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Development and evaluation of a novel robotic platform for gait rehabilitation in patients with Cerebral Palsy: CPWalker

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HIGHLIGHTS

- Rehabilitation with free displacement and not restricted to a treadmill.
- Integration of central nervous system into therapies.
- Postural control and partial body weight support for individuals with more severe disorders.
- "Assist as needed" approach.
- Locomotion strategy based on laser sensor.

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ABSTRACT

The term Cerebral Palsy (CP) is a set of neurological disorders that appear in infancy or early childhood and permanently affect body movement and muscle coordination. The prevalence of CP is two–three per 1000 births. Emerging rehabilitation therapies through new strategies are needed to diminish the assistance required for these patients, promoting their functional capability. This paper presents a new robotic platform called CPWalker for gait rehabilitation in patients with CP, which allows them to start experiencing autonomous locomotion through novel robot-based therapies. The platform (smart walker + exoskeleton) is controlled by a multimodal interface that gives high versatility. The therapeutic approach, as well as the details of the interactions may be defined through this interface. CPWalker concept aims to promote the earlier incorporation of patients with CP to the rehabilitation treatment and increases the level of intensity and frequency of the exercises. This will enable the maintenance of therapeutic methods on a daily basis, with the intention of leading to significant improvements in the treatment outcomes.

1. Introduction

Cerebral Palsy (CP) could be defined as a disorder that appears in infancy and permanently affect posture and body movement but does not worsen over time [1]. CP is often associated with sensory deficits, cognitive impairments, communication and motor disabilities, behavior issues, seizure disorder, pain and secondary musculoskeletal problems [1]. CP affects between two to three per 1000 live-births, reported to the European registers by the Surveillance of Cerebral Palsy European Network (SCPE) [2], and there is a prevalence of three to four per 1000 among school-age children in USA [3].

In some cases, the development of a secondary musculoskeletal pathology contributes to loss of function, gait impairments, fatigue, activity limitations, and participation restriction. Several technological advancements have been introduced into the field of rehabilitation to complement conventional therapeutic interventions.

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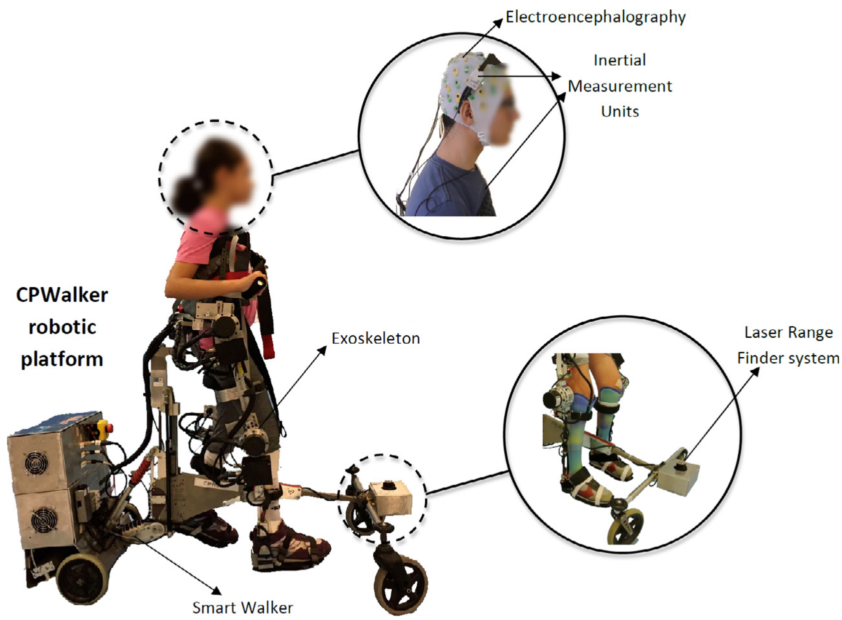

Fig. 1. CPWalker platform (smart walker and exoskeleton) and the technology used in the multimodal human–robot interface (MHRI): electroencephalography unit, inertial sensors for postural control and laser range finder.

Intense task-related strategies, comprehensive combination of non-invasive treatment, surgical interventions and new technologies have been initiated to improve rehabilitation strategies [4]. These novel technologies, such as robot-assisted gait training or other computer-assisted systems have been primarily developed for adults [5]. Nevertheless, after technological adaptations, these therapies have been implemented in the pediatric field [6]. Preliminary results have supported the feasibility of these novel approaches in the clinical context [7,8]. More specifically, robot-based therapy is a safe treatment option with no severe side effects [9]. In addition, clinical experience suggests that gait training in children with considerable cognitive deficits could be conducted even more effectively using robot-assisted therapy rather than conventional training [6].

Traditionally, robotic strategies have been focused on the Peripheral Nervous System (PNS) supporting patients to perform repetitive movements (a "Bottom-Up approach"). However, CP primarily affects brain structures, and thus suggests that both PNS and Central Nervous System (CNS) should be integrated into a physical and cognitive rehabilitation therapy [10]. Current studies manifest that such integration of the CNS into the human–robot loop maximizes the therapeutic effects, especially in children. This approach is known as "Top-Down" approach [10]: motor patterns of the limbs are represented in the cortex, transmitted to the limbs and feedback to the cortex. Although this approach has been previously studied in other populations (e.g. stroke [11], Spinal Cord Injury [12]), there is a lack of studies in Cerebral Palsy [13].

On the other hand, rehabilitation with progressive reduction of partial body weight support (PBWS) coinciding with over-ground walking encourages the patients and it is a motivated condition for recovery in childhood [14].

In this paper we propose a new robotic platform (CPWalker, Fig. 1) with the aim of supporting novel therapies following a "Top-Down" approach for CP rehabilitation. The platform is composed by a smart walker with PBWS and autonomous locomotion for free over-ground training, and a wearable robotic exoskeleton for joint motion support. The interaction between the patients and the robotic device will take place through a Multimodal Human–Robot Interface (MHRI) consisting in a set of sensors attached to the device, allowing the users to control the system through different modalities that are commented in the next points. We focus our attention on children with CP, who present increased brain plasticity compared to adults, and are more likely to have a change in motor patterns following an intervention [15]. With this platform we want to contribute beyond reducing the clinician's effort or increasing the duration of the treatment, giving the novelties of: (i) free movement (not restricted to treadmill training) to enhance the subject's motivation; (ii) tailored therapies depending on the user's needs through Assist as Needed (AAN) strategies to increase the patient's participation; (iii) the use of different sensors to improve the rehabilitation, controlling posture during robot-based therapy; (iv) integration of CNS to intensify the effects of the therapy.

This paper presents the development of such a platform, which is called CPWalker. Next section introduces the aspects related to the conceptual design of the platform and the description of the different components of CPWalker. In Section 3, the multimodal interface to enable the implementations of "Top-Down" rehabilitation strategies is presented. The elemental control strategies proposed for CPWalker are given in Section 4. Section 5 discusses the control architecture and the communication between its components. Preliminary technical validations are introduced in Section 6. Finally, Section 7 reported the discussions and conclusions of the work.

