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Chapter

An Active Exoskeleton Called P.I.G.R.O. Designed for Unloaded Robotic Neurorehabilitation Training

Guido Belforte, Terenziano Raparelli, Gabriella Eula, Silvia Sirolli, Silvia Appendino, Giuliano Carlo Geminiani, Elisabetta Geda, Marina Zettin, Roberta Virgilio and Katiuscia Sacco

Abstract

The development of innovative robotic devices allows the design of exoskeletons for robotic neurorehabilitation training. This paper presents the active exoskeleton called pneumatic interactive gait rehabilitation orthosis (P.I.G.R.O.), developed by the authors. The main innovative characteristic of this prototype is its design for fully unloaded robotic neurorehabilitation training, specific for brain-injured patients. It has six degrees of freedom (DOF) in the sagittal plane, an active ankle joint (removable if it is required); a wide range of anthropometric regulations, both for men and for women; a useful human machine interface (HMI); and an innovative harness system for the patient for the unloaded training. It is realized using light and strong materials, and it is electropneumatically controlled. In particular the authors also studied and defined some innovative input control curves useful for the unloaded training. In this paper, the main characteristics and innovations of P.I.G.R.O. are presented.

Keywords: active exoskeletons for unloaded robotic neurorehabilitation training, exoskeletons electropneumatic controlled, pneumatic actuators, robotic rehabilitation, lower limb exoskeletons

1. Introduction

Numerous studies in motor learning and neurorehabilitation training use robots to guide the patient in specific movements, while the clinicians analyze the behavior of the human motor control using the results obtained.

In general, the robotic exoskeletons for rehabilitation can be passive devices or active devices, where electric or pneumatic motors are used on the human upper or lower limb joints [1–10].

The use of robotic devices improves the neurorehabilitation trainings, their duration, and number [1, 2]. Many of these devices, used for rehabilitation on lower limbs, work with a fixed station and use a treadmill; generally they have motors on the hip and knee joints [8, 9], while the ankle joint is free. In fact in the traditional

neurorehabilitation training, the patient walks on a treadmill, and he is connected to a harness and counterweights to reduce the body weight [8].

Nowadays a rehabilitation robot simulates the pattern of the normal walking gait and leads the movement of each lower limb. It can also correct the gait pattern of hemiplegic patients, collecting all the data [9, 10]. In the robotic devices, the use of a treadmill allows repetitive and specific movements to be carried out, which can improve the work of the muscles and the coordination of the movement in the patients [1].

The advantage of using an active exoskeleton without a fixed station is the possibility for the patient to move into the room, walking partially unloaded and helping by means of a body weight support. In this way, the proper perception of the space and the equilibrium of the patient can be analyzed and improved.

Otherwise a treatment with the patient completely unloaded avoids the activation of the antigravity musculature, and the effects of underwater treatments can be simulated.

Furthermore an unloaded training allows to increase, if it is necessary, some range of movement (ROM) of the joints, improving the stimulation of the motor cortex.

An unloaded training also allows to use different input control curves, if it is required by the clinicians, from the curves proper of the physiological gait cycle on the ground, carrying out special training studied for the patient's disease or useful for motor learning studies with healthy volunteers.

Often the unloaded trial is important in the beginning of the neurorehabilitation training for starting the rehabilitation work with the patient [11, 12].

From the robotic and the bioengineering experience, developed in the Department of Mechanical and Aerospace Engineering (DIMEAS) of Politecnico di Torino (Italy), an innovative active exoskeleton for unloaded robotic neurorehabilitation training was developed by the authors. It is called pneumatic interactive gait rehabilitation orthosis (P.I.G.R.O.) [11–18]. It is called Pneumatic Interactive Gait Rehabilitation Orthosis (P.I.G.R.O.) [11–18] and its design is developed through the continuous co-operation of engineers and doctors, allowing the realization of a final prototype that was patented by the Politecnico di Torino [14]. Afterward a spin-off for an industrial process design of the prototype was established in May 2017. In June 2015, P.I.G.R.O. was selected as one of the five more interesting projects in the Soft Landing program, APAC Innovation Summit 2015 Series—Robotics—Hong Kong, June 22–27, 2015. Furthermore, in June 2017, during the 26th International Conference on Robotics in Alpe-Adria-Danube Region, RAAD2017, P.I.G.R.O. authors received the Gold Best Application Paper Award [18].

In this paper, the exoskeleton P.I.G.R.O. is presented, useful for completely unloaded training with adult patients (both women and men).

2. Materials and methods

Comparing P.I.G.R.O. with other exoskeletons [19–22], it is possible to underline the following considerations.

