Assistive Robots for Physical and Cognitive Rehabilitation in Cerebral Palsy

Rafael Raya, Eduardo Rocon, Eloy Urendes, Miguel A. Velasco, Alejandro Clemotte, and Ramón Ceres

Bioengineering Group, Spanish National Council for Science Research, (GBIO-CSIC) Crta. Campo Real Km 0.2 Arganda del Rey, Madrid, Spain
rafael.raya@csic.es

1 Introduction

Cerebral palsy (CP) is one of the most severe disabilities in childhood and makes heavy demands on health, educational, and social services as well as on families and children themselves. The most frequently cited definition of CP is a disorder of posture and movement due to a defect or lesion in the immature brain, [1]. The prevalence of CP is internationally 2-3 cases per 1000 births. Only in the United States 500,000 infants are affected by CP, [2]. In Europe these figures are even higher, [3]. The current definition of CP covers a heterogeneous range of clinical presentations and degrees of impairment. Therefore, individuals with CP are normally categorized into classes or groups. Traditional classification schemes focus on the affected limbs (hemiplegia, diplegia and tetraplegia), with an added modifier that describes the predominant type of movement abnormality (spasticity, dyskinesia, ataxia, or mixed), [1]. However, it has become apparent that additional characteristics must be taken into account in novel classification scheme that contributes substantively to the understanding and management of this disorder. Clinical decisions and medical research depend upon the ability to link clinically observable signs and symptoms to the underlying pathophysiology.

As cure for CP, which means a repair of the underlying brain damage, is not currently available, the management for children with CP usually focuses on maintaining and improving both quality of life and function, and on preventing secondary complications. Patients with CP are at high risk of develop musculoskeletal problems that are mainly related to physical growth, abnormal muscle tone, weakness, lack of mobility, poor balance and loss of selective motor control. Gait limitations are usual in children with CP. The Gross Motor Function Classification System (GMFCS) classifies CP into five levels according to the disability level in lower extremities, [4]. Additionally, people with CP often suffer difficulty with motor skills of upper limbs, such as reaching, grasping and manipulating objects with their hands. MACS scale, [5], classifies into five levels the upper extremity function, that means, the users capability for manipulating objects.

On the other hand, the motor disorders of CP are often accompanied by disturbances of sensation, cognition, communication, perception, and/or behavior, and/or by a seizure disorder. It is during early stages of development that

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fundamental abilities and skills are developed, [6]. Thus, it is essential to give infants with CP an opportunity to interact with the environment for an integral development (physical and cognitive).

The main therapies focused on the rehabilitation of people with CP are: (1) Physical and occupational therapy; (2) Oral medications; (3) Orthotics; (4) Botulinum toxin; (5) Casting; (6) Multilevel orthopedic surgery; (7) Neurosurgical procedures; (8) Partial bodyweight-supported treadmill training (PBWSTT) and constraint-induced movement therapy (CIMT); and (9) Gait robot-aided therapy.

Recent publications have demonstrated that robot-assisted therapies may be an effective tool to compensate and/or rehabilitate the function skills of people with CP, [7]. Most of the devices were previously designed for people with other disorders, such as stroke and spinal cord injury. Current trends in robotic rehabilitation are focused on validating these devices beyond these disorders and extend the benefits for people with CP.

In this chapter, we will present a bibliography review about assistive robotic devices for people with cerebral palsy, both rehabilitation and functional compensation. We will focus on devices designed to support users locomotion (lower limb) and manipulation (upper limb). Additionally, we will propose a holistic strategy (physical and cognitive) based on a playful robot, called PALMIBER, which will aim to enhance physical and cognitive users skills through mobility experiences. Finally, we will present an ambulatory robot for gait rehabilitation after multilevel surgery, called CPWalker.

2 Robot-Assisted Rehabilitation for People with Cerebral Palsy

Robot-assisted therapy is a form of physical therapy that uses a robotic device to help a person with an impaired functional ability learns to recover the function. The robotic device usually proposes a goal-directed task, which encourages the patient. This approach has interesting advantages compared to traditional therapy, because robotic therapy integrates functional tasks instead of repetitive movements without goal. As a result, it is usual to increase the number of sessions, frequency and intensity and finally the positive impact of the treatment. Additionally, these devices usually integrate assessment system to objectively measure the progress of the therapy. Sections 2.1 and section 2.2 present a review of robot-assisted therapies for cerebral palsy, for lower (ambulation) and upper limbs (manipulation) respectively.

2.1 Ambulation: Robot Assisted Rehabilitation for Lower Limbs

There are basically two groups of assistive devices to help people with mobility problems: the alternative devices and the empowering (or augmentative) devices. These solutions are selected based on the degree of disability of the user. In the case of total incapacity of mobility (including both bipedestation and locomotion), alternative solutions are used. These devices are usually wheelchairs or solutions based on autonomous especial vehicles.

People who have reduced mobility commonly use augmentative devices by using their residual capabilities. In particular, walkers and exoskeleton robots are augmentative devices to assist in standing, balance and locomotion. Walkers are intended to help users navigation. Smart Walkers are robotic devices based on walkers optimised to improve human-machine interaction and as a result to improve the acceptance and functionality of these systems in rehabilitation. As walkers take advantage of the users remaining locomotion capability, they also help avoid the early and deteriorative use of alternative devices, most commonly, the wheelchairs. The PAMM system (Personal Aids for Mobility and Monitoring),[8], and the GUIDO system, an advanced walker for people with visual and/or mental deficiency, [9], are illustrative examples of this technology. The SIMBIOSIS Project introduced an implementation of a smart robotic walker, [10], specifically aimed at functional compensation of gait, differently from its counterparts, principally oriented at guiding assistance.