2. Robotic platform

CPWalker is a robotic platform to help patients with CP (primarily children) to recover the gait function through rehabilitation training. The definition of the conceptual design of the platform was undertaken based on the results of several interviews with a population composed by 4 children with CP, 10 relatives, 4 doctors and 5 physiotherapists. The evaluation of these results provided some requirements, features and functionalities that were needed and should be integrated in the novel device. We defined the neurophysiological aspects for the development of each subsystem: anatomical joint and muscle groups target by our platform, as well as the kinematic and kinetic profile patterns of pathological gait of subjects with PC. The result of this analysis (Table 1) enabled the consortium to: (i) identify the needs and demands of gait rehabilitation for different user's profiles; (ii) recognize the problems and benefits presented by the current walkers; (iii) identify current gaps in the market; (iv) determine the features and functionality

Table 1
Results of the interviews that serve as base for the conceptual design of CPWalker

Criteria for the conceptual design of CPWalker		
To correct problems which concern about	To apply usability criteria which allow	To improve therehabilitation through
–Changing the previous gait pattern –Removing the crouch gait –Dissociating each side of the body –Improving the force in muscles	–To improve the balance –Patient's PBWS –To enhance the force	–Reducing the caregiver's physical effort –Allowing over-ground displacement in real rehabilitation environments –Including CNS into the therapies

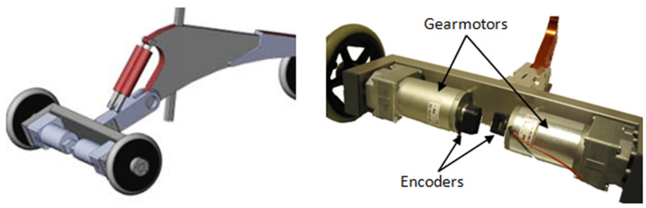

Fig. 2. Drive system of CPWalker.

needed in the new walker; and (v) determine the requirements of accessibility and usability to be considered in the design and development.

Based on this information we defined the conceptual design and the main requirements of CPWalker platform. As a result, we decided to build our robotic platform based on the commercially available device, NFWalker (Made For Movement, Norway). Some mechanical modifications on the NFWalker were carried out in order to transform this passive device into an active rehabilitation platform. The proposal of CPWalker platform is similar to others adopted before [7,14], but in this case we intend to design a fully active rehabilitation robotic platform, which will enable us to implement robot-based therapies according to the "Top-Down" approach. As a result, CPWalker will allow more intense exercises than passive devices. In order to do so, we incorporated four active systems in both the walker and the exoskeleton: (i) a drive system of the platform; (ii) a PBWS system; (iii) an active system for the adaptation of hip height; and (iv) a system for controlling joint motion of the exoskeleton. These systems will be described in depth in the following subsections.

2.1. Smart walker

The smart walker of CPWalker was designed with the aim of giving the necessary support and balance in gait rehabilitation of children with CP. The structure may resist a total maximum weight of 80 kg (exoskeleton + patient). The systems included in the smart walker are:

2.1.1. Drive system

This system is located in the back wheels, and it provides the translation movement required to achieve the necessary support for an ambulation over-ground treatment in real rehabilitation environments, instead of treadmill training (Fig. 2). It is composed by the following subsystems:

- Actuators: The traction system is constituted by two gearmotors K80 63.105 (Kelvin, Spain) coupled to each rear wheel. Motors work individually, providing independent speed to left and right wheels. The speed range of the device is encompassed between [−0.60, +0.60] m/s.
- Sensors: We installed two encoders, one at each traction engine. Information provided by the encoders is used to control the velocity of the translation.

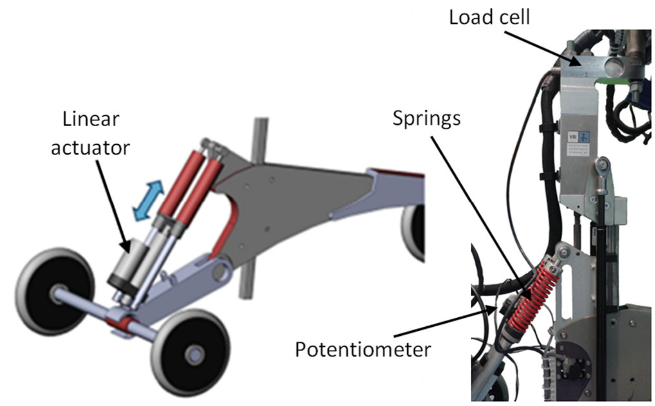

Fig. 3. System for PBWS of the patient.

2.1.2. Partial body weight support system

This system (Fig. 3) is responsible for the control of the discharge of user's body weight. The ability of discharging a partial user's weight during gait improves the patients' rehabilitation because they have to use less activity to neutralize the gravity, and can take advantage of their residual force to learn and coordinate movements [16]. It aims at making easier the exercises along the first sessions (when the patient is weaker) or with users with a greater Gross Motor Function Classification System (GMFCS) score [17]. The effectiveness of the PBWS in robotic rehabilitation has been demonstrated previously [14,18,19]. The actuators and sensors of this system are:

- Actuators: this system consists of an electric linear actuator CAHB-10-B5A-050192-AAAP0A-000 (SKF, Sweden), which with an input voltage of 24 Vcc can achieve 1000 N of load. This actuator compresses and decompresses the original springs of NFWalker (Fig. 3 left), and the user's weight is controlled by this compression and decompression. It allows a significant unloading respect to the ground up to 45 kg.
- Sensors: The sensory part of the PBWS system is composed by a potentiometer and a load cell:
    - Potentiometers: the elevation system is equipped with one potentiometer, which measures the compression or decompression of the springs of the suspension system, and it is located between them (Fig. 3 right). This measure is used to implement the fine control of the user's weight discharge.
    - Load cell: this force sensor is integrated into the walker structure (Fig. 3 right) in order to measure the amount of user's weight that is supported by the robotic platform. This information is therefore used for the control system.

2.1.3. System for the adaptation of hip height

This system is used to adapt the robotic platform to different anthropometric measures by adjusting the hip joint of the exoskeleton at a specific distance from the ground (Fig. 4). The system

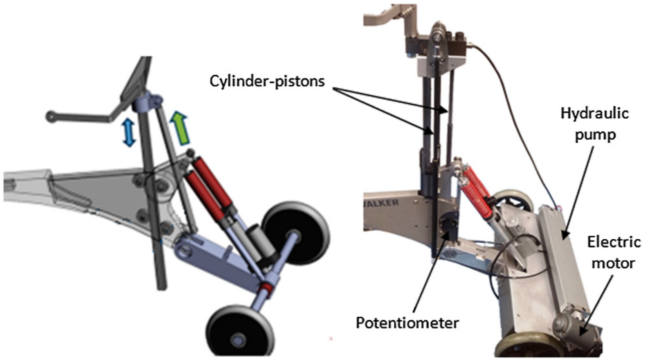

Fig. 4. System for the anthropometric adaptation of hip.

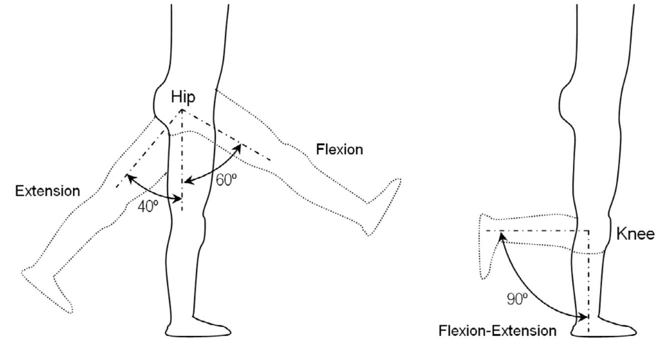

Fig. 5. Range of motion of the different joints of the CPWalker exoskeleton.

is able to elevate the patients from the floor and position them with legs stretched. Therefore, the user can walk without restrictions. In order to implement such actions, it is composed by the following actuators and sensors:

- Actuators: this system is activated by a linear actuator E21BX300-U-001 (Bansbach easylift, Germany) composed by a hydraulic pump and two cylinder-pistons. The hydraulic pump is controlled by an electric motor. The pistons are connected to the hip joint of the robot and by controlling its displacement the system may control the height of the user's hip in relation to the ground (Fig. 4). With a stroke length of 300 mm, this actuator is able to generate forces high enough to elevate the child. The cylinders work in parallel through a slideway that supports the bending moments generated by the user's weight.
- Sensors: this system has one potentiometer for the height regulation system, which is located in the docking between the exoskeleton and walker (Fig. 4). The potentiometer changes the measure according to the hip elevation with respect to the walker platform. This parameter gives information about the position of the hydraulic linear actuator.