In [19] an innovative assistive rehabilitation strategy is proposed by means of a wearable exoskeleton used without a treadmill and a body weight support. Here the dynamic stability of the patient is obtained by means of an efficient real-time stiffness adaptation for multiple joints (adaptive control system for assistive walking). In [20] an innovative robotic exoskeleton, designed as an ambulatory device, is presented and used during gait trainings on the ground. An adaptive strategy control is developed to guide the patient's legs in a specific gait pattern. In [21] an adaptive control model, controlled by means of the user intention, is proposed using an

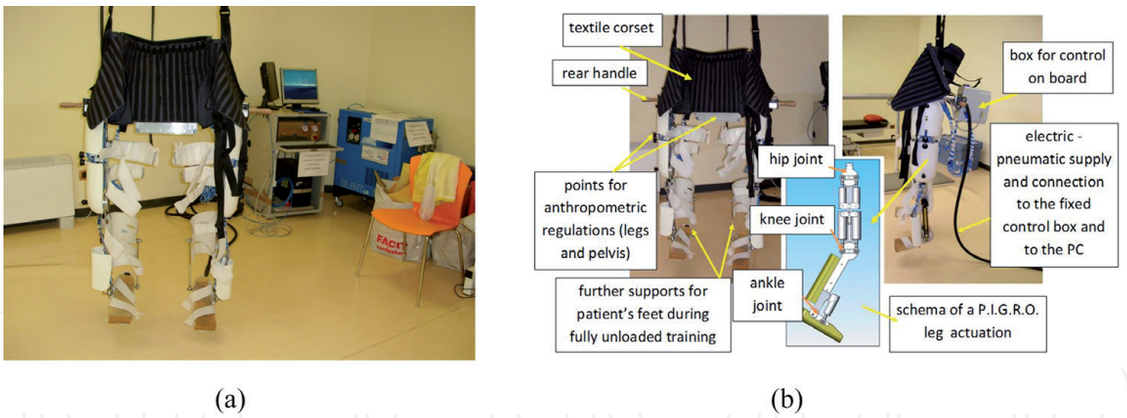


Figure 1.
(a) P.I.G.R.O. structure and (b) some P.I.G.R.O. details.

exoskeleton for lower limb. The study is particularly referred to spinal cord-injured patients. The aim of this assistive control device is the user gait initiation and assistance in real time. This system was tested using a wearable exoskeleton: this shows the reliability of the control equipment in order to ensure the dynamic stability of the user. In [22] an interesting review about hybrid exoskeletons use to restore the gait cycle after a spinal cord injury is presented.

In comparison with the other exoskeletons, P.I.G.R.O. shows some different characteristics, as it was designed for fully unloaded training.

In **Figure 1** some details of P.I.G.R.O. are shown.

An unloaded treatment is useful in the beginning of the neurorehabilitation program especially for brain-injured patients [12].

Through several experimental tests, the authors also studied and defined some specific control input curves in the system suitable for the unloaded training [17].

In particular P.I.G.R.O. is not a device for walking assistance. It is an active exoskeleton designed for robotic neurorehabilitation purpose, and it can be only used in specific rehabilitation centers by clinicians and never with the patient alone. Its main field of application is training for patient with brain lesions affecting motor circuits.

2.1 The structure and the main characteristics of P.I.G.R.O.

The authors analyzed several aspects during the design of this active exoskeleton for unloaded neurorehabilitation training, such as the kinds of trainings to do with the device; the possibility to work without a fixed station; a structure that is light, comfortable, flexible, easy, and quick to wear, and safe, with proper and wide anthropometric regulations, with a mass of about 30 kg; a proper and safe range of movement for each joint; an increased ROM in the ankle joint (possible if the patient is fully unloaded) useful for the motor cortex stimulation but removable if it is necessary; some flexibility of the structure in the frontal plane, in order to avoid a hard robotic gait cycle and to allow some movements of the patient's pelvis and legs also in the frontal plane; the kind of actuation; the values of the torques in the joints lower than those required in the physiological walking on the ground; the control system (here an electropneumatic control system) with some input control curves studied by the authors for the unloaded training; a human machine interface (HMI); a harness system to unload the patient; and an interface between the machine and the patient [12, 17].

All of these aspects were analyzed and solved, giving to P.I.G.R.O. own and useful characteristics.

