Effect of robotic-assisted gait rehabilitation on dynamic equilibrium control in the gait of children with cerebral palsy

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Abstract:

Due to the intensity and repetition of movement, robotic-assisted gait training therapy could have a beneficial effect on the recovery and improvement of postural and locomotor functions of the patient. This study sought to highlight the effects of robotic-assisted gait rehabilitation in gait of children with Cerebral Palsy (CP). We analyzed the different strategies before and after this rehabilitation which was used in order to generate forward motion while maintaining balance. Data were collected by a motion analysis system (Vicon® - Oxford Metrics, Oxford, UK). The children were divided into two groups in such a way as to obtain a randomized controlled population: i) a group of fourteen children (Treated Group) underwent 20 sessions of robotic-assisted gait training therapy using the driven gait orthosis Lokomat®Pediatric (Hocoma AG, Volketswil, Switzerland) compared to ii) a group of sixteen children without sessions of Lokomat®Pediatric (Control Group). Significant differences are observed for the TG between the pre- and post-test values of the locomotor parameters and of the kinetic data of the propulsive forces of the Center of Mass (COM) and of the Center of Pressure (COP) dynamic trajectory. This first study, although performed on a limited number of patients, shows the usefulness of this robotic gait rehabilitation mainly in the balance control in gait. Indeed after this rehabilitation, these children improve their gait that is especially characterized by a more appropriate time lag between the time instant of COM-COP trajectory divergence and the time instant when the forward propulsive forces became apparent.

Keywords: Cerebral palsy; Clinical gait analysis; Robotic rehabilitation; Dynamic equilibrium control; Kinetics.

1. Introduction

Walking may be defined as the forward displacement of the body requiring coordination between alternate successions of the swing phase and the stance phase. Consequently, walking can be summarized as the aptitude to produce and control propulsive forces through these alternating successions of double-support and single-support phases in order to move the body forward. To achieve this, it is necessary to create a distance between the Center Of Mass (COM) and the Center Of Pressure (COP) along the anteroposterior axis. The study of the distance between the COM and the COP trajectories provides information on the strategies used to control dynamic equilibrium and helps to explain the generation of the propulsive forces needed to walk [1-4]. This relationship between COM and COP constitutes a reliable indicator of strategies developed for children with typical development (TD) and cerebral palsy (CP) [4-6].

CP gait is generally characterized by a set of persistent movement and posture disorders [7]. This gait results in substantial postural instability and stiffness of the whole body, particularly of the upper part [8-12]. Indeed, they must control the disequilibrium generated by the decoupling between the projection of the COM and the COP during walking [6], which requires more energy than in TD children of the same age [13-15]. Therefore, the acquisition of new locomotor capacities represents one of the primary care objectives of these children.

In recent years, robot-assisted gait training (RAGT), such as the Lokomat® (Hocoma AG, Volketswil, Switzerland) was introduced in pediatric rehabilitation. These systems of rehabilitation assisted by robotics are based on sensorimotor learning principles, and are increasingly proposed as treatment modality for patients with locomotor disorders. Based on the body weight supported treadmill training principle, their main purpose consists of reacquiring functional gait through an intensive and repetitive simulation of the different phases of gait and sensory stimulation through visual and auditive feedbacks from different serious games (intensive task specific training) [16-21].

Research that has been carried out in children with CP [22-30] shows general improvement of locomotor parameter values (mainly speed gait, frequency and stride length), endurance (6 min walking test) and of the performance of functional tasks (dimensions D and E of the Gross Motor Function Measure [31]). But, to the best of our knowledge, only one study [30] concluded that spatio-temporal parameters and kinematics, gait symmetry, Gait Gillette Index and COP data do not show statistical significant variations due to the robotic treatment. However, the authors specify that the lack of statistical significant improvement in clinical evaluation may be explained by the high number of children classified with Gross Motor Function Classification System (GMFCS) [32] level III and IV. Children were classified as moderately severe to severely involved, characterized by mobility that requires technical walking aids such as the walker, the manual wheelchair or motorized wheelchair.