2.2. Exoskeleton

The exoskeleton of CPWalker has a kinematic configuration similar to the human body, and it can implement guided and repetitive movements to the user's lower limbs in the sagittal plane. The structure of the exoskeleton is based on the original NFWalker device, in which the requirements of actuators have been added, based on previous work [20]. Aluminum 7075 is mainly used in the structure of the exoskeleton and joints, due to its mechanical resistance and lightweight. The whole design of the exoskeleton is lightweight and, at the same time, rigid and strong in order to allow walking and increase strength and endurance of people with mobility disorders, in particular children with CP. In order to make the robot compatible with different users, the length of the structure can be adjusted to different patient's anthropometric measures. In addition, the exoskeleton prevents displacements of lower limbs to abnormal positions. The device has been designed for over-ground walking training, and according to this, the maximum allowed range during walking is: 60° for hip flexion, 40° for hip extension, 90° for knee flexion and 0° for knee extension (Fig. 5). The movable range ensures the necessary motion for proper gait rehabilitation. For safety reasons, the range limitation is kept by both hardware (adjustable end-stops) and software.

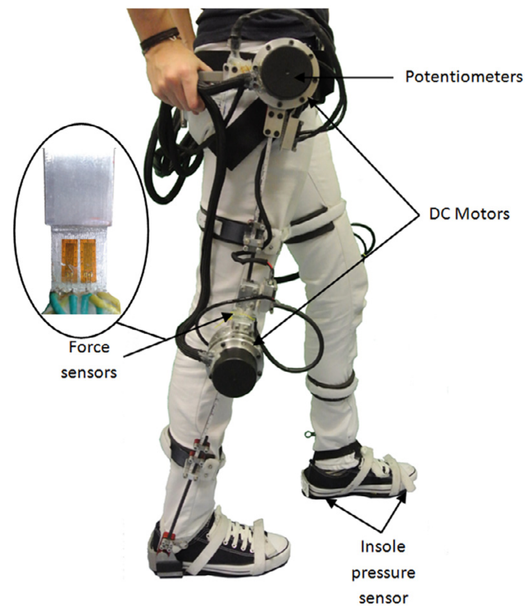

Fig. 6. User wearing the exoskeleton of CPWalker.

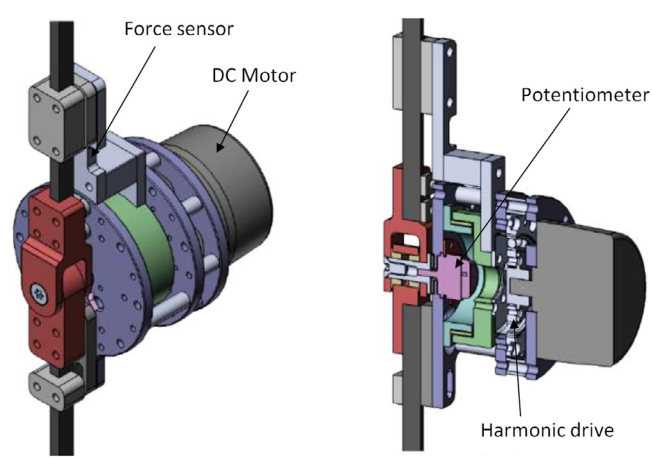

Fig. 7. Schematic drawing of joint assembly of CPWalker.

2.2.1. System for the control of joints movements

The exoskeleton system is composed by six active joints (both hips, knees and ankles), although at present it only has actuated hips and knees, while the ankle is left free to move (Fig. 6).

- Actuators: the actuation of each exoskeleton joint is composed by a harmonic drive coupled with a brushless flat DC motor EC-60 flat 408057 (Maxon ag, Switzerland). The harmonic drive mechanism CSD-20-160-2AGR (Harmonic Drive LLC, USA) was selected due to its capacity of working with high gear reduction ratios, allowing ensemble position accuracy with a low weight/volume ratio. The gear transmission of the joint is 1:160. This setup was adopted since it allowed the design of a compact actuation system [21]. The assembly (Fig. 7) provides an average torque of 35 Nm, which is in accordance with the requirements of [22,23].
- Sensors: The sensors included in this system are:
  - Potentiometers: The exoskeleton has one potentiometer placed concentrically to each joint assembly (Fig. 7). Voltages values received from these potentiometers are converted to angle values, which provide information on the angular position of each joint. This information is used for the implementation of the position and impedance controls.
  - Force sensors: we have included force sensors, based on strain gauges, in the metal rods of the exoskeleton, which are coupled with the joints. These sensors are responsible for the measurement of the interaction forces between the robot and human body. Strain gauges are connected in a complete Wheatstone bridge circuit with the purpose of achieving higher sensitivity [21].
  - Insole pressure sensor: CPWalker uses two force-sensing resistors (FSR) for each insole (one for the heel and another for the toe). These sensors provide information related to the footsteps of the user, useful to assess the gait pattern of the patient.

3. Multimodal Human–Robot Interface (MHRI)

A MHRI is an interface designed with the aim of integrating both the information of CNS and PNS in order to create a communication bus between the human subject and the robotic device. The rationale of the MHRI of CPWalker is to take into account the patient's intention to promote physical and cognitive interventions, and in a second place, to provide a high versatility to the platform allowing greater adaptability of the therapies to the patient's needs.

Several technologies are used to address these objectives, but in this case, the interaction between the child and the robotic platform will take place through a MHRI consisting of: (i) an electroencephalographic (EEG) acquisition unit, used as a method to take into account the patient's intention; (ii) inertial measurement units (IMUs) to improve the patient's postural control; and (iii) a Laser Range Finder (LRF) to measure the human locomotor patterns and to control the robotic platform accordingly. The rationale of this multimodal interface is to allow integrated PNS and CNS into physical and cognitive interventions. MHRI interaction with therapeutically selected tasks will promote the re-organization of motor planning brain structures and thus, integrating CNS into the therapy [10].

3.1. EEG acquisition unit

Promoting the participation of CNS in the rehabilitation strategy implies knowing and modulating the role of patients' brain activity depending of their motor capability. A non-invasive way for achieving this is to capture the electrophysiological activity related to motor behavior by EEG sensors placed along the patients' scalp. Based on such signals, the aim is to build a brain computer interface for initiating the rehabilitation therapy. Additionally, this system will enable to assess the changes induced on the brain by the implemented robot-based therapies.

The EEG control in CPWalker (Fig. 1) is proposed as a method to begin the therapies according to the patient's intention. The process carried out to integrate the EEG into the MHRI comprises two stages: (i) a first early phase aimed at remodeling cortical activity related with gait; (ii) a second phase where the subject controls actively the beginning of the robot-based therapy on the CPWalker platform. In the first phase of training with EEG, the child is lain on a bed and uses a pair of virtual reality glasses Oculus Rift (Oculus, United States) through he/she can see a virtual environment in first person. Once the subjects have trained with the virtual reality glasses and they dominate the control of the EEG signals, they are prepared to implement this strategy into the robotic platform.

3.2. IMUs sensors

IMUs sensors (TechMCS, Technaid, Spain) are used in CPWalker (Fig. 1) to give feedback to the patients when they lose the control of the desirable orientation of the body. The system measures the orientation of the child's trunk and head. This information was a request of our clinical partners since it is a parameter of paramount importance due to with IMUs-based interface we can report to therapists about therapy progress and motor evolution of children with CP [24–26]. These exercises with IMUs consist in giving acoustic feedback to the users when subject's trunk or head are not in a proper position. The aim is to correct the patient's crouch gait and to achieve a better extended hip position.