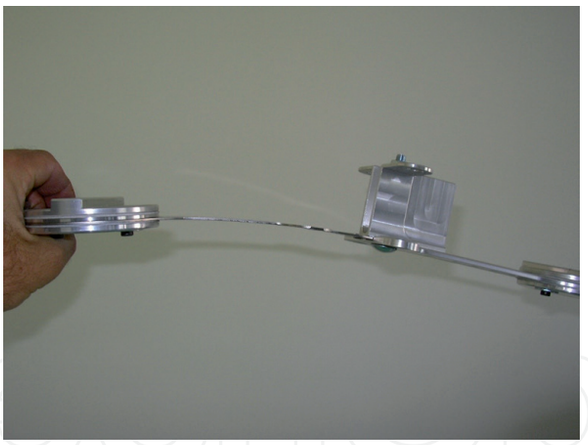


Figure 2.
A detail of the P.I.G.R.O. leg flexibility.

In particular P.I.G.R.O. includes the active exoskeleton (six DOF—degrees of freedom—in the sagittal plane with some possible little movements in the frontal plane too), moved using pneumatic cylinders and electropneumatic valves; a 10-m-long cable, in which both the tubes for the compressed air and the electric wires for the other source are collocated; a fixed box, where the final part of the electropneumatic control is located; a PC and two monitors, one for the operator and the other for the patient's biofeedback; and a movable compressor.

In order to allow some little movements of the patient's pelvis in the frontal plane too during the training, P.I.G.R.O. legs were built in C72 steel and in aluminum 7075 (Ergal) with a specific hardening treatment, giving to this exoskeleton a proper and useful flexibility.

Figure 2 shows the possible deformation in a part of a P.I.G.R.O. leg.

The elements with movement (for the anthropometric regulation of femur and tibia length) have some Turcite© parts interposed in order to reduce the friction.

2.2 P.I.G.R.O. range of movement and anthropometric regulations

The range of movement in P.I.G.R.O. has 40° for the hip joint (from −20° to +20°), 60° for the knee joint (from 0° to 60°), and 40° for the ankle joint (from −25° to 15°). This last ROM is increased, in comparison with the range of the physiological walking on the ground, in order to improve the motor cortex stimulation during the unloaded training.

P.I.G.R.O. anthropometric regulations are between the 10%ile woman and 95%ile man [18], with a variation of the pelvis width from 300 mm, in the 10%ile woman, to 650 mm in the 95%ile man. The femur length varies from 370 mm, in the 10%ile woman, to 500 mm in the 95%ile man, and the tibia length varies from 360 mm, in the 10%ile woman, to 500 mm in the 95%ile man [23, 24]. These

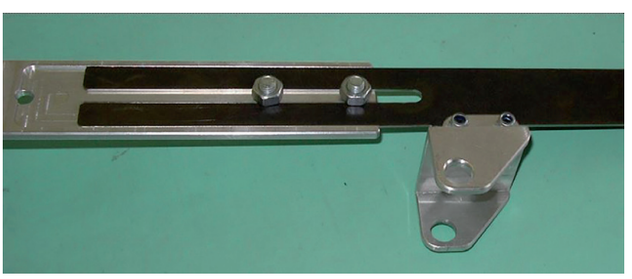


Figure 3.
A detail of an anthropometric regulation in P.I.G.R.O.

anthropometric regulations are done manually by the operator before the beginning of the trial. These regulations are obtained as the femur and the tibia of P.I.G.R.O. are both made of two rigid parts having a related movement, allowing the adjustment of the length required. Some Turcite© parts were interposed to reduce the friction. **Figure 3** shows a detail of an anthropometric regulation in P.I.G.R.O.

2.3 The pelvis regulation system design

On the back of the patient, P.I.G.R.O. has an adjustable structure, to which the two legs of the exoskeleton are connected, which allows the pelvis width to be regulated.

This structure has two screws, with one electric motor through which it is possible to increase or to decrease the pelvis width.

The movement can be conducted using a fast or a slow speed, selecting two different buttons. To this structure, the two legs of P.I.G.R.O. are connected, and two rigid bars, used also to guide the movement of the screws, are inside the structure and give it a strong rigid structure.

The geometry was obtained after several studies on various configurations, in order to design a system that allows a wide pelvis width regulation, that gives a proper speed during the pelvis width adjustment, that gives a strong support for P.I.G.R.O. legs, that provides two lateral supports through which the therapist can stabilize the patient's vertical position during the training, and that improves the wearability of P.I.G.R.O.

3. P.I.G.R.O. electropneumatic actuation design

In P.I.G.R.O. each joint is actuated by means of pneumatic cylinders.

In particular the choice of pneumatic actuators is due to the advantages existing in the compressed air, such as a soft and comfortable way of driving the patient's legs, an easy regulation of the forces during the training, and a safe and clean kind of actuation, useful for hospital applications.

