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Case Studies of a Robot Enhanced Walker for Training of Children with Cerebral Palsy

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Abstract— **Cerebral palsy (CP) is a disorder of movement and posture in children caused by non-progressive insult of the immature brain. The characteristic features are weakness, spasticity, muscle contractures, and poor motor coordination. The gait patterns of children with CP are slow, uncoordinated, and unstable. Our hypothesis is that these impaired children will benefit from robot enhanced walkers to improve their balance, coordination, and speed during gait. In addition, this experience will also impact their clinical scores that relate to their functional performance and caregiver assistance.**

In this study, we used a specially-designed robotic walker which children used to perform a series of walking tasks, in increasing order of difficulty. This study was performed in 30 training sessions over a period of 3 months. Each training session lasted for 20 minutes. The outcome measures were variables recorded by the robot such as travel distance, average speed, and clinical measured variables that characterize their disability profiles.

I. Introduction

Cerebral palsy (CP) is a disease that impairs physical ability in children resulting in crucial constraints in their active daily lives. This status is not progressive and causes damage in the infant brain and developing fetus [1]. CP is also well known for the most common motor disability, counted about 3.6 per 1,000 school-aged children, in the United States [2]. Every year, more than 8000 new CP patients are reported in the United States [3] and more premature infants survive due to newer medical technology, increasing the prevalence of CP population [4]. Compared to developed countries, a higher number of CP population is observed in developing country due to increased neonatal asphyxia and low-weight birth. Due to increased prevalence and a longer life expectancy of CP children, earlier interventions are required for their functional care and management.

The etiological cause of cerebral palsy in very young children is rarely identified [5]. Main factors of CP and brain injury are coagulopathy, infection and prematurity [6, 7, 8]. Premature and low birth-weight babies with CP average 40 to 150 per 1,000 constituting a major portion of CP children [9]. The pattern of movement is used to classify children with CP, e.g., ataxic, dyskinetic, hypotonic, spastic, or combination of these forms. Spastic is the mostly observed form among these children [9]. Even though CP is described as a motor disorder, impairment of the premature brain affects other brain activities. CP accompanies other diseases including social, auditory, oromotor, psychological, and/or visual malfunctions. Musculoskeletal, gastrointestinal, genitourinary, respiratory, and seizure disorders are also observed among the children with CP.

For this study, we used the following tools to assess the clinical status of children with CP: the Gross Motor Function Measure 88 (GMFM-88), Gross Motor Function Classification System (GMFCS), Manual Ability Classification System (MACS), Quality of Upper Extremity Skills Test (QUEST), Pediatric Evaluation of Disability Inventory (PEDI), and Denver Developmental Screening Test II (DDST II).

The GMFM-88 is designed to evaluate changes in gross motor function of children with CP as they grow. It can be used both for research purposes and clinical evaluation [10]. The GMFCS is a questionnaire to classify and stratify children with CP into five groups based on gross motor skills, for example, sitting, transfers, and mobility [11]. MACS provides information about adaptive methods of how children with CP use their hands when handling objects in daily activities with their spastic or contracted arms [12-14]. QUEST evaluates movement pattern and function of upper extremity in four domains: dissociated movements, grasp, protective extension, and weight bearing. It is designed to be used for children with CP, who have movement disorders with spasticity [15, 16]. PEDI is a comprehensive tool to assess capability of skills with or without caregiver assistance in 3 domains: self-care, mobility, and social function [16]. DDST II is a screening test for sorting cognitive or behavioral problems in preschool children [17, 18]. DDST II has 4 task domain (social contact, fine motor skill, language, and gross motor skill) and other categories (smiling, building blocks, speaking words, and hopping on one leg).

The goal of this case study was to design a robotic walker and use this to help children perform a series of walking tasks, in increasing order of difficulty. The study was performed in 30 training sessions over a period of 3 months with each training session lasting for 20 minutes. The results of this training were evaluated in terms of robot and clinical measured variables. All participants were assessed with the

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evaluating tools before the training, after 15 sessions of training and after 30 sessions of training.