The aim of this study was to highlight the effect of robotic-assisted gait rehabilitation on dynamic equilibrium control in the gait of children with CP, and more specifically on different strategies used in order to propel themselves forward while maintaining their balance. We make the assumption that robotic-assisted gait rehabilitation presents beneficial effects on recovery and improvement of postural and locomotor functions of the patient. These improvements result in a reorganization of gait pattern, which become less jerky. This translates to a decrease in braking upon heel strike increasing especially the displacement mean speed.

2. Methods

2.1. Participants

Gait analysis data was obtained from 30 children aged 8-10 years. These children were recruited from the Unit of Clinical Movement Analysis of the Health Center – Rossetti Institute (PEP06). Inclusion criteria were: children with bilateral spastic with a jump knee gait pattern; being able to independently walk without or with assistance (*e.g.* walking stick) on at least 60 m; classified as GMFCS level II. At this level, the severity of motor impairment is moderate. Children may experience difficulty walking and balancing on uneven terrain and inclines and they may require physical assistance when walking over long distances. The jump knee gait pattern [33] is defined as a knee bending disorder at the time of foot contact with the ground. The foot is in plantar flexion with a tibial-tarsal angle always greater than 90°, especially at the end of support. Hips and knees are in excessive flexion at the end of swing phase flexion and during the beginning of the stance phase. Finally, in order to observe the actual effects of this rehabilitation, none of the participants had undergone surgical treatment nor received injections of botulinum toxin at the latest one year before the intervention period. Randomization and allocation into the two groups were made by drawing lots, limiting the selection biases.

The children were divided into two groups to obtain a randomized controlled population: i) Treated Group (TG) including 14 children (8 boys and 6 girls, mean ± SD age 8.3 ± 1.2 years) receiving only twenty sessions of Lokomat®Pediatric ii) Control Group (CG) including 16 children (7 boys and 9 girls, mean ± SD age 9.6 ± 1.7 years) without sessions of Lokomat®Pediatric. The CG received only daily physical or occupational therapy with a physiotherapist. The characteristics of the children of the two groups are presented in Table 1.

The participants and their legal guardians (parents or guardians) were informed of the progress of the study and gave their signed consents. The experiments were performed according to the Declaration of Helsinki. All subjects were recruited and agreed to the study, which was approved by the local ethics board.

Insert Table 1

2.2. Procedure

Data was collected by a motion analysis system with 8 infrared cameras recording at a frequency of 200 Hz (VICON® - Oxford Metrics, Oxford, UK) and 4 force platforms (AMTI®, 0.60x0.60 meters) in order to provide a clinical gait analysis. The children were equipped with 34 reflective markers that were aligned to anatomical landmarks on the head, trunk, pelvis and bilaterally on the arms, thighs, lower legs and feet. Following the full body Plug-In-Gait protocol [34], it enabled the reconstruction of the segmental axes and of their respective joint centers. The participants walked barefoot without walking aids at their preferred speed for a minimum of ten trials on a 10 m x 0.60 m gait track.

Clinical gait analysis and GMFM test were performed for the Treated Group three days before (T0) and three days after (T1) a robotic rehabilitation. The treatment consisted of twenty Lokomat®Pediatric sessions with a duration of 40 minutes, spread over a period of four weeks. The same exercises were offered to the fourteen participants with the same time, variation of speed, and game difficulties. For all participants, the initial body-weight support was 70%, and was then gradually decreased to 40% over the sessions, according to the participant's functional capacity. Body-weight support was reduced as much as possible until the knee started to collapse into flexion during stance phase due to the increased load of body weight. The therapist was always present at the child's sessions in order to follow the progression as well as to raise the child's awareness to correct gait patterns and posture during the training session. For the Control Group, clinical gait analysis and GMFM test were performed at the start (T0) and at the end (T1) of this four week period.

The GMFM test (GMFM - 66 score) was performed in order to evaluate motor skills such as walking on level ground and/or on mat, unipodal and bipodal balance (postural stability), up and down stairs, etc. This test is a rating scale of global motor function in children with CP [31]. We examined for this study mainly the dimensions D (standing abilities - GMFM-D score) and E (walking/running/climbing abilities - GMFM-E score).

