involved arms.[10] For this condition, it was found that the arm swing amplitude of the non-hemiplegic arm exceeds that of healthy control[11,12] and diplegic children with good motor control of both arms show altered arm movements and greater variability.[13]

For rehabilitation the evidence emerges that upper and lower limb movements influence each other during locomotor-like tasks. The use of arm movements during gait seems to have a potential beneficial influence on gait rehabilitation and for several pathological states including CP.[14,15] In CP, it has been suggested in fact that normalizing interlimb coordination could improve gait pattern[14] leading to a normalization of the angular momentum.[16]

It may seem strange that there is only a limited body of work assessing arm movements during pathological gait and evaluating the potential role of arm swing in gait rehabilitation. To our knowledge, only few papers[13,11,16,17,18] evaluated quantitatively the upper body movements during gait in children with CP, and in particular only Romkes et al.[13] and Meyns et al.[14] conducted their analysis in diplegic children. In particular, both Romkes et al.[13] and Meyns et al.[11,14] evaluated upper body kinematics of arms in diplegic children using a full-body marker set (34 markers), founding important movements for compensation by the upper limbs in order to control balance[13] and to increase walking speed[11] and altered coordination.[14] Accordingly, the literature on upper limb movement during walking in diplegic children is scarce.

Recently, literature[12] proposed an experimental set-up which allows the simultaneous assessment of upper and lower limb motion during GA using a lower number of markers compared to previous researches[11,13,14,17,19] (28 markers versus 34 markers) and showed its easy appropriateness especially for the clinical application in difficult cases and in small children for the low number of additional markers.

Therefore, the aim of this study is to quantify movement of the upper limb during walking in children with diplegic CP using the proposed simplified marker set-up and to compare the obtained results with literature.

2. Materials and methods

2.1. Participants

16 children with diplegic CP participated in this study (CP group; age: $M = 11.3$ years, $SD = 3.1$ years; weight: $M = 38.5$ kg, $SD = 13.2$ kg; height: $M = 1.42$ m, $SD = 0.18$ m). All participants were community ambulators without assistive devices such as walkers or crutches. They had no history of functional upper or lower limb surgeries and of pharmacological treatments for at least one year before data collection.

A control group of 20 non-affected subjects (CG: Control group; age: $M = 9.2$ years, $SD = 5.7$ years; weight: $M = 33.5$ kg, $SD = 9.4$ kg; height: $M = 1.35$ m, $SD = 0.07$ m) was included. Selection criteria for the CG included no prior history of cardiovascular, neurological, or musculoskeletal disorders. They exhibited normal range of motion and muscle strength, and had no apparent postural or motor deficits.

Table 2 – Lower limb parameters and descriptors.

Gait parameter	Description
Spatio-temporal parameters	
Velocity (m/s)	Mean velocity of progression
Cadence (step/min)	Number of step for
% stance (%gait cycle)	% of gait cycle that begins with initial contact and ends at toe-off of the same limb;
Step length	Longitudinal distance from one foot strike to the next one, normalized to subject's height
Step width (mm)	Medio-lateral distance between the two foot during double support
Kinematics (degrees)	
ROM Pelvic Tilt	The range of motion at pelvic joint on the sagittal plane (Pelvic Tilt graph) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot;
ROM Pelvic Obliquity	The range of motion at pelvic joint on the frontal plane (Pelvic Obliquity graph) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
ROM Pelvic Rotation	The range of motion at pelvic joint on the transversal plane (Pelvic Rotation graph) during the gait cycle, calculated as the difference between the maximum and minimum values of the plot
HIC	Value of Hip Flexion–Extension angle (hip position on sagittal plane) at initial contact, representing the position of hip joint at the beginning of gait cycle;
HmSt	Minimum of hip flexion (hip position on sagittal plane) in stance phase, representing the extension ability of hip during this phase of gait cycle
Mean Hip Rotation	Mean value of Hip Rotation angle (hip position on transversal plane) during all the gait cycle
KIC	Value of Knee Flexion–Extension angle (knee position on sagittal plane) at initial contact, representing the position of knee joint at the beginning of gait cycle
KmSt	Minimum of knee flexion (knee position on sagittal plane) in mid-stance, representing the extension ability of knee during this phase of gait cycle
KMSw	Peak of knee flexion (knee position on sagittal plane) in swing phase, representing the flexion ability of knee joint during this phase of gait cycle
AIC	Value of the ankle joint angle (on sagittal plane) at the initial contact, representing the position of knee joint at the beginning of gait cycle
AMSt	Peak of ankle dorsiflexion (on sagittal plane) during stance phase, representing the dorsiflexion ability of ankle joint during this phase of gait cycle
AmSt	Minimum value of the ankle joint angle (on sagittal plane) in stance phase, representing the plantarflexion ability of ankle joint at toe-off
AMSw	Peak of ankle dorsiflexion (on sagittal plane) during swing phase, representing the dorsiflexion ability of ankle joint in this phase of gait cycle
Mean Foot Progression	Mean value of Foot Progression (foot position on the transversal plane) during all the gait cycle
Kinetics (W/Kg)	
APMax	The maximum value of generated ankle power during terminal stance (maximum value of positive ankle power during terminal stance) representing the push-off ability of the foot during walking
APmin	Minimum value of absorbed ankle power in early stance and mid-stance, when muscle is contracting eccentrically and absorbing energy (minimum value of negative ankle power)

All subjects were volunteers and their parents gave their written consent to the children's participation in this research, in accordance with the local ethical committee requirements.