II. Participating Subjects

The study was approved by the Institutional Review Board of Hanyang University Medical Center (HYUMC) in Seoul, South Korea. All subjects were informed with the approved consent form. Three CP pediatric patients were collected from the outpatient department of rehabilitation medicine in HYUMC. The appropriate conditions for the children to participate in this study were: (1) the child should be diagnosed with CP by a medical doctor and (2) the child has the physical ability to hold on to the robotic walker for at least 30 minutes. The conditions for exclusion from this study were: (1) additional neurologic problems except CP, (2) too short a height to fit into the training device, (3) existence of other medical conditions making it difficult to participate in the training, e.g., orthopedic problem to grasp the steering wheel, and (4) serious emotional instability or cognitive malfunction that could affect the experiment.

After an initial screening for inclusion and exclusion, all participant's functional scores were checked on GMFCS, GMFM-88, MACS, QUEST, 6 domains of PEDI (self-care, mobility, social function, self-care with caregiver assistance, mobility with caregiver assistance, and social function with caregiver assistance), and DDST II were evaluated before, during and after the training.

III. Robot Hardware and Interface

The robot hardware consisted of the mobile robot as the base, an on-board computer, an off-the-shelf walker, a steering wheel, a wireless joystick, and a laser range finder (Figure 1). A walker with non-actuated four casters was attached to the front of the mobile robot and the child in the walker was located roughly 1 meter from the center of the rotational axis of the mobile robot. A wireless joystick and a steering wheel from Logitech were used to control the robot programmed via DirectX. The care giver provides the linear velocity using a wireless joystick and the child manipulates the rotational velocity with the steering wheel. The encoders on the mobile robot provided the robot's current position and orientation. Since the wheels of the robot do not satisfy the no-slip condition, the position error accumulates as the robot moves. In order to correct for this error, a Monte-Carlo localization algorithm was used along with data from the laser range finder. This helped to achieve an accuracy of 5cm in robot position. All programs were run on an on-board computer. As a result, a log file, which contains the robot's position, orientation, and time was generated as illustrated in Figure 1.

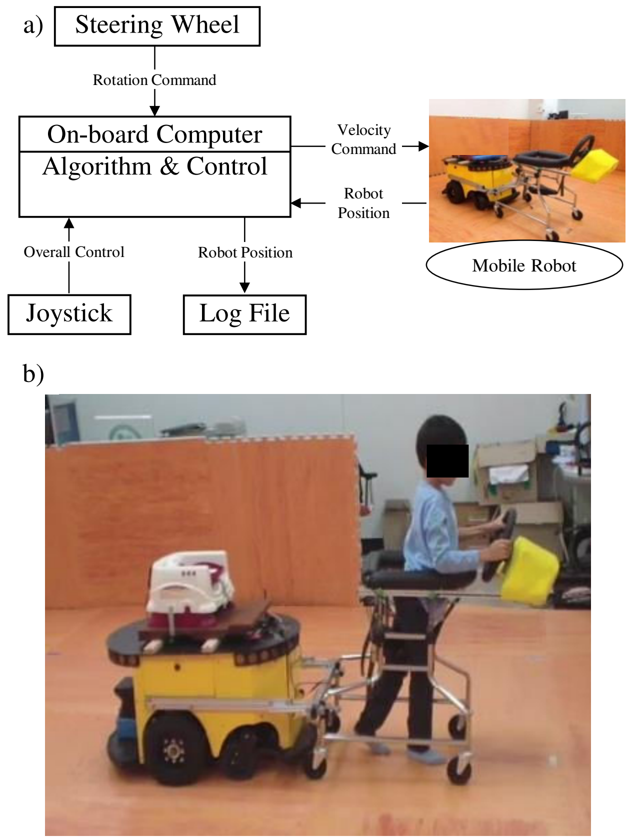

Figure 1. An overview of the robot system: a) Diagram of the robot system hardware, b) The walking child with robot enhanced walker. Child used a steering wheel to provide the direction of movement and the robot controller used this command to move the robot along this direction. The data from encoders on the wheels and laser scanner were used to determine the current position and orientation of the robot.