3.3. Laser Range Finder

The subsystem to detect the user's legs location in CPWalker is composed by a LRF sensor URG-04LX (Hokuyo, Japan) that is able to scan 240° and the legs detection module (Fig. 1). The main controller receives a full sample of the LRF scanning, and an algorithm calculates the position of the legs in real time. The sensor is installed on the front of CPWalker at a height of 15 cm from the floor, in order to assess legs movements.

The leg detection approach presented in this work combines techniques presented in [27,28], and it is split into four basic tasks: (i) LRF data pre-processing; (ii) transitions detections; and (iii) extraction of pattern and estimation of legs coordinates. In the pre-processing phase, the delimitations of the right leg zone and left leg zone are performed. Inside of these zones the transitions associated with each leg are identified to define the leg pattern. After that, the distances are calculated in relation to the middle point of each leg. The legs detection module returns the distances of the left and right legs, d_l and d_r respectively. This interface will enable clinicians to access a vast amount of information related to the progress of the therapy, which will reveal a deeper understanding of the underlying mechanisms relating to the development of the therapy. Based on this approach, we plan to develop a subject-specific framework where robot assessment will inform robot therapy.

In a nutshell, 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 to optimize the therapy, in terms of intensity and duration, for each user. Secondly, it enables the investigation of the motor patterns (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.

4. CPWalker basic functions

This section describes the different lower-level controllers developed for the control of basic functions of the robotic platform. These basic control strategies, in combination with information provided by the multimodal interface and the different sensors distributed along the platform, will support the implementation of various novel therapies, which will be in accordance with the opinion of our clinical partners. Gait training will be provided according to the level of disability while encouraging patient's participation in the training process. CPWalker robot may use trajectory or impedance control as the base of training therapies that will be developed in the future. These strategies may be combined, selecting different subtasks of walking for each controller. We expect that this possibility will improve the common rehabilitation, insomuch as the therapy is more adapted to the subject's necessities. Moreover, we include a locomotion strategy based on LRF sensor as novel concept of basic strategy. The LRF sensor will work when zero-force control is selected in the exoskeleton. In this case, will be the patient who controls the velocity of the translation through the movement of the lower limbs.

4.1. Trajectory control strategy

Trajectory tracking or position control is a strategy based on the principle of guiding the joints of the user's lower limbs following fixed reference gait trajectories, [29–31]. It consists on an internal control loop that uses the error (θ_{error}) provided by the difference between a reference of normal gait pattern (θ_{ref}) and the angle measured by the potentiometers on each exoskeleton joint (θ), (Fig. 8).

An important question for gait rehabilitation robots is how to assist the patient with the minimum interaction forces between robot and human. This implies that subjects will be able to walk more naturally maintaining the safety, stability and effectiveness of the system. In order to achieve this, the gait pattern applied by the robotic device must be adapted both to the individual user and to the characteristics of the gait. The reference trajectories of CPWaker platform are generated according to the algorithm presented by Koopman et al. in [32], which reconstructs reference joints trajectories based on user's height and gait speed. These reference trajectories consist of normal gait patterns represented by joint angles (θ_{ref}). The controller of each joint is responsible of ensuring the guidance of its own motion in order to get a correct normal gait pattern in the whole exoskeleton. As a result, the generated trajectory for CPWalker corresponds with a matrix of three columns (hip, knee and ankle), while the rows are the angles along the gait cycle (Eq. (1)).

$$\theta_{\text{error}} = \theta_{ref} - \theta = \begin{pmatrix} \theta_{refHip} \\ \theta_{refKnee} \\ \theta_{refAnkle} \end{pmatrix}^T - \begin{pmatrix} \theta_{Hip} \\ \theta_{Knee} \\ \theta_{Ankle} \end{pmatrix}^T = \begin{pmatrix} \theta_{errorHip} \\ \theta_{errorKnee} \\ \theta_{errorAnkle} \end{pmatrix}^T . \quad (1)$$

With this simple strategy, the exoskeleton will be able to guide patient's lower limbs following reconstructed normal reference trajectories for any given speed or percentage of range of motion (ROM). An example of that is given in Fig. 9.

4.2. Impedance control strategy

Although position control has been proven with positive results in several cases [33,34], robot-based therapies might be optimized in order to increase the patient's participation. The impedance of a system (Z(s)) is defined as the relation between the force of this system (F(s)) against an external movement imposed upon it and the movement itself ($\theta(s)$), (Eqs. (2) and (3)). The concept was introduced by Hogan in 1985, [35].

$$Z(s) = \frac{F(s)}{\theta(s)} = I \cdot s^2 + B \cdot s + k \quad (2)$$

$$f = I \cdot \ddot{\theta} + B \cdot \dot{\theta} + k \cdot \theta. \quad (3)$$

In Eqs. (2) and (3): f is force, I inertia, B damping and k stiffness of the system. θ, $\dot{\theta}$ and $\ddot{\theta}$ are position, velocity and acceleration of the robot respectively.

Following the impedance concept developed by Jezernik [31], and Riener et al. [36], for the Lokomat robotic trainee, we implemented an algorithm that attempts to prevent undesired efforts on patients' lower limbs and, most important, to apply the philosophy of AAN to take advantage of patients' residual movement. The method considers the human–exoskeleton interaction to allow a variable deviation from the predefined reference trajectory, [29–31,36]. The approach proposed (Fig. 10) is based on a cascaded *position and force controllers*, whose internal loop is able to track force profiles in a determined bandwidth. In order to perform the parameters identification for both *position and torque controllers*, we took into account that CPWalker moves with sufficiently low values of velocity and acceleration and, consequently, the effects of inertia and damping could be disregarded. Besides, the adjustment followed empiric trial and error calibrations without human users. The *torque controller* was adapted in first place, keeping the proportional *position controller* equals to zero. Once we ensured a proper torque tracking with a zero set point, we started to adjust the external position loop, which tries to perform the generated trajectories in joint-space, if the force detected by the strain gauges of the exoskeleton is close to zero. The relation between both loops determines the impedance applied by the exoskeleton to user's lower limb movements.

Following this approach, the impedance control algorithm of CPWalker was set to provide three levels of AAN: (i) high impedance (more proximal to a pure trajectory tracking); (ii) medium impedance; and (iii) low impedance (more proximal to patient in charge mode). The relations between the extremes of impedance modes (high and low modes) respect to the medium impedance were determined increasing and decreasing around 50% the impedance parameters. Consequently, if the position controller is higher, the torque controller must be reduced and vice versa. Fig. 11 represents he effects of each level of impedance for the same values of reference trajectory in hip joint (red line) and force (blue line) measured in opposition and in favor of movement. When a high level of impedance is applied, the real trajectory of the exoskeleton (green line) follows in a better way the imposed reference (red line). This situation is closer to trajectory tracking control. The opposite situation occurs with a low level of impedance, since in this case, the patient is who has more participation in the control of CPWalker, without becoming a total management of the device.

Each exoskeleton joint has its own controller with specific parameters estimated individually for each case and control mode, so the assistance may be generated separately for each part of the exoskeleton. That means that the type of control may be selected separately for each joint, but the tracking is ensured in all the exoskeleton because the reference is sent for all the controllers in each cycle. This possibility increases the modularity of the system.