Exoskeleton Robots are mechatronic devices of which segments and joints correspond to some extend to these of the human body and the system is externally coupled to the person, (fig. 1). In rehabilitation applications, exoskeletons should be able to replicate with a patient the movements performed with a therapist during the treatment. In the case of functional compensation, exoskeletons are designed to support the execution of activities of daily living by assisting the user in the basic motor functions. The exoskeletons have been intended to provide either joint support by means of brakes or clutches, [11], [12], [13], [14], or actively add power to the joints, thus providing a mean to control and complete joint movements, [15], [16], [17], [18]. In addition, the sensors attached to the exoskeleton can assess forces and movements of the patient. This would give to the therapist quantitative feedback on the recovery of the patients and would imply a more efficient rehabilitation process. Therefore, the exoskeleton could act as tool for the measurement of the performance and the evolution of the treatment, [19]. In the REHABOT project, [20], the proposers have put through and developed the idea of functional restoration of walking in spinal cord injury patients through a synergistic strategy, in which both exoskeletal robots and motor neuroprostheses (MNP) are combined to improve functional recovery. MNPs constitute an approach to restoring function by means of artificially controlling human muscles or muscle nerves with functional electrical stimulation (FES). These hybrid approaches have demonstrated their capability to improve overall motor substitution outcome, as each individual component helps overcome the technological limitations of the counterpart. These effects are particularly critical in the case of unbalanced activity of agonist antagonist muscles, typically found in CP.

An interesting hybrid (exoskeleton and walker) approach was proposed by Stauffer et al.,[18]. They presented the WalkTrainer, a combined exoskeleton and FES systems in hybrid configuration with a smart walker. While the WalkTrainer

Fig. 1. Example of an exoskeleton robot: lower limb orthotic exoskeletons

exoskeleton controls hip, knee and ankle joints, and the pelvis movement, the deambulator supports the exoskeleton and the user, via a weight bearing system, similar to treadmill training systems. A closed-loop control of FES applies muscle stimulation, relying on the estimation of the interaction forces between the user and the exoskeleton.

The NF-Walker (made for movement) is a hybrid device for people with CP that combines dynamic standing and walking support. NF-Walker comprises two main parts: a base (similar to a walker) and the braces. The braces are fixed to the base allowing to stimulate an adequate gait pattern. The base pressures towards the ground through the wheels. Weight support of the user is taken up inside the shoes (independent from the pressure towards the ground). The Lokomat, manufactured by Hocoma, is a driven gait orthosis that automates locomotion therapy on a treadmill and improves the efficiency of treadmill training.

Partial body weightsupported treadmill training (PBWSTT) and constraint-induced movement therapy (CIMT) are therapies based on current theories of motor learning. They promote a normalized pattern of gait involving the sensory information and the reflex components of gait. This has been demonstrated to be useful to obtain patterns of gait in spinal cord injury patterns. However, for other types of pathologies it has been demonstrated the need to involve actively the user in the training as well as allowing some kind of error to promote the mechanisms of motor learning. This has lead to approaches such as assist as needed or error enhancement in which the amount of support to the patients is dynamically changed, usually as a factor of the number of sessions.

Meyer-Heim et al, [21], described the current state of the robot-assisted and computer-enhanced therapies for children with cerebral palsy. According to the Gross Motor Function Classification System (GMFCS), especially mildly affected children with GMFCS level I and II profited more from the intervention in contrast to those with GMFCS levels III and IV. Remarkably, one study demonstrated that the improvements in gait capacity induced by 12 sessions of robot-assisted gait training were maintained for 6 months, [22]. Motivation as an emotional process is recognized as being an important factor in the rehabilitation process and therapy outcomes,[23], [24]. For instance, the therapist can provide verbal encouragement and verbal feedback for selective muscular training and raise the childs awareness to correct gait patterns and posture. Some works have demonstrated that robot-assisted therapy in combination with virtual reality could increase the user involvement and, as a consequence, enrich the treatment. Therapies based on goal-oriented tasks can be easily configured using virtual scenarios, [25].

A few of the assisted-mobility systems described in the literature address the particular problems of children affected by neuromotor disorders attending to cognitive rehabilitation through mobility experiences. One outstanding case worthy of mention is the Communication Aids for Language and Learning (CALL) center that developed a smart wheelchair specifically for children with mobility impairment. In this case, a standard wheelchair was instrumented and adapted in terms of the users interfaces. The Gobot is a special vehicle that enables mobility for children with CP created by the Hospital of Lucile Packard Stanford (US). It moves easily from a horizontal to a vertical position. Tray, hip, lateral supports and full foam knee supports are also simple to adjust. The Magellan Pro Robot is a commercial robot made by the IRobot Corporation. Researchers from the Delaware University (US) used it for rehabilitation of children with CP, [26],[27]. The robot was equipped with an on-board computer and odometry. Their results demonstrated that young infants independently move themselves via a mobile robot. Their data do provide indirect evidence that infants were not simply focused on moving the joystick but were associating joystick activation with their motion.