IV. Task Descriptions and Methods

All experiments were carried out at Hanyang University Labs. To guarantee the safety of participants, protective mats were used on the floor and the wall. The mats covered a 5 m x 5 m area divided into 8 sub-regions. Detailed descriptions of these sub-regions are given in Figure 2.

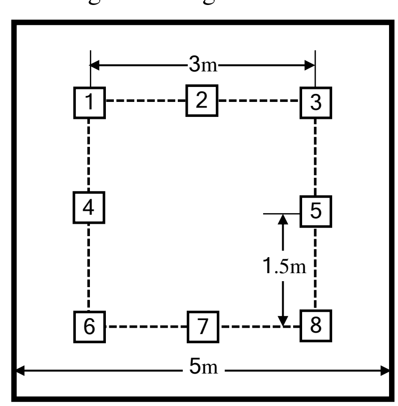

Figure 2. Target subareas on the mat used to describe the different task levels.

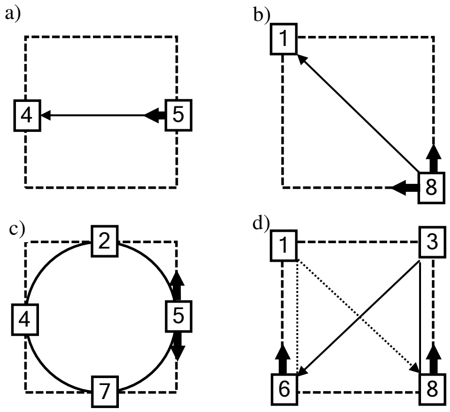

Figure 3. Task descriptions– bold arrows indicate the initial starting direction. a) Task 1, b) Task 2, c) Task 3, and d) Task 4.

Figure 3 shows the four tasks which are defined based on progressively increasing level of difficulty. Tasks 2, 3, and 4 were further completed both in a clockwise and counter-clockwise direction. Therefore, each task had two initial starting directions. Each child completed 30 training sessions over 10 to 15 weeks. The duration of each session was 20 minutes. Some specifics of the method were as follows:

(1) The forward speed of the robot was controlled by a caregiver using a wireless joystick and the rotational motion was controlled using the steering wheel by the child.

(2) In the first session, the initial velocity of the robot was determined based on the distance between the bumper of the mobile robot and the heel of the child during experiment.

(3) Once a child got used to the velocity of the vehicle, a caregiver gradually increased the velocity until the distance between the bumper of the mobile robot and the heel of the child roughly became 10cm.

(4) If a child got tired and supported himself/herself on the walker, the caregiver stopped the robot temporally.

(5) If a child came too close to the walls, or got out of the designated path, or moved with a large rotational velocity, the task was considered as a failure. The child restarted the task in these three failure cases.

(6) Toys, sound, and hand gestures were used to encourage the child to go to the next designated via point.

(7) Every session started from Task 1 and moved progressively to Task 4.

(8) Once a child got closer than 1 meter to a targeted via point, it was assumed that the target point was reached. The caregiver moved to the next designated via point, as defined by the task.

V. Clinical Results

Clinical results were obtained to assess the improvements in mobility. These measurements were made without any assist or robotic devices.

Table 1. Scores of self-care, mobility, and social function domains of PEDI in Case 1

Domain	Measured scores on Case1		
	Pre-training	Mid-training	Post-training
Self-care	64.6	66.8	66.8
Mobility	73.3	89.2	89.2
Social function	55.4	62.3	62.3

Table 2. Scores in other evaluating tools for Case 1

Evaluating tool	Measured scores on Case 1		
	Pre-training	Mid-training	Post-training
GMFM	95.6	97.3	97.3
QUEST	81.3	84.8	84.8

Case 1: This child was a 53-month-old girl affected with ataxic CP as a result of germinal matrix hemorrhage in the brain. She showed increased scores on all 3 PEDI domains. Scores of mobility domain produced the highest change from 73.3 to 89.2. Social function domain also showed improvement in score from 55.4 to 62.3 (Table 1). The child made small changes in GMFM and QUEST (Table 2).