4.3. Locomotion strategy based on LRF sensor

Working in parallel with a pure patient in charge mode, CPWalker uses a motion control based on the detection of users' legs position (using LRF) and the motors movements (using encoders). The locomotion model is based on the human–walker interaction model presented in [37] and aims at controlling the

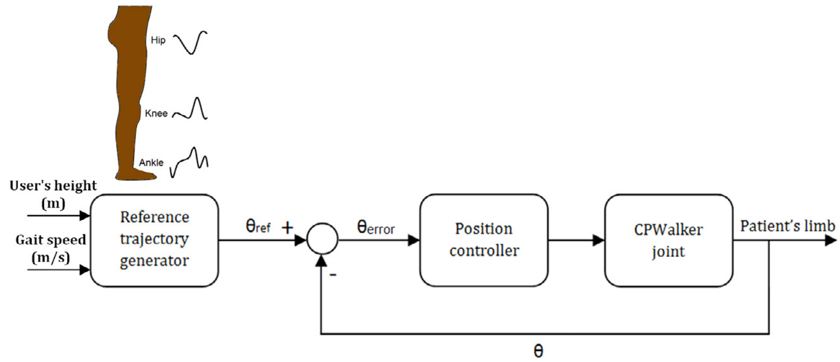

Fig. 8. Trajectory control algorithm of each joint of the exoskeleton. The error of each joint (θ_{error}) passes through the *Position Controller* box, which is a proportional controller whose parameters are individually selected for each joint of the exoskeleton.

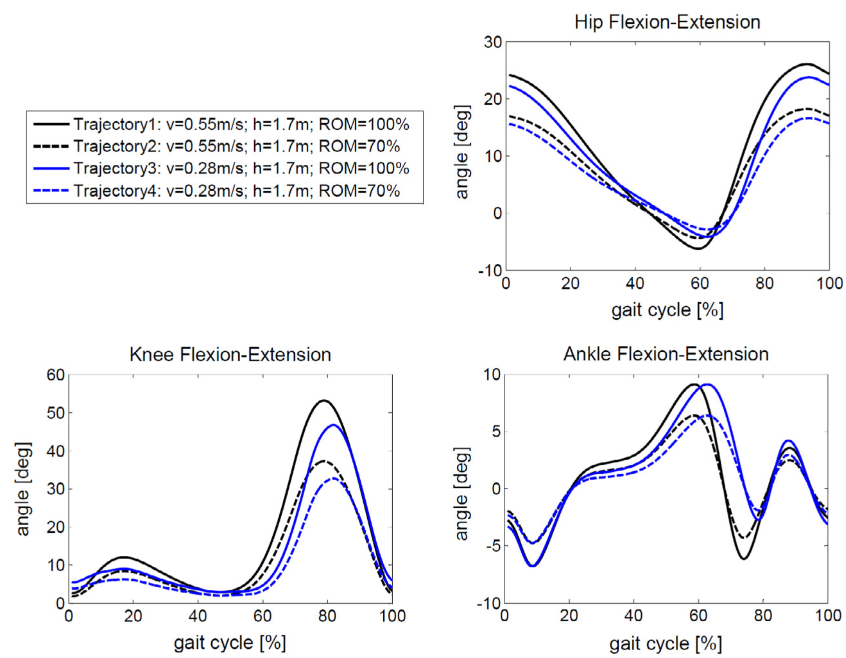

Fig. 9. Changes in reference trajectories for hip, knee and ankle flexion-extension depending on the different parameters as percentage of ROM applied and gait speed.

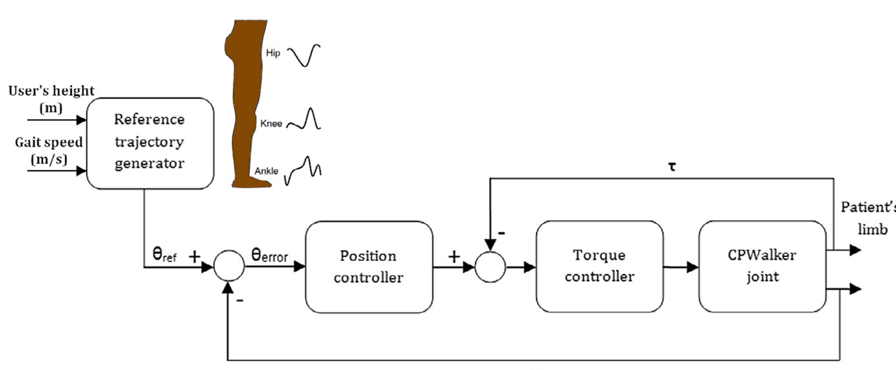

Fig. 10. Impedance control algorithm of each joint of the exoskeleton.

linear velocity (v_r) of the CPWalker platform, see Fig. 12. Following the recommendations of our clinical members, this strategy only enables the control of the velocity of the platform for forward direction.

We defined the mean value of the distance of legs measured by the LRF sensor (d) as the variable to be controlled. The control objective is to achieve a desired distance, ($d = dd$), which is identified by the system when the user is placed on the platform. As a result, $\tilde{d} = dd - d$ is defined as the control error, which represents legs motion at three stages depending on its sign: (i) when $\tilde{d}$ is close to zero, it represents a stable legs position (double support, Fig. 12(a)); (ii) when $\tilde{d}$ is negative, it represents legs motion in

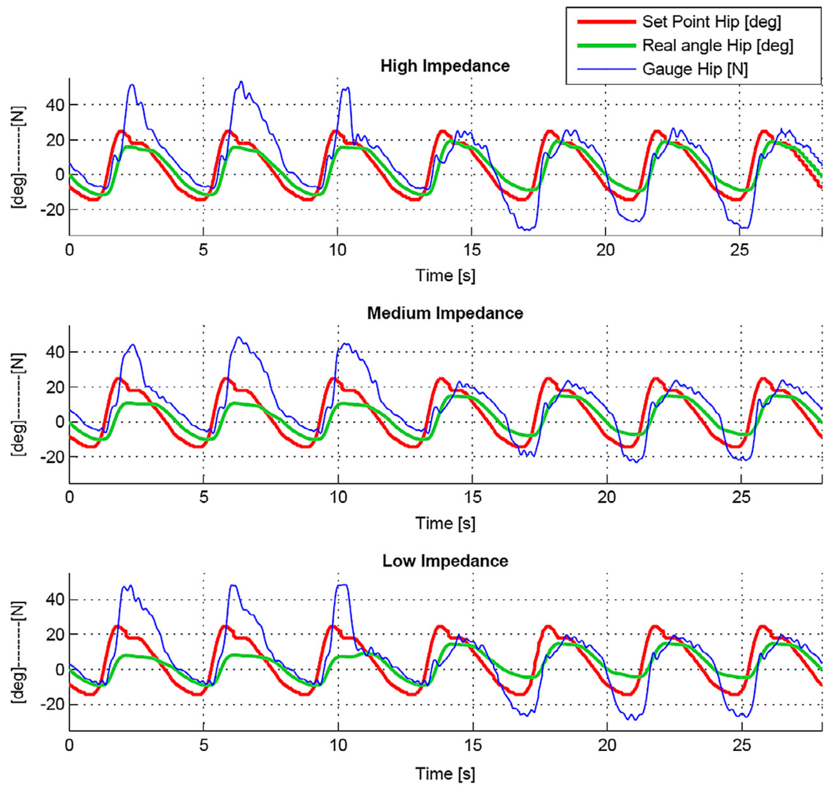

Fig. 11. Different levels of impedance control strategy depending on the assistance provided in the hip joint: high impedance, medium impedance and low impedance. Similar values of references (red lines) and forces (blue lines) cause diverse real trajectories (green lines) according to the type of impedance level.