Figure 4 shows some details of the P.I.G.R.O. structure (**Figure 4a**) and of the P.I.G.R.O. activation design (**Figure 4b** and **c**).

Figure 4b shows a detail about the connection of the pneumatic cylinders in the hip and knee joints.

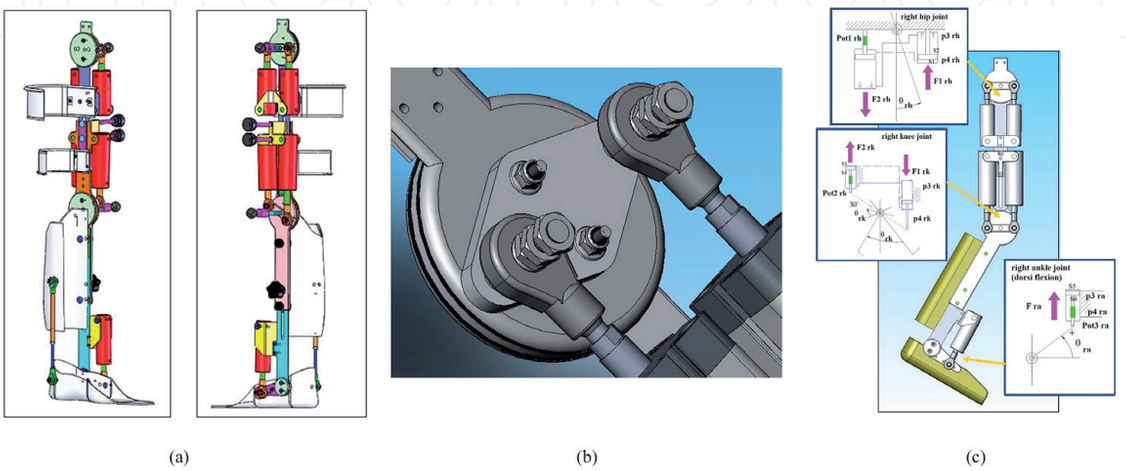


Figure 4.
(a) P.I.G.R.O. complete structure, (b) a detail of the pneumatic cylinder connection, and (c) P.I.G.R.O. hip, knee, and ankle joints activation design.

In **Figure 4c** the pneumatic activation of each joint of one leg of P.I.G.R.O. is shown. In particular an agonistic-antagonistic configuration, using cross-connected chambers, is used to connect the pneumatic cylinders of the hip and of knee joints.

This agonistic-antagonistic structure allows to have a proper surface for the actuator action, reduces the encumbrance of the system, if it is compared with the solution obtained with a single actuator in each joint, and gives a more equilibrated force in both directions of the movement of each cylinder. The ankle joint uses only one pneumatic actuator, when an unloaded training is carried out.

All of the movable elements are covered by means of proper protective caps for safety.

The pneumatic cylinders in P.I.G.R.O. are as follows: hip actuators bore 40 mm stroke 24 mm, knee actuators bore 40 mm stroke 35 mm, and ankle actuators bore 32 mm stroke 40 mm. With the maximum supply pressure (6×10^5 Pa = 6 bar then used in the next text), the torque values for each joint are equal to hip joint, 45 Nm; knee joint, 45 Nm; and ankle joint, 25 Nm. These values are useful for the unloaded walking [17, 18].

In particular the evolution of the torque in each joint was evaluated versus the angle joint, observing a constant trend with a defined supply pressure.

Overall P.I.G.R.O. pneumatic actuation has also n.° 32 2/2 electropneumatic valves to control the cylinders. These valves are normally open and normally closed in order to realize a PID-PWM control system. The number of the electropneumatic valves was chosen in order to have a right conductance for the flow. Two electronic pressure regulators, put in the fixed box, allow the setting of the supply pressure value from the monitor of the operator.

Some more details on the electropneumatic circuit will be explained in the paragraph of the control system.

4. P.I.G.R.O. electropneumatic control system and the input control curves

The hardware of the control system has two main parts: a fixed control box with a PC, a keyboard, two monitors (one for the operator and the other for the patient's biofeedback), and a complementary equipment made of an onboard real-time control system with also the electropneumatic valves and the sensors.

In the fixed box, there is one card for the control and the data acquisition, as well as some electropneumatic valves for the P.I.G.R.O. pneumatic supply and emergency circuit. The onboard part has two cards, for the control and the data acquisition and for their transmission to the fixed box, the electropneumatic valves for the movement of the cylinders.

Some details of the electropneumatic control circuit of P.I.G.R.O. are shown in **Figure 5**.