Table 3. Scores of self-care, mobility, and social function domains of PEDI for Case 2

Domain	Measured scores on subject 2		
	Pre-training	Mid-training	Post-training
Self-care	56.8	58.6	58.6
Mobility	67.4	73.3	73.3
Social function	66.2	66.2	66.2

Table 4. Scores in other evaluating tools for Case 2

Evaluating tool	Measured scores on Case 2		
	Pre-training	Mid-training	Post-training
GMFM	95.0	96.8	97.1
QUEST	40.5	40.5	40.5

Case 2: This patient was a 48-month-old CP boy with right hemiplegia. He had a medical history of encephalomalacia in the left basal ganglia. He showed slight changes in mobility domains scores from 67.4 to 73.3 (Table 3). In other

evaluations, he also showed slight changes in GMFM (Table 4).

Table 5. Scores of self-care, mobility, and social function domains of PEDI for Case 3

Domain	Measured scores on Case 3		
	Pre-training	Mid-training	Post-training
Self-care	56.8	56.2	56.2
Mobility	47.9	49.7	49.7
Social function	63.2	67.4	67.4

Table 6. Scores in other evaluating tools for Case 3

Evaluating tools	Measured scores on Case 3		
	Pre-training	Mid-training	Post-training
GMFM	71.7	76.0	80.2
QUEST	30.4	32.3	39.5

Case 3: This subject was a 49-month-old girl with spastic triplegia combined with diplegia and left hemiplegia due to hydrocephalus. Scores of social function domains increased from 63.2 to 67.4 (Table 5). Her scores on GMFM and QUEST also respectively increased from 71.7 to 80.2 and 30.4 to 39.5 (Table 6).

VI. Robot Measured Results

The metric used in the robotic measurement was the task execution time. The time was measured from the start to the end of the task with the robotic walker during a session. For task 1, the time duration of walking from subarea 4 to 5 with the robotic walker was measured. Decrease of this metric implies faster walking speed and elimination of redundant movements of the subject to execute the given task.

Figs. 4 and 5 show the task execution times for each session for Tasks 1 and 2 for Cases 1-2, overlaid on the same plot. Figs. 6 and 7 show the execution times for Tasks 1 and 2 for Case 3. The children showed rapid improvement in execution time of the task during sessions 1-15 and plateaued during sessions 16-30. Cases 1 and 2 showed that the execution time decreases across the sessions and comes to a plateau by the end of 15 training sessions. We expect this behavior which is captured by best fit regression lines. Tables 7 and 8 show that linear regression fits well between the task execution time and sessions ($p < 0.05$). Sessions 1-15 show a strong decrease in the driving times across sessions.

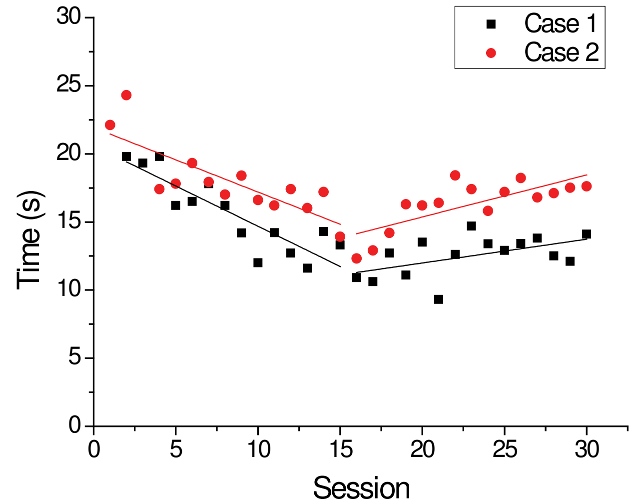

Figure 4. Execution time for Task 1 for Cases 1-2.