Although these devices are focused specifically for children with CP, they are based on standard or commercial devices. In this work, we propose two assistive platforms, called PALMIBER and CPWalker, designed specifically for alternative mobility of children with CP, in which the cognitive aspects are also considered as main part of the therapy.

2.2 Manipulation: Robot Assisted Rehabilitation for Upper Limbs

There are currently a limited number of robotic systems targeting the upper extremity that have been applied to children with CP, [21]. These devices propose goal-directed tasks and reaching movement to rehabilitate the hand and arm function.

The InMotion2 robot, is an end-effector robot, a commercial version of MIT-MANUS, which is capable of continuously adapting to and challenging each patients ability. This device aims to improve the range of motion, coordination, strength, movement speed and smoothness. It demonstrated functional improvements in the Quality of Upper Extremity Skills test (QUEST) and the Fugl-Meyer upper limb subtest, [28].

The HapticMaster is a 3 degrees of freedom, force-controlled haptic interface. It provides the user with a crisp haptic sensation and the power to closely simulate the weight and force found in a wide variety of human tasks. The programmable robot arm utilizes the admittance control (force control) paradigm, giving the device unique haptic specifications. People with CP used it in combination with virtual scenarios to improve the shoulder and elbow movements. The patients with in this study, [29], improved in measures of motor activity in the Melbourne Assessment.

The ARMEO system (based on T-WREX system) proposes a rehabilitative exercise that allows early rehabilitation of motor abilities and provides adaptive arm support in a 3D workspace. It is focused on patients with not sufficient strength to move their arm and hand against gravity, [30], [31]. There is a lack of clinical trials using this system with people with cerebral palsy. However, interesting results with patients who suffer stroke suggest promising result for people with CP.

In the case of children with CP is especially important the motivational aspect. For this reason these type of devices are usually designed in combination with playful scenarios such as videogames, which promote motivating and challenging tasks for a prolonged time.

According to some authors, [21], these approaches need to be refined and critically analyzed to determine their functional benefit for children with different levels of sensory-motor or cognitive impairment or both. Additionally, the current level of evidence regarding the efficacy of new technologies in the rehabilitation process still remains scarce. It would be necessary well-designed randomized clinical trials with better description and meaningful number of subjects. Furthermore, it would necessary to study the functional improvements for a prolonged time after the therapy.

3 A Mobile Robot for Physical-Cognitive Rehabilitation: The PALMIBER Vehicle

3.1 The Importance of Mobility and Interaction

The motivation of this work arises from the limitations caused by CP in the fundamental areas of human being: mobility, communication, manipulation, orientation and cognition. On the one hand, self-produced locomotion is essential for child development at the early ages. Independent mobility plays a crucial role in this exploration, leading to the child physical, cognitive and social development, [32]. According to the state of the art of mobility devices for people with CP, most devices are more focused on mobility than the integral development.

On the other hand, human-machine interaction is a critical factor. The posture and motor disorders associated to unable users with CP to control assistive devices. According to the state of the art of person-computer interfaces for people with CP, there is a wide diversity of solutions. However, authors assert that the usability decreases dramatically when users have a severe motor disability.

We propose a playful robotic vehicle to promote the interaction between the child with CP and his/her environment through mobility experiences. The vehicle has been designed under the assist as needed paradigm. Different driving modes with gradual intervention of the user are proposed. Additionally, different interfaces (driving console, switches and head-mounted interface) to drive the vehicle are proposed.

3.2 The PALMIBER Vehicle

The PALMIBER (figure 2) is a pre-industrial robotic vehicle designed and built with the main objective of providing severely disabled children the ability to explore the environment through independent mobility and be engaged in the same type of activities as their non-disabled peers. A multidisciplinary team participated in this project following a holistic approach in order to create a useful assistive device, which allows independent mobility in severely disabled children.

Fig. 2. Two children driving the PALMIBER vehicle with different interfaces (console of directions and single switch)

The objectives defined by the team of researchers led to the definition of the following technical requirements for the vehicle:

– A wide range of driving modes, adaptable to the various levels of cognitive performance of the potential users
– The capability to be used with several human machine interfaces as a function of the end user motor capabilities
– Monitoring functions for self-evaluation to help estimate the appropriate driving mode and the achieved progress;
– Playful aesthetics to attract child attention;
– Robust, safe, ergonomic and reasonable cost.

The vehicle is open and flexible so that it can be adapted to varying cognitive and physical performance levels. There are five levels implemented (figure 3):

– Level 0. Automatic. The vehicle detects and avoids obstacles without user intervention using an ultrasonic system.

- Level I. Cause-Effect. The child presses any key and the vehicle moves. The vehicle stops when it finds an obstacle.
- Level II. Training directions. The vehicle stops after detecting an obstacle (a crashing noise and alarm light warn of the eventual crash). The child must press the correct button proposed by the vehicle otherwise the vehicle does not move. If response is not obtained from the child, he is invited to do so by a verbal message. There are two partial modes: a) forward and backward keys alternatively and b) right and left keys alternatively.
- Level III. Deciding directions. The user decides and presses the driving buttons, but the vehicle automatically stops if any obstacle is detected. Verbal commands are generated. At this level, the children start deciding on a navigation target.
- Level IV. Fully guided. The vehicle is fully driven by the user; ultrasonic sensors are not active in this operation mode.