2.3. Data analysis and statistical methods

Data was processed using VICON-Nexus® acquisition software (Oxford Metrics, Oxford, UK) and Motion Inspector® software (Biometrics France, Orsay, France) in order to reconstruct, for each subject, an appropriate biomechanical model of the trajectory of the reflective markers. This reconstruction allowed to calculate the trajectory of the COM [3] for each participant. The progress of the COP in the anteroposterior and mediolateral axes was extracted using forces platform data. The COP was computed from the reaction forces and torques of an equivalent platform calculated as the sum of the four platforms used (reference to König's theorem). These results were subsequently used to calculate i) COM (from VICON-Nexus®) – COP (from platform data) trajectory relative to the propulsive forces [6] and ii) the time lag resulting at the time-instant of COM-COP trajectory divergence and the time-instant when the propulsive forces created become apparent around the anteroposterior (Y) and mediolateral (X) axes in each group at T0 and T1.

After checking each variable for normal distribution (according to a Shapiro-Wilk test), the following statistical analyses (intragroup and intergroup comparisons) were conducted using the R software: (i) for participant demographics data, we used a t-test in order to quantify potential differences between the two groups; (ii) for locomotor parameters data and GMFM test, we used a two way Analysis Of Variance with repeated measures in order to compare the spatial and temporal parameters of gait and thus quantify differences after rehabilitation; (iii) for kinetic data, we used a) an intercorrelation and a correlation coefficient [4, 6] between the COM - COP trajectory and the propulsive forces, around the anteroposterior (Y) and mediolateral (X) axes, using the Motion Inspector® software. These intercorrelation and correlation coefficients show the quality of dynamic stability during walking. These trajectories reveal how the subject produces the propulsive forces necessary for forward motion [4]. They permit an analysis of a participant's capacity or strategy used in generating the necessary imbalance between the COM and the COP. The aim of intercorrelation was to measure the time lag between the COM-COP trajectory and the production of propulsive forces. The correlation coefficient was used to establish and measure the intensity of the relationship between the two observed variables, namely COM-COP trajectory and the production of propulsive forces; b) a two way Analysis Of Variance with repeated measures in order to observe significance between the correlation coefficient differences. The statistical model used was the ANOVA type III, namely two fixed factors which are the "group" effect (Treatment Group vs. Control Group) and the "treatment" effect (T0 vs. T1) correlated with the dependent variables (kinetic data and locomotor parameters data). This analysis enabled us to identify two types of comparisons: i) an intergroup comparison corresponding to the variances of the means between the groups and ii) an intragroup comparison corresponding to the variances of the observations around the mean of the group, and thus to explain the effect of a specific intervention on the kinetic and functional parameters. In all cases, results were considered statistically significant where $p \leq 0.05$.

3. Results

The intergroup comparison corresponds to the observed values: i) at T0 between TG and CG and ii) at T1 between TG and CG.

The intragroup comparison corresponds to the observed values: i) between T0 and T1 for TG and ii) between T0 and T1 for CG.

3.1. Participant demographics data

No significant differences between the two groups were found for the height (*p*-value: 0.076) and weight (*p*-value: 0.069). Only age showed significant differences between the TG and CG. The children of the CG group were found to be significantly older than the children of the TG group (*p*-value: 0.001).

3.2. Descriptions of the RAGT sessions

The mean duration/therapy session was 39:25min ± 04:12 and the mean of walking distance/therapy session was 1.267km ± 206. The mean of total distance walked/patient during the trial was 25.34km ± 1.9 and the mean of total time walked/patient was 785min ± 82. The average of weight unloading was 43% ± 6%.

3.3. Spatio-temporal gait parameters and postural stability indices data

The locomotor parameters data are divided into two categories i) the spatio-temporal gait parameters which include speed, cadence, length and width step (Table 2) and ii) the postural stability indices which include the GMFM test, the single and the double support time (Table 3).

No significant differences were found for the spatio-temporal gait parameters at T0 between TG and CG for the intergroup comparison and between T0 and T1 for CG for the intragroup comparison. Significant differences were found between T0 and T1 for the intragroup comparison for TG. Significant differences were also found for the intergroup comparison between TG and CG at T1, except for left step length.

For the postural stability indices, we observe significant differences in the intergroup comparison at T1 and in the intragroup TG. Only the intragroup comparison for CG shows significant difference for the GMFM test.