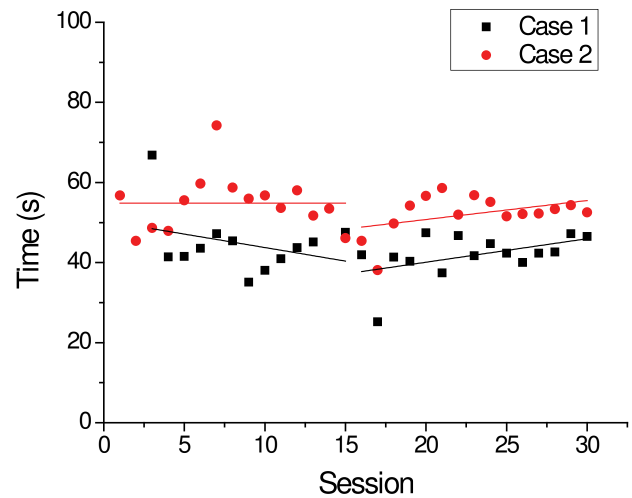

Figure 5. Execution time for Task 2 for Cases 1-2.

It must be noted that Cases 1 and 2 had a higher motor function classification system level (GMFCS – Level 1) and showed a larger decrease in task execution time compared to Case 3 (GMFCS - Level 2). The execution time for Task 1 showed a larger improvement than Task 2. Task 2 contained a rotational component to it and was more difficult to accomplish than Task1.

Cases 1 and 2 showed a large improvement in task 1, and the case 3 had superior improvements in task 2. The only difference between the tasks 1 and 2 is the rotational component in task 2. Recalling clinical scores of case 3, the subject showed increased scores for the hand movement represented by QUEST score. Relating these two facts, we can conclude that case 3 enhanced the manual skills to make a rotational movement with the steering wheel, while cases 1 and 2 benefited from the robotic device to advance their walking speeds. Even though the children were trained with the same device, the children gained different benefits from the mobility.

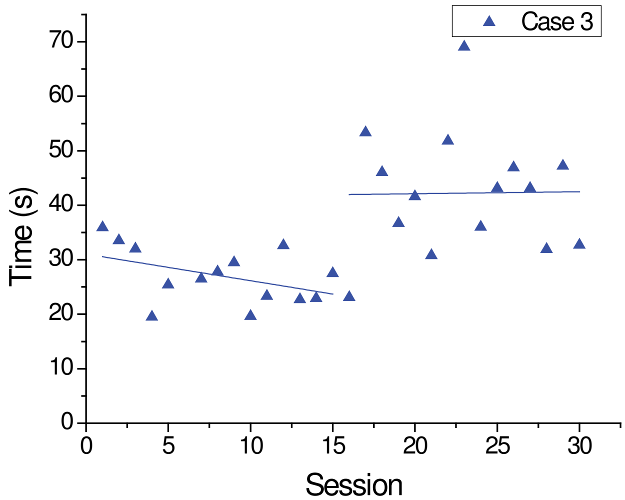

Figure 6. Execution time for Task 1 for Case 3.

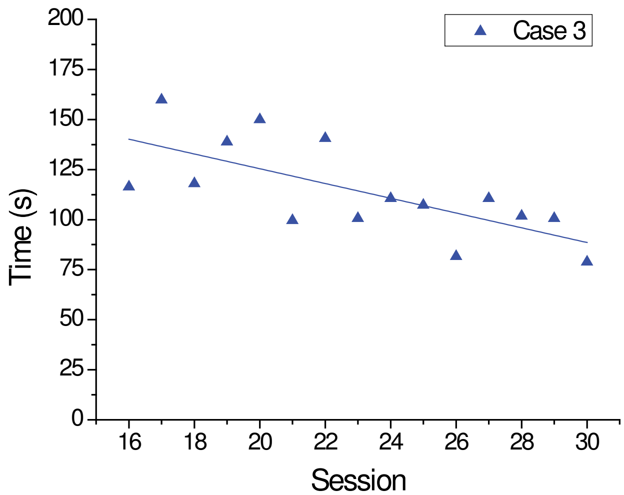

Figure 7. Execution time for Task 2 for Case 3

Table 7. Results– p-value for linear regression analysis of task executing time for Cases 1-2 through sessions 1-15 and 16-30 (regression model: y= $\beta_1 x+\beta_0$).