2.2. *Experimental set-up*

The complete evaluation consisted of video-recording and 3D gait analysis (GA). GA was conducted using an optoelectronic system with passive markers (ELITE2002, BTS, Milan, Italy) with a sampling rate of 100 Hz, 2 force platforms (Kistler AG, Winterthur, Switzerland), and a 2-TV camera Video system (BTS, Milan, Italy) synchronized with the optoelectronic system and the force platforms.

After collection of the anthropometric data (arm and forearm length, wrist and elbow diameters, height, weight, tibial length, distance between the femoral condyles for the diameter of the knee, distance between the malleoli for the diameter of the ankle, distance between the anterior iliac spines) passive markers were placed at specific points of reference on the subject's skin. The markers were positioned according to literature[12] and represented both the lower limb (pelvis, thigh, shank, foot, and trunk) and the upper limbs (upper arm and forearm) segments.

Each subject was asked to walk barefoot at his or her self-selected speed along a 10 m walkway containing two force platforms. All acquisitions were done by the same experienced operator, thus ensuring reproducibility of acquisition technique and avoiding errors due to different operators.

2.3. *Data analysis*

All graphs were normalized as percentage of gait cycle. Graphs for the upper limb were normalized as percentage of gait cycle of the ipsilateral lower limb according to the literature.[20] For upper limb kinematic computation the SMARTanalyser software (version: 1.10.375.0; BTS, Italy) was used.

Some parameters were identified and computed from upper limb graphs for each individual and for each side[12,13,18]: the angle value at initial contact and the Range of Motion (ROM) during the gait cycle of trunk and shoulder (sagittal, frontal and transversal planes) and elbow (sagittal plane) (Table 1).

Lower limb kinematics and kinetics were also acquired but the results were not presented in this study (Table 2).

2.4. *Statistical analysis*

All the previously defined parameters were computed bilaterally for each participant and the mean and standard deviation values of all indexes were calculated for each group (CP group and CG).

Kolmogorov–Smirnov tests were used to verify if the parameters were normally distributed; the parameters were not normally distributed, so we used Wilcoxon signed rank test for comparing data of the right and the left side and the Mann–Whitney *U*-test for comparing CP group and CG (both in terms of anthropometric and biomechanical data). A statistically significant difference was accepted as $p < 0.05$.

3. Results

Anthropometric data (age, body weight and height) were not significantly different ($p > 0.05$) between the CP and CG groups. All upper limb parameters were compared initially right to left side. As no statistical difference was seen, the data from both sides were pooled (Table 3).

Table 3 – Comparison of selected upper limb kinematic parameters in PC group and in CG.

	CP group	CG
Trunk (°)		
IC T Tilt (+=posterior tilt)	−11.62 (3.53)	−8.21 (3.49)
ROM T Tilt	4.94 (2.56)*	2.27 (1.98)
IC T Obl (+=contralateral)	−2.62 (5.19)	−0.92 (2.17)
ROM T Obl	7.92 (7.10)*	3.18 (2.99)
IC T Rot (+=ext. rotation)	−2.38 (5.76)	−1.19 (3.98)
ROM T Rot	12.99 (4.32)*	5.94 (3.95)
Shoulder (°)		
IC S Fl–Ex (+=flexion)	−15.27 (14.99)	−21.58 (5.86)
ROM S Fl–Ex	21.54 (12.11)	23.15 (9.36)
IC S Ab–Ad (+=abduction)	12.81 (5.84)*	3.72 (5.55)
ROM S Ab–Ad	16.57 (12.05)	15.34 (4.70)
IC S Rot (+=int rotatio)	−8.02 (10.34)	−0.95 (9.01)
ROM S Rot	19.07 (7.98)	12.45 (7.91)
Elbow (°)		
IC E Fl–Ex (+flexion)	36.81 (11.91)*	27.97 (8.23)
ROM E Fl–Ex	24.02 (8.87)	30.52 (11.34)

Values are expressed in mean (standard deviation). CP group. Cerebral Palsy group; CG: Control Group. * = $p < 0.05$, CP group versus CG.

As concerns the trunk strategy, the diplegic patients showed a significant greater ROM in all planes then control group ($p < 0.05$). No statistical differences were found at initial contact ($p > 0.05$).

The shoulder of the CP group at initial contact showed a normal position in the sagittal and transversal plane ($p > 0.05$). However, the shoulder was more abducted ($p < 0.05$) at this time compared to the CG. Shoulder ROMs, however, did not differ from CG in all the three planes ($p > 0.05$).