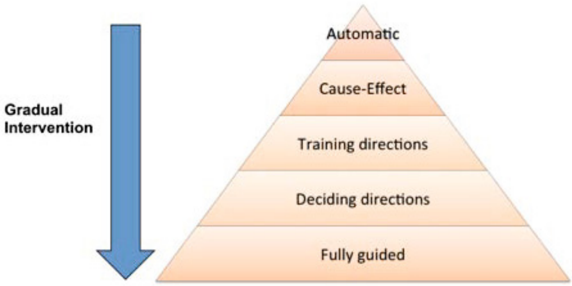

Fig. 3. Driving modes of the PALMIBER vehicle to adapt the system to the user cognitive skills

3.3 Human-Machine Interaction for People with CP

People with CP often have severe limitations using conventional human-machine interfaces, thus diminishing their opportunities to communicate and learn through computers, [33]. Therefore, the selection of the usable human-machine interfaces for driving the vehicle or another assitive device (as computer) is a key factor in order to reduce the barriers of manipulation and control due to motor disorders that affect upper limbs.

Davies et al. presented a systematic review of the development, use and effectiveness of devices and technologies that enable or enhance self-directed computer access by individuals with CP, [34]. They divided HMI into five categories: 1) pointing devices, 2) keyboard modifications, 3) screen interface options, 4) speech and gesture recognition software and 5) algorithms and filtering mechanisms.

Eye and face tracking interfaces are powerful pointing devices for people with motor disorders. They often succeed in improving human-computer interaction, [35]. They have the potential to be a very natural form of pointing, as people tend to look at the object they wish to interact with. However, they often present low performance with people with severe motor disorders.

As regards keyboard-based solutions, some studies have demonstrated that keyboard adaptations improve speed and accuracy, [36], [37]. The category screen interface includes the interfaces that scan through screen icons or dynamically change the icon position. Children with significant physical impairments (who are unable to point) use visual scanning and switches to select symbols. Symbol prediction software is a method of access that involves highlighting a specific symbol within an array on the basis of an expected or predicted response, [38]. The prediction software reduces the response time required for participants but there is a trade-off between speed and accuracy.

Some devices are voice-based human-computer interfaces in which a set of commands can be executed by the voice of the user. Speech-recognition software is difficult to customize for users with CP who have dysarthria. Finally, algorithms and filtering mechanisms are focused on improving the accuracy of computer recognition of keyboard input or tracking of the pointer motion.

Access solutions for individuals with CP are in the early stages of development and future work should include assessment of end-user comfort, effort and performance, as well as design features, [34]. A fundamental conclusion is that there is a wide diversity of solutions but their authors frequently assert that usability decreases dramatically when users have a severe motor disability.

The PALMIBER project proposes to use three types of interfaces for driving the vehicle:

- A console that consists of membrane keys to select the directions, (figure 4)
- A single switch and scanning methods (sequential activation of buttons and the user must press the switch when the desired direction is highlighted),
- The ENLAZA interface (figure 4) is a head-mounted interface, which transmits commands of control using the head movements. The interface integrates algorithms for discriminating, predicting and evaluating the normal and abnormal motor behavior of the user and his/her functional limitations and abilities. The ENLAZA interface integrates filtering techniques to reduce the effect of the involuntary movements on the control of the device. As a result, users who are unable to control conventional interfaces can access to the computer or other devices (e.g. PALMIBER vehicle).

This vehicle intends to follow the universal design approach. That means that the vehicle proposes different channels of interaction for people with different capabilities.

3.4 Experiments and Results

The vehicle proposed has been validated experimentally with users with cerebral palsy. A multidisciplinary team has participated during the different phases of

Fig. 4. Interfaces for driving the vehicle: console of direction, ENLAZA, an inertial head-mounted interface for driving the vehicle and control the computer

the work from the study of the users needs to the construction and validation of the devices. More than twenty users participated in different phases of the experimentation, [39], [40], with different levels of physical and cognitive capabilities. Depending the user capabilities, he/she worked with and specific driving mode, from automatic to fully guide mode.

According to the results, the PALMIBER device adapts efficiently to the particular users skills through the different driving modes (cognitive skills) and different interfaces (physical skills). This vehicle expands the current therapeutically approach to treat infants and adults with CP, by providing an autoadaptive therapy that enhance their fundamental abilities. According to the studies the vehicle improves the executive function of children unable to walk. The child learns to manage decisions, plans and predict the effect of his/her actions through mobility experiences.

Regarding to human machine interaction, users with manipulation capabilities are able to use the mechanical interfaces, as console of directions and switches. The lights and the mechanical feedback from the interface is essential to motivate children through physical stimuli. That means that keys based on capacity membranes were found less usable than mechanical switches, which provide mechanical feedback to the user. Additionally, some users with severe motor disorders in upper limbs participated. These users were unable to control conventional interfaces, console of directions and switches. Although all areas of the motor function can be limited, limbs are usually more affected than the head motion in infants with severe CP. The ENLAZA was demonstrated to be an effective human-computer interface to control the vehicle for those users unable to control the switch or the console of directions. The interface reduces the time between action planning and action execution, promoting the cause-effect process in an effective way. Additionally, the relation between movement direction and the arrow symbols on the console of directions requires mental abstraction, which can result difficult for these users. As a conclusion, the control with the head movement is a more intuitive method of control compared with pressing a key.