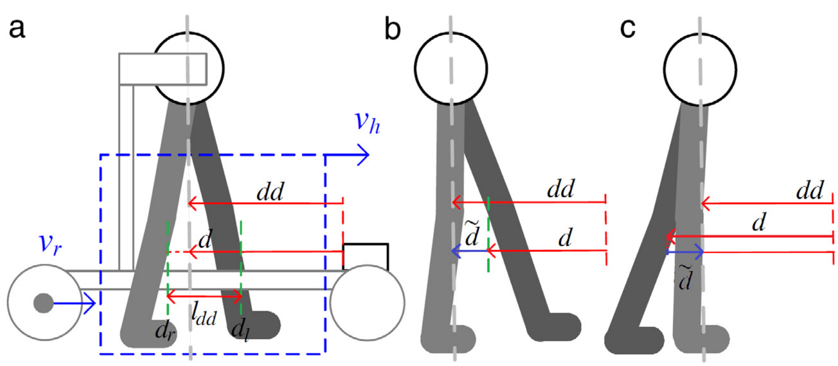

Fig. 12. Locomotion model based on LRF of CPWalker: (a) Bilateral foot contact on the floor (double support); (b) Swing phase for left leg and stance phase for right leg; (c) In this condition both legs are behind the platform, which stops the movement.

order to perform a step (forward direction, Fig. 12(b)); and (iii) a positive value for $\tilde{d}$ indicates that the legs are behind the trunk axis (Fig. 12(c)). In order to warranty the patient's safety, this stage stops the platform to restrict only forward motion according to clinician's recommendation.

A useful variable for the development of natural human–robot locomotion is human velocity v_h. The goal is that the velocity of the robotic platform (v_r) follows v_h to promote user's reliance during therapy. The direct kinematic of Fig. 12(a) is described by the Eq. (4).

$$\dot{\tilde{d}} = -v_h + v_r. \tag{4}$$

The inverse kinematic controller obtained from the kinematic model presented in Eq. (4) is shown in Eq. (5).

$$v_r = v_h - k \cdot \tilde{d}. \tag{5}$$

Human gait consists of slow movements, especially in human–robot interaction scenarios. According to this kinematic approach, using the proposed control law and assuming a perfect velocity tracking, the control error $\tilde{d}$ converges to zero. This conclusion becomes after substituting Eq. (4) in Eq. (5), thus obtaining Eq. (6).

$$\dot{\tilde{d}} = \frac{\partial \tilde{d}}{\partial t} = -k \cdot \tilde{d}. \tag{6}$$

Finally, the control system is exponentially asymptotically stable, as it can be seen in Eq. (7).

$$\tilde{d} = \tilde{d}\,(0) \cdot e^{-kt}. \tag{7}$$

Fig. 12 also shows the l_{dd} signal that represents the distance between both legs produced by the difference between d_l and d_r (defined in Section 3.3). Such signal has a sinusoidal evolution during walking, and it is useful to estimate human velocity (v_h), [37]. v_h is obtained through the product of gait cadence estimation (l_{dd} frequency) and the estimation of step length (l_{dd} amplitude estimation). This estimation is used as a control input of the inverse kinematics controller previously defined.

5. Control architecture

The control architecture of CPWalker is shown in Fig. 13. It intends to favor the interaction of the whole platform. The control architecture is composed by four main parts:

(1) *Robotic platform* constituted by the exoskeleton and the smart walker with their structure, sensors and actuators, as described in Section 2.

(2) *Control unit*, which receives information from the different sensors of the robotic platform. At the same time, it executes the algorithms for the implementation of the therapies in real time, and generates the control signals for the actuators. The control unit is composed by two PC-104, one responsible for the control of the smart walker, and the other responsible for the exoskeleton. The control of the entire robotic platform is implemented into the MatLab RT environment. This environment enables the development of mathematically complex control strategies in real time. The interface between the MatLab environment and the CPWalker platform is based on a data acquisition boards and on particular drivers developed for the control of motors that communicate through a CAN (Controller Area Network) bus [30].

(3) *MHRI Remote computer* runs the interaction of MHRI with the user. This computer is able to acquire the information from the different sensors of the multimodal interface (EEG, IMUs, LRF), process it and send the processed information to the control unit for its implementation. This computer also allows the extraction of user parameters during the therapy: identification of EEG patterns, locomotion pattern and interaction force between the user and the device. It is also possible to save all the information retrieved by the sensors for future offline analysis.

(4) *Clinician unit*, which consists of a smartphone/tablet *device*, that executes an application developed for the interface between the system and the doctor who is using it. This clinical interface, monitors signals and tunes controller parameters in real time during the control strategy execution. It has the following main objectives: (i) monitoring and validation of algorithms for CP rehabilitation; (ii) data analysis (statistics, algorithms performance, etc.); (iii) storage of user information such as clinical and anthropometrics data; and (iv) comparison between different robot-based rehabilitation therapies.

The communication among the different components of the control architecture is illustrated in Fig. 13 and was based on the control architecture defined in [30]. The communication protocol is based on CAN, a bus topology for the transmission of messages designed to reduce the volume, complexity and difficulty of wiring and to achieve a high control speed in real time. To read the message, each driver has an identifier associated to it, which allows that it can be distinguished from other by the main controller [38].

The communication cycles of the difference being controlled in our system occur at a fixed rate (1 kHz) set by the control scheme on the control unit. As a result, this protocol allows for deterministic control and it provides built-in network error detection as, for every message received, each system has to return data information to the control unit. Moreover, the control unit has a robust means to determine the integrity of the network and the correct operation of the joint's actuators. If some failure occurs on the network that cannot be corrected automatically (for instance, a cable disconnection), the control unit instantly shuts down the robotic platform power and stops the CPWalker platform for safety reasons.

6. Technical validation of the different systems

This section describes the technical validation of essential parts of CPWalker platform. It is not a clinical validation, instead it is designed to demonstrate that the different components are integrated into the control strategy and crucial systems are correctly performed. This technical validation enables the clinical staff to design novel therapies for a future use of our platform as benchmark for the experimentation with patients. The local ethical committee at "*Hospital Universitario Niño Jesús*", gave approval to the technical experiment, and warranted its accordance with the Declaration of Helsinki. All patients were informed beforehand, and signed a written informed consent to participate. Future work will be focused on a proper clinical and functional validation of the performance of our system as a rehabilitation tool.

6.1. Validation of EEG system

The practical implementation of our MHRI faced a number of scientific and technological challenges [39]. Amongst the major scientific challenges was the online detection of movement intention in patients with CP, which had not been properly investigated before. According to Section 3.1, EEG unit has been introduced in the rehabilitation through CPWalker platform with the aim of integrating not only the PNS but also the CNS into the rehabilitation therapies of children with CP.

A preliminary technical evaluation of the EEG system was done at Niño Jesús Hospital with three children with CP, aged 11, 13 and 15 years respectively. All patients presented no cognitive deficit and they started the first EEG session few days after surgery. Considering that they were weak, we evaluated only the first phase presented in Section 3.1 (patient lying using EEG in combination with virtual reality), with the aim of training them for the future exercises with CPWalker platform.

EEG signal was captured from 32 Ag/AgCl electrodes (actiCAP, Brain Products GmbH, Germany), placed over the somatosensory and motor areas, according to the international 10–20 system, while an experimental environment is shown by virtual glasses (Oculus Rift) to each child in a first-person view. The signal was amplified and sampled at 256 Hz. The power values were estimated in overlapping segments of 1.5 s and frequencies between 2 and 30 Hz in steps of 1 Hz. Welch's method was used to this end (Hamming windows of 1 s, 50 % overlapping [40]). The glasses cover the total of the human vision range, so providing an absolutely immersive feeling and, therefore, a realistic visual feedback. The virtual environment consisted of a fantasy world designed with Unreal Development Kit (UDK), an open-source 3D graphic and game engine. It is projected in stereoscopic mode to the glasses for a more realistic experience. Each session corresponds to a walk (in first person) through a defined path around the world. Along the path, there are different 22 obstacles (gates, stones, trees…). Each time the patients got close to an obstacle, the walk stopped and they were instructed to relax for 3 s, following a phase of walking imagination for other 3 s. Then the obstacle disappears and the walk slowly resumes.

From these sessions, we selected the pair (channel, frequency band) with the most pronounced and longest decay of the EEG signals power or PSD (Power Spectral Density) during the "obstacle disappearing" and "start walking" periods, with respect to the resting periods. In the BCI-controlled sessions, an obstacle does not disappear until the selected pair (channel, frequency band) reaches and keeps the learned power associated to rest for 1 s. Analogously, once the obstacle disappears, the walk is not re-started until the power value reaches the learned desynchronization for 1 s. Each session was performed after two weeks from the last one.