Insert Table 2 and Table 3

3.4. Kinetic data

The kinetic analysis resulted in the mean correlation coefficient and the time lag between the COM-COP trajectory and the propulsive forces around the anteroposterior (Y) and mediolateral (X) axes in each group at T0 and T1.

The intergroup comparison highlighted no significant differences at T0. However, at T1 we observed significant differences for both the mean correlation coefficient and the time duration.

For the intragroup TG, all the data showed significant differences. On the other hand, only data around the anteroposterior axis highlighted significant differences for the intragroup CG.

Insert Table 4 and Fig.1

4. Discussion

This study was performed to analyze and highlight the effect of robotic gait rehabilitation in children with bilateral spastic CP, extending and complementing our first study [35] on the full-body kinematic gait parameters which did not take into account the kinetic data of the gait. Although performed on a limited number of patients, this study highlighted modification of the dynamic equilibrium control in gait.

The observed results on thirty children with spastic diplegia confirm those reported by previous studies [22-30]. Indeed, the analysis of the locomotor parameters showed that children belonging to the Treated Group were seen to adopt new gait organization with improvement of postural and locomotor functions and a gait pattern significantly different compared to the Control Group.

The intragroup (T0/T1-TG) results translated a statistically significant increase in gait speed and step length which were associated with a significant decrease in cadence and step width highlighting a dynamic control (cf. Table 2). These improvements in the dynamic control were observed along the anteroposterior axis (increase of step length) and the mediolateral axis (decrease of step width). In addition to this, these children showed statistically significant improvement in gait symmetry (judged from an overall comparison of the results from the left and right side), notably during the support time (cf. Table 3). Indeed, a decreased average of the double support time was observed associated with an increased average of the single support time. This illustrates, for the TG, a better postural stability and control of dynamic balance during imbalance phases, at the time of body-weight transfer. The GMFM D and E data (cf. Table 3) were in agreement with the locomotor parameters data. The results showed task-specific improvements in gait parameters as measured by the dimension E of the GMFM. The improvement in the standing dimension (D) of the GMFM was equally as good as in the walking dimension (E) of the GMFM. This suggests an additional effect on the stabilization of posture beyond the task-specific improvement of walking parameters [26]. The GMFM D and E data correlated with the bilateral improvement in the single support time with a better control of body weight transfer, and with a decrease in daily use of technical walking aids. Overall, these first results show a dynamic and active postural control in gait by these children with an increased dynamic and smooth control between the successive phases of balance (stance phase) and imbalance (swing phase). The intragroup results for CG (T0/T1) showed no significant differences. Moreover, for the intergroup comparisons (T1-TG/T1-CG), all the differences were significant, except for the left step length. This confirms the benefits of a robotic gait rehabilitation with intensive and repetitive movement added to a traditional physiotherapy rehabilitation.

The kinetic data (cf. Table 4 and Fig.1) confirms the spatio-temporal gait and postural stability indices data. Overall, in the TG, we observed a normalization of the production of the propulsive forces necessary for forward motion underlying the quality of the dynamic stability in gait. Children of this group showed a more controlled COM-COP imbalance with a less important time lag between imbalance production and forward propulsive forces generation, supporting the occurrence of an active propulsive gait strategy. The results showed that the distance between the COM and the COP along the anteroposterior axis increased after the robotic gait rehabilitation and that this increase was mainly correlated with an increase in velocity and step length. The initial values COM-COP observed before the robotic gait rehabilitation are correlated with a small velocity and the production of short steps. This can be interpreted as the minimal effort to provide to move forward without falling. Indeed, as shown in a previous study [6], these children walked with a "bloc pattern" strategy illustrated by a fall of the whole body in order to produce the displacement. After the robotic gait rehabilitation, these children are now organized on a propulsive gait with a better COM-COP control. This new dynamic gait organization expresses an index of the child's capacity to create the dynamics of gait movement. The results of the previous study [6] have also shown that children with CP used a strategy characterized by a greater time lag between the time-instant of COM-COP trajectory divergence and the time-instant when the forward propulsive forces became apparent.