Session		1-15			16-30		
Task	**Case**	β_1	β_0	**p-value**	β_1	β_0	**p-value**
1	**1**	-0.590	20.6	0.000	0.174	8.50	0.043
	2	-0.472	21.9	0.001	0.308	9.20	0.001
2	**1**	-0.674	50.5	0.006	0.587	28.4	0.070
	2	-0.001	54.8	0.616	0.473	41.3	0.177

Table 8: Results– p-value for linear regression analysis of task executing time for Case 3 through sessions 1-15 and 16-30 (regression model: y= $\beta_1 x+\beta_0$).

Session		1-15			16-30		
Task	**Case**	β_1	β_0	**p-value**	β_1	β_0	**p-value**
1	**3**	-0.489	31.0	0.120	0.037	41.4	0.958
2		-	-	-	-3.685	199	0.086

VII. Discussion

The three cases showed definite improvements in PEDI domains. However, case 3 showed only slight increase of scores in the two domains. Subtle decreased scores were found in self-care items. The execution times for the tasks were also different from the other 2 cases. Case 3 showed the longest execution time compared to the other 2 cases.

Nonetheless, it should be noted that the scores evaluating mobility domain increased in all three subjects. It has already been demonstrated in previous studies that self-generated mobility in very young children simultaneously improves motor, cognitive, perceptual and social functions [19, 20]. Power mobility training in other studies has also shown the desire in children for self-propelled locomotion [21, 22]. A similar underlying mechanism with the robot walker may have helped the 3 subjects to develop the observed mobility skills.

In other studies, increased muscle strength and range of motion (ROM) in the ankle by robot-assisted training was also reported with CP patients. Traditional passive ROM exercise combined with robot-assisted training on spastic ankle could have significantly increased ankle ROM and strength [23, 24]. Considering that the ankle plays a strong role in propulsion during gait cycle [25], robot-assisted training would be able to encourage children with CP to perform exercise and improve walking.

Our observations indicate that the robotic walker training, as a task-specific gait exercise, would be a useful training tool for CP patients especially with gait disability. It improved mobility skill in all 3 children whether their gross motor function was low or high. As explained above, the scores in mobility domain of PEDI increased in all 3 cases, whereas the scores of the other 2 domains (self-care and social function) had different results.

Except for the PEDI, the GMFM and QUEST scores were also increased. Cases 1 and 2 showed mild improvement, and Case 3 produced a higher increase in the GMFM and QUEST. These scores were contrary to the results of PEDI. We must take note that Cases 1 and 2 had high scores in both GMFM and QUEST domains at the beginning of the training. However, Case 3 had relatively lower scores, addressing poor gross motor function and hand skills. These findings present a hypothesis: the children with higher gross motor function and hand skills show greater improvement in the PEDI domain.

This hypothesis in our study was based on the fact that Case 1 had higher scores in QUEST and GMFM, and, at the same time, showed higher improvement in PEDI domains. It is widely believed that the haptic stimulation by robot-assisted training can be used to present a novel and dynamic extrinsic environment for humans [26-29]. During our robotic walker training, the children were expected to change direction with the steering handle, and the trainer gave them auditory or visual stimulation to lead them towards a certain direction. As a result, the children were exposed to continuous haptic stimulation by manipulating the handle towards the sound or visual target. Moving the arms and hands would also work as coordinated multi-joint interaction that requires the CNS activation [30, 31]. Together with the haptic stimulation in extrinsic environment, this multi-joint interaction could have enabled the CNS to compensate the imbalanced movement of arms [32]. We may postulate that this mechanism probably helped Case 1, who had the best hand skills (highest QUEST scores), to achieve the higher improvement in all PEDI domains.

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