Preliminary results indicate that all patients were able to overcome all obstacles and complete the paths after two sessions. The

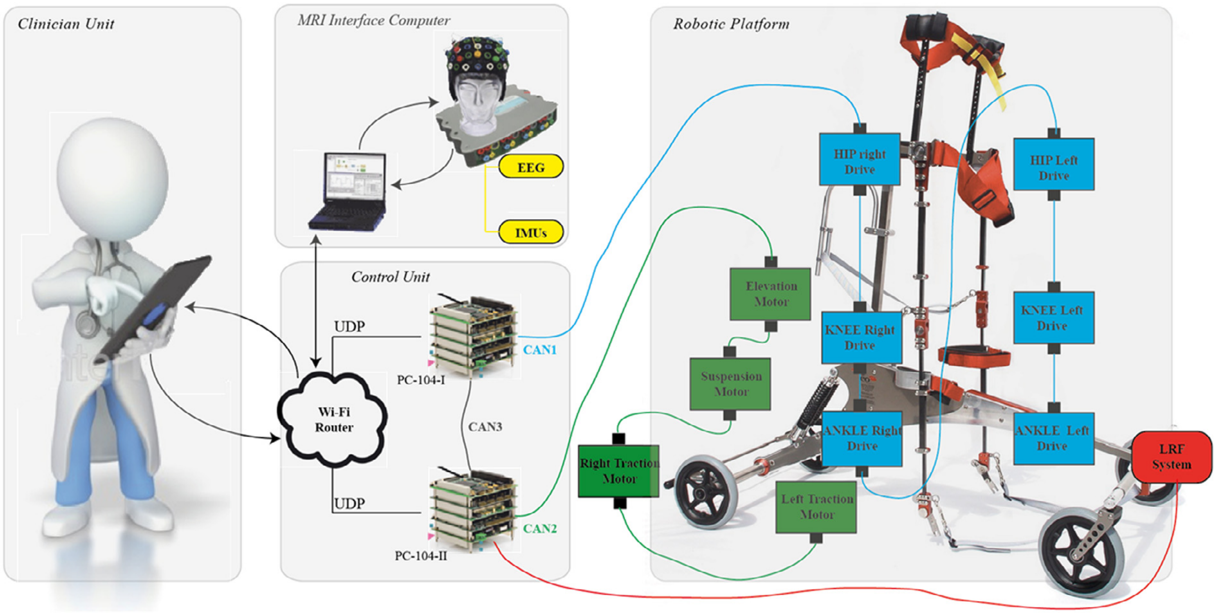

Fig. 13. CPWalker overall control architecture. All sensors in both exoskeleton legs communicate to PC-104-I through a CAN (deterministic real-time) network (CAN1). Motor drivers of the exoskeleton are connected to D/A boards of the PC-104. PC-104-I communicates with PC-104-II via another CAN network (CAN3). PC-104-II is responsible for the control of the traction and PBWS systems. Drivers for controlling the motors of these systems and for reading their sensors communicate with PC-104 via another bus CAN (CAN2). PC-104I and PC104-II together constitutes the control unit of CPWalker platform. Both PC-104 systems are connected to a Wi-Fi hub that enables the communication of both controllers with two external computers: (1) responsible for the acquisition and processing of the MHRI sensors, and (2) a smartphone/tabled that executes the clinician interface and allows clinicians to access platforms information and to control it.

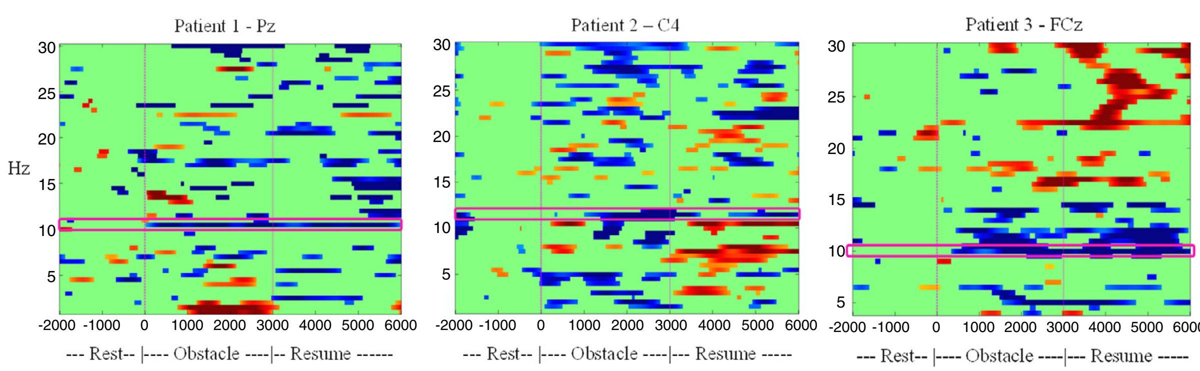

Fig. 14. Average time-frequency graphs showing the most desynchronized pair channel/frequency-bin (pink box) during automatic sessions for the three patients with CP ($p < 0.05$, with respect to "rest" period; blue: lower PSD; red: higher PSD).

average time/frequency graphs of the best channel for each patient are shown in Fig. 14 ($p < 0.05$, with respect to "rest" period; blue: lower PSD; red: higher PSD). These results demonstrate the ability of the EEG system to control the start of the rehabilitation strategy, allowing the implementation of the "Top-Down" approach proposed for this platform.

6.2. Postural control with IMUs based interface

Children with CP presented an altered gait pattern with an increased ROM of the trunk during gait. This problem must be addressed as an independent movement limitation and rehabilitation strategies must be oriented to correct it [41]. In order to address this issue we developed a specific posture control therapy based on the CPWalker, that provides feedback to the patients while allow they to move their legs. The rationale of this IMUs based interface is to enhance the cognitive interaction between the child and the robot.

Such this therapy was preliminarily evaluated in one child with spastic diplegia in order to assess the usability of the system as a rehabilitation tool in clinical practice. The main objective of this trial was oriented to assess the motor control improvements of the trunk during gait. One IMU sensor was placed on the patient's head and the other on the patient's chest. The exercises consisted on giving acoustic feedback to the user through a disturbing sound when the subject's trunk or head were not in a proper position. At the same time, the patient was walking with CPWalker following the position control strategy.

In order to measure the progress of the subject after this robot-based therapy, trunk kinematic data was obtained from 3D gait analysis before and after the experiment. The data collection was performed using an eight infrared cameras system (BTS BioEngeneering). Reflective markers were applied on the shoulder girdle (spinous process of C7 and both acromio-clavicular joints). Marker trajectories were processed and analyzed. For comparisons a pre-post graph was performed for this child (Fig. 15).