After robotic gait rehabilitation, the results showed a significant decrease of the time lag that was similar to that observed in typically developing (TD) children [1-4, 6]. Gait was thereby illustrated by a dynamic and smooth organization with a significant decrease in braking upon heel strike, increasing especially the displacement mean speed. These results confirm those of our previous study [35] which showed that Treated Group use new dynamic strategies of gait that are especially characterized by a more appropriate control of the upper body associated with an improvement of the lower limbs kinematics.

The results of this experiment thereby confirmed our original hypothesis, namely that robotic gait rehabilitation presents beneficial effect on recovery and improvement of postural and locomotor functions of the patient. These improvements result in a reorganization of gait pattern, which become quantitatively more harmonious. These improvements show indeed significant differences between results obtained before and after robotic rehabilitation for these children. Finally, this highlights the usefulness of robot-assisted gait rehabilitation which allows the patient to walk a greater distance for an equivalent duration to that of a physiotherapy session.

In this study, we sought to get two groups as homogeneous as possible with the same cognitive and motor learning levels in order to compare the actual effects of such a robotic gait rehabilitation. No significant differences between the two groups were found, except for the age. Indeed, the CG was significantly older than the TG. That means that the results of this study cannot be generalized. Furthermore, this study assessed the effects of Lokomat®Pediatric directly after therapy, without follow-up, because of logistic reasons. Hence, the results do not provide any indication that benefits are maintained or on the necessity to repeat Lokomat®Pediatric regularly or to use it continuously. This limitation could be addressed by evaluating the evolution of improvements over time. Nevertheless, the results of this study dealing with the use of robotic rehabilitation have proved its real benefits in the therapeutic and clinical treatment of children with CP. Consequently, it seems useful to reconsider from a therapeutic and clinical point of view the contribution of this rehabilitation to the types of rehabilitation usually proposed. This should be considered from a complementary perspective and not as a replacement or a substitution one for existing therapies. Moreover, it could be useful to provide the means to confirm more strongly the benefits of this assisted process. Finally, it will be very important to enrich the overall biomechanical data by taking into account other factors (for example, EMG data / muscle strength, mechanical work / energy expenditure or other kinetic and kinematic parameters).

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Tables:

Table 1. Morphological and clinical characteristics of the children. Periventicular Leukomalacia (PVL);

	Treated Group	Control Group
Gender	8 boys and 6 girls	7 boys and 9 girls
Age (years)	8.3 years ± 1.2	9.6 years ± 1.7
Height (m)	1.21m ± 0.17	1.23m ± 0.11
Weight (kg)	18.6kg ± 1.21	19.8kg ± 1.74

Table 2. Spatio-temporal gait parameters between Treated Group and Control Group at T0 and T1.

		Treated Group (TG)		Control Group (CG)		*p*-values			
						Intergroup comparison		*Intragroup comparison*	
		T0	T1	T0	T1	T0-TG / T0-CG	T1-TG / T1-CG	T0/T1 (TG)	T0/T1 (CG)
Speed ($m.s^{-1}$)		0.84 ± 0.17	0.96 ± 0.21	0.85 ± 0.20	0.87 ± 0.12	0.053	**0.031**	**0.046**	0.062
Cadence (step/min)		136.5 ± 12.06	129.30 ± 14.12	135.2 ± 9.11	134.6 ± 10.09	0.078	**0.043**	**0.029**	0.081
Length (m)	Left	0.38 ± 0.07	0.43 ± 0.06	0.40 ± 0.02	0.41 ± 0.09	0.062	0.051	**0.045**	0.079
	Right	0.42 ± 0.05	0.45 ± 0.04	0.40 ± 0.08	0.39 ± 0.10	0.064	**0.042**	**0.049**	0.061
Width (m)	Left	0.39 ± 0.09	0.21 ± 0.04	0.41 ± 0.07	0.39 ± 0.06	0.093	**0.022**	**0.037**	0.059
	Right	0.40 ± 0.06	0.23 ± 0.08	0.40 ± 0.08	0.39 ± 0.03	0.105	**0.029**	**0.021**	0.057

Table 3. Postural stability indices between Treated Group and Control Group at T0 and T1.