Children with CP flexed the elbow at initial contact associated with a physiological motion during the entire gait cycle compared to the CG ($p > 0.05$). It was evident that the standard deviations for some angles were rather large indicating great differences between participants for these angles.

4. Discussion

Arm movements during gait seem to have two major aims: 1st they are used for balance control (especially visible in balancing acts),[19] and 2nd to optimise energy consumption.[7–9] CP gait is more unstable and requires more energy. Indeed CP may lead to various abnormalities also in arm movements during walking. It may therefore be expected that pathological gait is energetically more demanding for this reason as well, not only because of the pathology. It has been reported that preventing arm swing during gait does change the gait pattern in healthy adults, in particular with respect to the interlimb coordination and cadence.[21] In CP Meyns et al.[19] found in fact that children appear to rely on guard arm postures as a compensation strategy to maintain balance during walking similar to the newly walking toddlers' strategy. The comprehensive assessment of lower and upper limb biomechanics during walking could be of great clinical interest, especially when difficult and complex gait disorders in young subjects and subjects with musculoskeletal disabilities are analysed. It offers more compound understanding of compensatory mechanisms in these pathological gait patterns, in particular considering the specific arm movements. Few researches were generally conducted using full marker set. As recently the literature[12] proposed an experimental set-up which allows the simultaneous assessment of upper and lower limb motion during GA using a lower number of markers compared to previous studies,[11,13,14,17,19] the aim of this research was the quantification of upper limb movement during gait in children with diplegic CP using a simplified marker set-up conducting a comparison with literature.

Our results showed that diplegic patients walked with increased ROM of the thorax in all three planes and the shoulder at initial contact more abducted compared to the CG; the range of motion of the shoulder joint, however, was not significantly different from the healthy individuals. The elbow was held more flexed throughout the entire gait cycle with physiological motion. The abnormal arm position which was found in diplegic children could be considered a compensation strategy to increase stability during gait similar to that observed in the newly walking toddlers.[19] However, as affirmed by the same authors, in the diplegic children the altered arm posture is additionally altered by the presence of spasticity.

In addition, it has previously been reported that the increased elbow flexion present in the early childhood spontaneously normalizes with age in hemiplegic children. The patients suffer from locomotor retardation, and the more the development gets to maturity, the more the elbow position becomes normal. This interpretation in combination with the discouraging results of surgical tendon lengthening has prompted the recommendation to follow the natural history and not intervene in young age groups.[17] From our data the position of elbow at initial contact revealed more flexion but at a very large standard deviation: it could mean that there are some patients who remain retarded in spite of maturation, and our results indicate that these individuals might be identified at an early stage. This could be a helpful parameter for deciding on timing of surgery.

Our results are generally in agreement with literature.[13,19] So, even if the used experimental set-up is extremely simplified, our data are consistent with values of the previous researchers, which were obtained using a more complex experimental set-up. However, we remark that if the simplification with few markers of this experimental set-up could be seen an advantage for the clinical application in difficult cases and in small children, for more accurate and specific analyses of spinal function a more complex marker set should be used.

The experimental set-up used in this research revealed to be easy to use in our patients and we showed that measuring not only lower limb but also upper limb movement during gait does not take much more time than just legs and important insights may be gained.

Further studies will be necessary with the integration of EMG analysis in terms of timing and action of muscles. Understanding the activity of the muscle as well as the other forces acting on a moving body is critical to understand the root causes of the movement. As free arm swing leads to reduced peak muscle activation at the trunk in comparison to restricted arm swing,[22] the integration of our results with kinetics and EMG signals could be the object of further studies, in healthy but also in pathological individuals. This type of analysis could be in fact innovative since literature on this matter is currently lacking. In addition, the research of a correlation between upper and lower limb parameters during gait could be conducted; more variety in the lower limb pattern may be also combined with more variety at the arms, which would emphasise that the arms have a crucial role for balance control. Then, the improvement of leg function in gait may also improve arm swing.[23] In this study AFOs provided stability and thus reduces the need for balance control. However, the improvement was only found by visual analysis due to the lack of an upper limb marker set. An adequate assessment of arm movement during gait in these children may be crucial to better quantify the functional limitation and to measure treatment efficacy of gait including the movement of the affected arm.

A limitation of this study is related to the different walking speed of the two evaluated groups (0.84 ± 0.18 m/s versus 1.29 ± 0.21 m/s; $p < 0.05$). The diplegic patient in fact walked slower than healthy children and this could influence the upper limb motion. However, as in this research we aimed to quantify movement of the upper limb during walking in children with diplegic CP using a simplified marker set-up and to compare the obtained results with literature, which did not take in consideration this element, we did not conducted any corrections of the upper limb data according to the walking speed. Further research should be conducted in order to evaluate if different velocity could have some effects on the arm strategy during walking.

Competing interest

All authors do not have any conflicts of interest and any financial interest. All authors attest and affirm that the material within has not been and will not be submitted for publication elsewhere.

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