6.3. Validation of locomotion strategy based on LRF sensor

As a representative case, Fig. 16 shows the control data recorded during an experiment for 12 s; it corresponds to a patient with CP

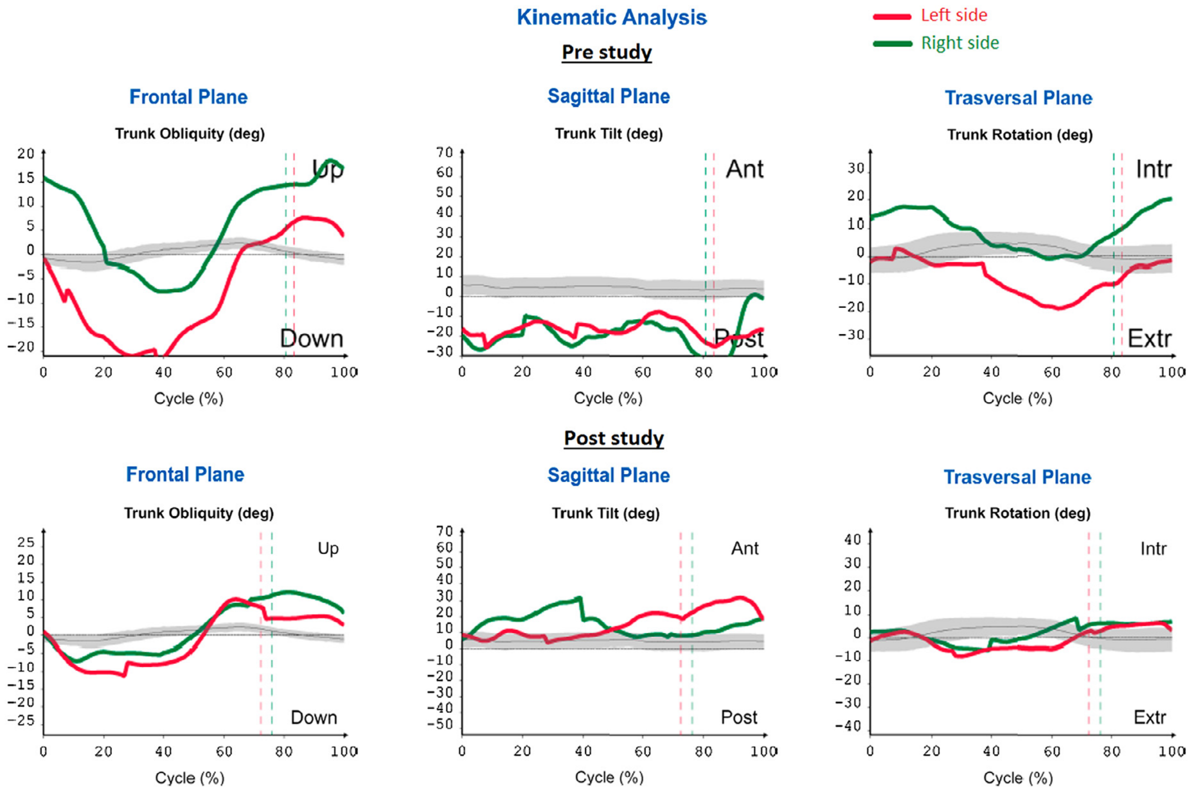

Fig. 15. Trunk kinematics of the child during the pilot trial. Normal trunk kinematics data is represented in grey. Pre-intervention data is represented above. Post-intervention data is represented below. Left side in red and Right side in green.

using the assistance of CPWalker locomotion controller performing a straight path. Fig. 16(a) shows the distance of the legs obtained by the LRF data. $\tilde{d}$ is negative most of the time showing that the patient is walking in forward direction as can be seen in Fig. 16(b). In Fig. 16(c) the control action $v_r(C)$, which is the CPWalker velocity command, follows (v_h), as expected. Finally, there is no significant delay between the control action, $v_r(C)$, and the CPWalker velocity measured $v_r(R)$ from the encoders of the wheels.

In Fig. 16(a), it is possible to observe that the user decreased the step length from the 2th to the 6th second, and it was also increased form the 8th to the 12th seconds. These changes are reflected in the human velocity estimation (v_h) (see Fig. 16(c)). Consequently, both $v_r(C)$ and $v_r(R)$ are updated accordingly and the platform is able to follow the user (see Fig. 16(c)).

Although v_h has the majority of the contribution in the control action (see Fig. 16(c)), there is also an oscillatory component. Such component is the contribution of $\tilde{d}$ to the adjustment of the CPWalker motion during each step. Considering that the trunk is fixed to the platform, when the user performs a step (swing phase), $\tilde{d}$ assumes a negative value. Consequently, the control action is incremented to move the CPWalker with the human trunk in order to achieve a zero error. Therefore, the velocity of CPWalker is also proportionally incremented with each step (swing phase) and it is reduced when the step is finished (double support). This strategy showed a natural Human–CPWalker interaction during preliminary experiments.

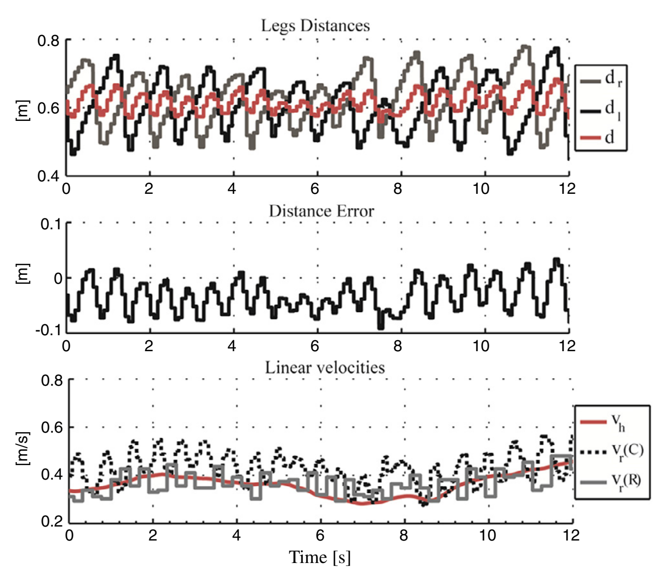

Fig. 16. Experiment of a CP patient using CPWalker with human velocity changes: (a) Legs position detection from the LRF; (b) Distance error that represents the forward walking; (c) Human velocity estimation (red line), CPWalker velocity commands (segmented line) and CPWalker velocity measured (grey line).

7. Discussion and conclusions

This paper has presented a novel robotic system for gait rehabilitation in children with CP and similar motor disorders, which was developed in the framework of the project CPWalker. The overall aim of this project is to develop a robotic platform to provide means for testing new therapies for gait rehabilitation in subjects with CP. This paper has been focused on the conceptualization, development and technical validation of this robotic platform.

The robotic trainer integrates a robotic exoskeleton, a neuroprosthesis, and a smart walker. The combination of these devices into the integrated platform enables the therapists to implement novel interventions for gait training in CP. CPWalker is the first trainer with dynamic bodyweight support and active driven gait in real environments.

CPWalker is equipped with kinematic and kinetic sensors. In addition, the interaction of the user with the platform is implemented through a MHRI based on EEG, IMUs and LRF sensors. These sensors will be also used to both provide a real-time biofeedback to the children, and an off-line report to therapists and caregivers on therapy progress and patient's motor evolution. Feedback information will be derived from the MHRI system, e.g. trends in involuntary movements like effort during motor planning; and from robot information, e.g. trajectories and driving time. The software tool developed to interface the clinician with the robotic platform will allow the therapist to configure the intervention and to obtain feedback of its outcome, both during the rehabilitation session and offline, in order to evaluate the patient's evolution.

Results demonstrated that the different systems of the robotic platform are integrated and performing. Preliminary results show the capacity of the novel robotic platform to serve as a rehabilitation tool [8]. This platform will allow authors to precisely evaluate the effects of different robot-based control strategies on population with CP. The obtained outcomes with future clinical validations aim at providing important results to understand and justify the use of robotic therapy.

This project is built on vast previous clinical evidence that neural plasticity is the central core of motor development, and on studies suggesting that robot-mediated intensive therapy is beneficial for improving functional recovery [42]. Nevertheless, current level of evidence regarding the efficacy of new technologies in the rehabilitation process still remains scarce. These approaches need to be refined and critically analyzed to determine their functional benefit for children with different levels of sensory-motor, cognitive impairment or both.

The presented platform enables the development of different therapies based on the "Top-Down" approach. Future studies using the robotic platform are in place and involve follow-up measurement to determine if gains will have long-term and lasting impact for children with CP.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.robot.2016.12.015.

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