PALMIBER and ENLAZA have been validated technically and functionally for short-time periods. Currently, the Bioengineering group is carrying out longitudinal experiments (one year) to measure the impact of the PALMIBER vehicle on the physical-cognitive rehabilitation. ASPACE Cantabria, a specialized center, is collaborating to test these devices and measure the changes on motor and cognitive skills of the user.

At this time, nine users (age 2-10 years) are participating in the experiments. All participants started with the automatic mode, and after four months five users have achieved the level Cause-Effect and four users achieved the level of Training directions. The Bioengineering Group is registering all the data related to the driving exercise and will correlate the objective metrics with functional and subjective skills to measure more precisely the effect of the therapy.

The integration of PALMIBER and ENLAZA constitutes a powerful platform to analyze both approaches and gain a deeper knowledge on the dynamics of learning, due to the interrelationship between physical and cognitive aspects related with cerebral palsy. This approach relies on the hypothesis that the therapies based on the vehicle and the interface will create a positive spiral of physical/cognitive rehabilitation, that is to say, the improvements on physical capacities of the patients will enable them to live new experiences, for instance, to interact with the cognitive therapies. On the other way around, improvements in patients cognitive capacities will result in improvement of their motor control.

4 Robotic Platform for Gait Rehabilitation after Multilevel Surgery: CPWalker

The main objective of CPWalker is to develop and validate a robotic platform to support novel therapies for CP rehabilitation. This platform (Smart Walker + exoskeleton + neuroprosthesis) will be controlled by a multimodal interface to establish the interaction of CP infants with robot-based therapies. The objective of these therapies is to improve the physical skills of infants with CP and similar disorders. CPWalker concept will promote the earlier incorporation of CP patients to the rehabilitation therapy and increase the level of intensity and frequency of the exercises, which will enable the maintenance of therapeutic methods in daily basis, lead to significant improvements in the treatment outcome. Three research groups participate in this project: the Bioengineering Group of CSIC (GBIO-CSIC), the Biomechanic Institute of Valencia (IBV) and the Jesus Child Hospital, national reference of cerebral palsy treatment.

4.1 Robotic Rehabilitation after Multilevel Surgery

In some cases, the development of secondary musculoskeletal pathology contributes to loss of function, gait impairments, fatigue, activity limitations, and participation restriction. Orthopaedic surgeries are considered one of the best treatments for significant musculoskeletal problems in CP, and thereby minimizing the subsequent impairments and activity limitations,[41]. One of the main techniques is the Multilevel orthopedic surgery, [42], which focuses on correcting all deformities and to improve gait. It is often referred to as Single-Event Multilevel Surgery (SEMLS) when is performed in a patient without previous surgeries. SEMLS has shown benefits in the treatment of musculoskeletal problems of children with CP by reducing the effort and the appearance of walking, [43], improving GMFM, [44], [45], kinematic parameters,[46], gait speed, [47], and Gillette Gait Index score, [48]. Godwin et al. described that children categorized preoperatively at GMFCS levels II, III and IV showed greater change (trend toward lower GMFCS) compared with children classified as GMFCS levels I and V, [49]. After this procedure, a period up to 2 years is often required to get a functional plateau level, although there is a lack of published recommendations about the more efficient post-surgical rehabilitation program. New strategies are needed to help to promote, maintain, and rehabilitate the functional capacity, and thereby diminish the dedication and assistance required and the economical demands that this condition represents for the patient, the caregivers and the society,[50].

Most of the therapies for rehabilitation after surgery are peripherally driven and are based on motor control reorganization triggered by peripheral physical therapy. However, CP affects primarily brain structures. This suggests that both Peripheral Nervous System (PNS) and Central Nervous System (CNS) should be integrated in a physical and cognitive rehabilitation therapy. This is exactly the approach of CPWalker. It is important to highlight the plasticity of the target patients of this study, young children present increased brain plasticity compared to an adult, and is more likely to have a change in motor patterns following an intervention.

The main objective of CPWalker is to develop and validate a robotic platform to support novel therapies for CP rehabilitation after SEMLS surgery. The goal is to reduce the period of rehabilitation after surgery. This will be achieved by developing a robotic platform (Smart Walker + exoskeleton + neuroprosthesis) controlled by a multimodal interface to establish the interaction of CP infants with robot-based therapies.

4.2 The CPWalker Concept

CPWalker proposes the use of a robotic platform through which the infant can start experiencing autonomous locomotion in a rehabilitation environment. This robotic platform will consist of a smart walker with body weight and autonomous locomotion support and a wearable exoskeleton robot + motor neruprosthesis for joint range of motion support. The load on the human skeleton define the bone development, as a result, the pathological gaits typical of CP infants induce bones deformities. CPWalker will provide the infant with a structure that will rehabilitate his/her gait to physiological patterns, which will prevent deformation of their bones.

The interaction between the infant and the robotic platform will take place through a Multimodal Human-Robot Interface (MHRI) consisting of an (1) Electroencephalographic (EEG) acquisition unit; (2) an Inertial measurement unit (IMU), (3) wireless Electromyography (EMG) system for measuring residual movement and activation strategies, and (4) force sensors to measure the interaction between the user and the robotic platform. The rationale of this multimodal interface is to allow integrated PNS and CNS physical and cognitive interventions. MHRI interaction with therapeutically selected tasks will be based on volitional motor planning, the aim being promoting reorganization of motor planning brain structures and thus integrating CNS in the therapy. Figure 5 depicts the overview of the CPWalker concept.