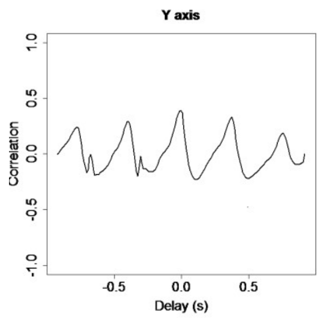
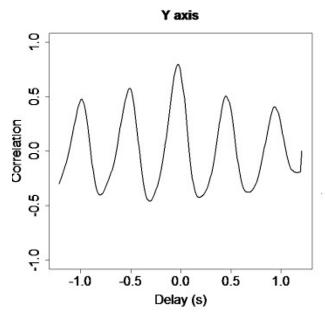
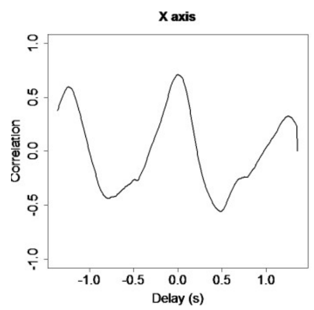
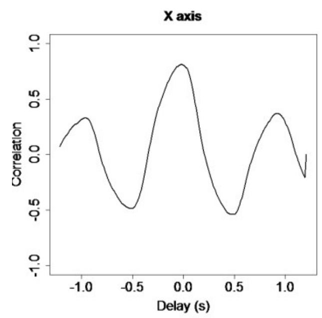
		Treated Group (TG)		Control Group (CG)		*p*-values			
						Intergroup comparison		*Intragroup comparison*	
		T0	T1	T0	T1	T0-TG / T0-CG	T1-TG / T1-CG	T0/T1 (TG)	T0/T1 (CG)
GMFM (%)	D	53.89 ± 16.02	60.58 ± 14.71	53.81 ± 14.67	55.74 ± 15.02	0.073	**0.048**	**0.037**	0.053
	E	42.23 ± 14.65	50.87 ± 15.82	42.51 ± 13.09	43.61 ± 12.59	0.090	**0.026**	**0.033**	0.098
Single support time (s)	Left	0.41 ± 0.04	0.47 ± 0.03	0.40 ± 0.07	0.42 ± 0.10	0.061	**0.045**	**0.041**	0.085
	Right	0.43 ± 0.13	0.46 ± 0.08	0.41 ± 0.09	0.42 ± 0.05	0.075	**0.05**	**0.046**	0.104
Double support time (s)	Left	0.26 ± 0.05	0.18 ± 0.03	0.24 ± 0.08	0.22 ± 0.01	0.095	**0.048**	**0.024**	0.056
	Right	0.28 ± 0.19	0.20 ± 0.07	0.27 ± 0.09	0.24 ± 0.11	0.110	**0.047**	**0.031**	0.058

Table 4. Kinetic data between Treated Group and Control Group at T0 and T1. Correlation Coefficient (CC); Time Duration (TD).

		Treated Group (TG)		Control Group (CG)		*p*-values			
						Intergroup comparison		*Intragroup comparison*	
		T0	T1	T0	T1	T0-TG / T0-CG	T1-TG / T1-CG	T0/T1 (TG)	T0/T1 (CG)
CC	AP axis	0.59 ± 0.03	0.80 ± 0.02	0.57 ± 0.06	0.62 ± 0.04	0.102	**0.011**	**0.031**	**0.042**
	ML axis	0.56 ± 0.02	0.83 ± 0.01	0.54 ± 0.03	0.59 ± 0.02	0.131	**0.016**	**0.028**	0.103
TD (s)	AP axis	0.06 ± 0.01	0.02 ± 0.01	0.06 ± 0.02	0.04 ± 0.01	0.195	**0.031**	**0.032**	**0.049**
	ML axis	0.04 ± 0.02	0.01 ± 0.01	0.05 ± 0.03	0.04 ± 0.02	0.115	**0.024**	**0.025**	0.109

Figure:

Fig.1. Means intercorrelation (A) and correlation coefficient (B) between the COM-COP trajectory and the propulsive forces around the anteroposterior (Y) and mediolateral (X) axes, before (T0) and after (T1) robotic gait rehabilitation for Treated Group.

	Anteroposterior axis (Y)		Mediolateral axis (X)	
	T0	T1	T0	T1
A				
B