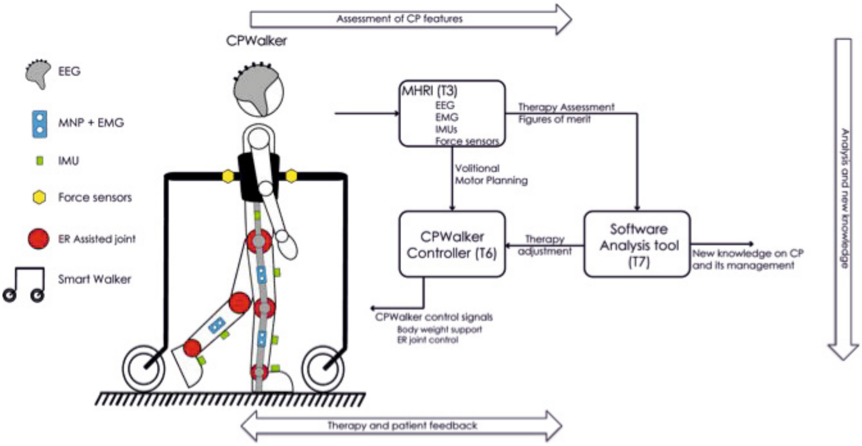

Fig. 5. Overview of CPWalker concept

Summarizing, CPWalker methodology will unify and standardize technological, biomechanical, neurophysiological and clinical concepts that will culminate in the development of the following instruments:

- A smart walker with body weight support to promote the autonomous locomotion,
- An exoskeleton + neuroprosthesis able to apply forces to lower limbs joints,
- A multimodal human-robot interface to promote the integration of the patient into the therapy,
- A software analysis and capture tool to quantify the rehabilitation progress in three domains: kinematic, physiological and functional.

4.3 Strategies for Gait and Body Weight Support

As decribed in previous sections, there are different gait training devices based on PBWS in the market. However, most of them do not propose ambulatory training and present difficult procedures to transfer the user from the wheelchair to the standing position. It is required for the therapist or caregiver to do important physical effort. In general, these devices seem to have promising results for rehabilitation, according to the literature, but present some limitations such as heavy weight, complex set-up and non-ambulatory mobility or poor maneuverability in the case of mobile devices, making them inappropriate for small interior spaces with narrow doorways.

The CPWalker project is involved in the framework of a research line to design ambulatory devices for rehabilitation and functional compensation in the Bioengineering group of CSIC. These devices are the evolution of the classical walkers, which play an important role when the user has residual capabilities to push the system. However, the usability decreases when the user suffers severe motor impairment, as a patient after a multilevel surgery. This is the context where smart or robotic walkers are emerging as a feasible solution. Some works related to the CPWalker project have been previously developed by the authors and their colleagues. The SIMBIOSIS project proposed a smart walker, which analyzed dynamically the user gait adapting the active support according to user needs, [10], (fig. 6). The SIMBIOSIS measures the forearm forces to improve human-machine interaction. This walker embodies several innovative aspects, such as: i) enhanced user unloading by means of forearm support, ii) augmented stability in static and dynamic conditions, iii) improved guiding control skills based on detection of users intention and iv) accurate safety-oriented strategies.

Fig. 6. The SIMBIOSIS Smart Walker

An interesting result was extracted in the clinical validation of the SIMBIOSIS device in spinal cord injury (SCI) patients. The user unloading is crucial to improve the functionality of these systems in rehabilitation due to the lack of motor control and muscle tone in the lower limbs. Therefore, it is recommendable to implement body weight support to modulate the user unloading improving assisted ambulation and reducing the high metabolic energy expenditure required.

In this context, the HYBRID project, developed by GBIO-CSIC, tries to solve these issues. This system considers the use of a bilateral lower limb robotic exoskeleton integrated with an external ambulatory and active structure with electric traction, REMOVI (fig. 7), which provides support and stabilization to the user through a harness in real ambulatory scenario. This system is proposed as a device to develop rehabilitation exercises for patients with SCI or other pathologies, who present serious mobility problems. The patient wears an integral harness in order to perform the elevation process from wheelchair to standing-up position. Two electrically actuated lifting arms or bars, placed on a superior plane, elevate the user by means of the harness. This motor sets the level of unloading. Finally, two tractor motors with encoders are mechanically coupled to the system allowing overground training.

Fig. 7. The REMOVI device

Preliminary studies with healthy subjects have been carried out with 0%, 30%, 50% and 70%. It was observed that the range of motion and the heel contact decreases as a function of the height support but the PBWS does not influence on the cadence or the step length, [51].

This background has been partially applied to the CPWalker concept. The design of the device is based on the framework of the NF Walker system, (Movement for Movement). The NF Walker is widely used as a very effective mobility aid for some users with CP, thereby, the CPWalker project will use the framework of this device to include elements that supports the gait and weight actively. Fig. 8 depicts a CAD design of the device. The design includes to DC motor for the gait support and a linear actuator for the weight support. Additionally, the system will include a pediatric exoskeleton, [52], which consists of an external structure that assists the natural skeleton of the user. The exoskeleton is composed of three parts, which are articulated by three joints and adjusted to the body by means of several belts. This exoskeleton is based on the devices designed from previous adult version develped in the context of the EU projects Hyper, [53] and Gait, [54], [55].

4.4 Multimodal Human Robot Interface

One of the main contribution of the CPWalker is to take into account the cognitive processes of the user to guide the device actively. The CPWalker includes a

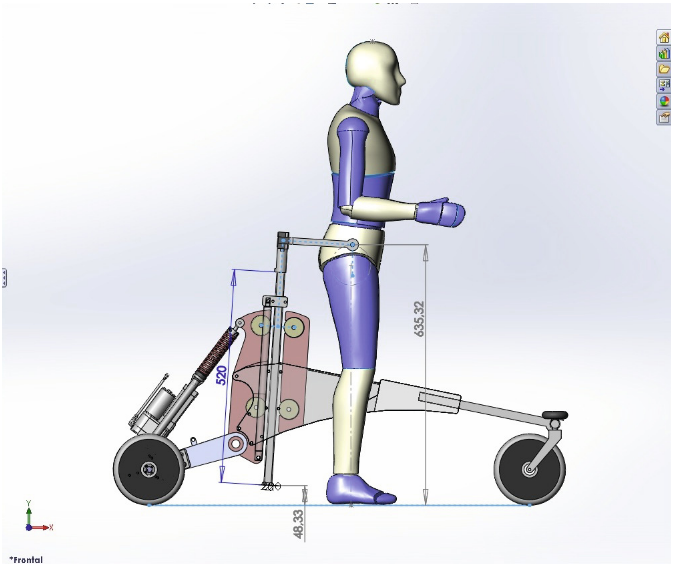

Fig. 8. CAD design of the CPWalker device

Multimodal Human Robot Interface (MHRI), which is a novel type of interface that integrates information from the central nervous system (CNS), and the peripheral nervous system (PNS) in order to characterize the full state of the user. MHRIs are topics of research in many contexts, and have proven, for example, to be able to characterize concomitant voluntary and pathological components of movement in tremor patients, [56]. MHRIs appear as an upgrade of traditional brain-computer interfaces (BCIs) and brain-machine interfaces (BMIs), which have been used for a large number of problems, e.g. wheelchair control, [57], spelling systems, [58,59], restore hand grasp, [60], or to improve upper or lower limb rehabilitation [61,62].

The rationale for using MHRIs in the CPWalker project is that by integrating the PNS one can obtain a more detailed representation of the behaviour of the CNS. This arises from the fact that the motor units that compose the muscles (and hence the PNS) are the smallest transductor of the commands generated at the brain, and muscle activation is responsible for the actual movement. Therefore, concurrent recording of these data provides with a richer and better characterization of the mechanisms of motor control. MHRIs are implemented using different technologies that range from highly invasive interfaces to record very localized neural ensembles, [63,64], to their noninvasive counterparts, electroencephalography (EEG) and surface electromyogrpahy (sEMG). The MHRI here proposed is aimed at integrating the CNS and PNS into the rehabilitaiton therapy, in order to optimize it according to the users skills.

In more detail, the CPWalker MHRI will comprise EEG, sEMG and inertial sensors (based on results obtained from ENLAZA project) in order to characterize both the generation, planning and execution of movement, and the users state during the therapy. This will be achieved based on: i) a previous characterization of the strategies that underlie volitional motion planning, [65], in CP affected children, ii) the neural drive to muscles (defined in terms of activation patterns, central pattern generators, [66], and muscle synergies) and iii) the kinematics of the actual movement, [67].

Movement parameters will also be exploited by the controller of the CPWalker to adjust certain features such as walking speed or initiation of gait. Furthermore, the MHRI data will serve to assess the outcome of the CPWalker therapy in terms of reorganization of the neural structures, which will be assessed by analysing the raw neural drive to muscles and the muscle synergies. This will in turn permit elucidating the neural mechanisms that mediate the recovery, such as the normalization of the muscle synergies or the correction of their activation and combination, [68], which will constitute a major neuophysiologic finding.

The CPWalker MHRI constitutes a novel means to integrate the CNS and PNS into the robotic therapy. First, online characterization of the level of attention (at the CNS) and of the neural drive to muscle (at the PNS) will permit optimizing the therapy, in terms of intensity and duration, for each user. Second, the reorganization of the muscle activation patterns will be investigated (at the CNS and PNS) as a means to objectively assess the outcome of the therapy, and also elucidate the neural mechanisms that mediate such recovery. Fig. 9 depicts an user with CP using the experimental MRI at the Jesus Child Hospital (Madrid) where the experiments took place.

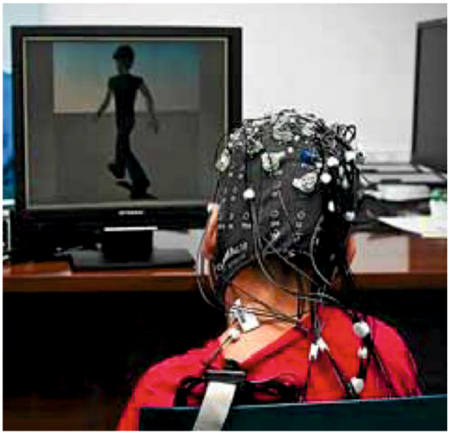

Fig. 9. Experiments of an user with CP using the MRI device

4.5 Current and Expected Results

Currently, the CPWalker project has concluded the conceptual design of the platform and the definition of user needs. Additionally, the control and mechanical architecture have been designed. At this time, CPWalker expects to achieve the following results:

- Description of the users needs (children with CP) for the different subtypes of CP, the functional level (GMFCS) and the special aspects of this still growing population,
- Description of the special features and actual difficulties in the current rehabilitation process,
- Definition of musculoskeletal models through the gait in CP to select and to draw up a plan for adaptive control strategy of the CPWalker,
- Establishment of the pathological kinematic pattern and the central pattern generators (muscle synergies) of children affected with CP,
- Evaluate the long-term benefits obtained with the CPWalker concept, alone or in combination with pharmacotherapy, in a group study. This evaluation will be carried out during continuous periods of use, while patients under traditional and robotic-based therapy.
- Definition of objective figures of merit that will assess the status of the disorder and its evolution. Such metrics will provide the clinician and the patient with feedback on the CP.

As a conclusion, we propose to create a prototype of pediatric sized and adapted wearable exoskeleton becoming the main device in the CPWalker technology. The equipment will support and assist the walking process, and will count in with modifing options to customize the therapy to the necesities of every user.

5 Conclusions

This chapter presented the state of the art of robot-assisted rehabilitation for people with cerebral palsy. According to the review, numerous devices for the rehabilitation of gait exist. Robotic exoskeletons to support the human gait have become very popular because they propose interesting strategies to increase the frequency and intensity of the sessions. Some of these devices, which were designed for spinal cord injury or stroke, have been recently adapted for people with cerebral palsy. On the other hand, robot systems for the rehabilitation of upper limbs are scarce. However, some studies demonstrate that robotic therapy may provide new opportunities for improving upper limb coordination, strength and functions, such as reaching and grasping. Generally, a lack of longitudinal and randomized clinical trials (RCT) exists. This fact makes difficult to evaluate the impact of the robotic device after the robotic training.

Recent studies suggest that the users motivation and cognitive aspects, e.g. (attention) is essential to achieve the maximum impact on physical skills. That means that the combination of the physical and cognitive aspects will lead to better results of the rehabilitation. In this context, the design of virtual scenarios (e.g. videogames) in combination with robotic devices is providing promising results. This aspect is particularly important in the children with cerebral palsy cases, because their cognitive, social and perceptive skills are often more affected respect to other pathologies such as stroke or spinal cord injury.

In this chapter, we presented the PALMIBER vehicle, a robot platform to promote the integral development of children with cerebral palsy through mobility experiences. The vehicle is based on the fact that fundamental skills are developed at early ages when the brain plasticity is higher. The PALMIBER integrates different driving modes with gradual user intervention (from Cause-effect to Fully-guided mode) in order to adjust the robotic therapy the different cognitive levels of the child. Additionally, the vehicle includes a group of human-computer interfaces to adjust the driving task to the user manipulation skills. A head-mounted interface called ENLAZA allows users with severe motor disability to control the vehicle with head motion. The inertial interface is an effective channel to reduce the barriers between the user and the vehicle. Additionally, the interface is an intuitive method to drive the vehicle and learn spatial concepts, because the head movement is translated to the vehicle displacement. On the other hand, inertial technology provides a new opportunity for analysis and extraction of kinematic patterns of voluntary and pathological movement. The impact of therapies will be evaluated with objective parameters as complement to the functional and subjective evaluation of the therapists. According to the state of the art, virtual and playful applications (e.g. video games) will increase the interest and motivation of us-ers, which will have a positive impact in rehabilitation. In this context, motion capture systems and virtual representation allows users to encourage the exercise therapy by biofeedback methods. The ENLAZA interface, through head movements, allows the user with CP to control the vehicle but also it may be use for the computer.

The PALMIBER vehicle and the ENLAZA interface propose an auto-adaptive physical-cognitive and dual therapies, which will promote active participation of the infant with CP, implementing a gradual intervention tailored to his/her functional physical and cognitive limitations and abilities. Additionally, these devices provide objective metrics that assess the status of the user based on this multimodal information, which will be employed to provide support to the therapist, and to establish definite, personalized, criteria to assess the outcome of the rehabilitation, and guidelines for it. The final outcome of these robotic devices is a framework for the integrative (i.e. physical and cognitive) assessment and rehabilitation of infants with CP.

Additionally, we present the CPWalker project, which proposes an ambulatory robotic platform for gait rehabilitation after surgery. CPWalker platform includes a smart walker for weight support, an exoskeleton for support the joint range of motion, a human-machine interface and assessment software to generate objective outcomes metrics of the therapy progress. The main contribution of the project is to include the cognitive dimension into the physical therapy. The CPWalker Human Machine Interface constitutes a novel means to integrate the central neural system and peripheral neural system into the robotic therapy. Online characteriza-tion of the level of attention (at the CNS) and of the neural drive to muscle (at the PNS) will permit optimizing the therapy, in terms of intensity and duration, for each user.

The results and problems that these developments faced suggest a field of work that must be addressed in future. One of the interesting factors to consider is to analyze how physical and cognitive learning affects the device control. Therefore, there will be carried out a long term planning experimentation.

The work presented in this chapter has given rise to new challenges to be addressed within a line of research with a commitment to find new solutions for people with CP. The state of the art shows that new Assistive Technologies and, specifically, robot-assisted therapies designed specifically for people with PC are taking up the interest of numerous research groups. This fact will lead to more efficient devices, auto-tailored to the particular users cognitive and physical needs and, finally, improve the autonomy of people with cerebral palsy.

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