As shown in **Figure 5**, P.I.G.R.O. has onboard n.° 10 pneumatic actuators; n.° 32 2/2 electropneumatic valves for the supply and for the vent of the actuators; n.° 12 pneumatic sensors, one for each cross-connected chamber of the actuators; and n.° 6 position sensors, one for each joint of each leg. The supply pressure in the actuators of the right and left legs can also be different during the test, and it can be increased or decreased, depending on what the training requires.

On the PC, a proper software for the control of the whole system and for the acquisition/analysis of the data is installed.

The realization and the configuration of the P.I.G.R.O. control system were carried out with the following steps.

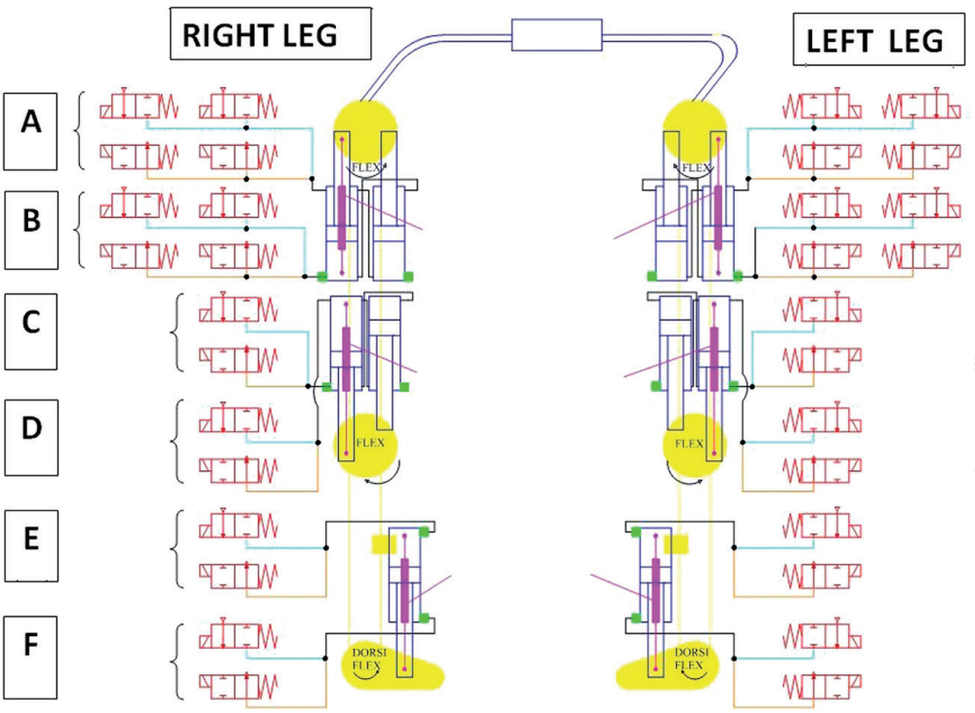


Figure 5.
P.I.G.R.O. electropneumatic system onboard, with the electropneumatic valves and with the sensors. A = hip extension; B = hip flexion; C = knee flexion; D = knee extension; E = ankle plantarflexion; F = ankle dorsiflexion; in magenta = potentiometers; in green = pressure transducers.

4.1 The definition of the reference system

In order to control properly the movement of each joint, a reference system for the P.I.G.R.O. legs joints is established, as shown in **Figure 6**. In particular, in **Figure 6** the reference system is referred to the right leg, seen in the sagittal plane from an external point of view. In P.I.G.R.O. it is possible to use various kinds of input control curves (required by the doctors) and, if it is necessary, different input control curves for the right and left leg.

4.2 The study and the definition of the input control curves useful for the unloaded training

The curves of a physiological gait cycle on the ground were analyzed and studied by the authors. As in this step, P.I.G.R.O. is designed for a completely unloaded training; several tests were carried out by the authors in order to define some input control curves suitable for this application [17].

In **Figure 7(a)** and **(b)**, the curves of the physiological walking on the ground (a) and the curves defined by the authors for the unloaded walking (b) are shown. In **Figure 7(a)** some red circles illustrate the main points of the difference between the physiological and the unloaded curves, such as the points where the contact between the foot and the ground occurs (points absent in the unloaded walking); the shape in some parts of the joints curves; the ROM of the ankle joint, increased for the unloaded walking; and some variations in the increasing/decreasing trend of the hip-knee-ankle angle joint curves [17].

The curves of **Figure 7(b)** reproduce the human gait cycle in a fully unloaded condition and allow a proper treatment of the patient during this rehabilitation step. Some experimental tests carried out controlling P.I.G.R.O. with these curves defined for the unloaded walking show their reliability.

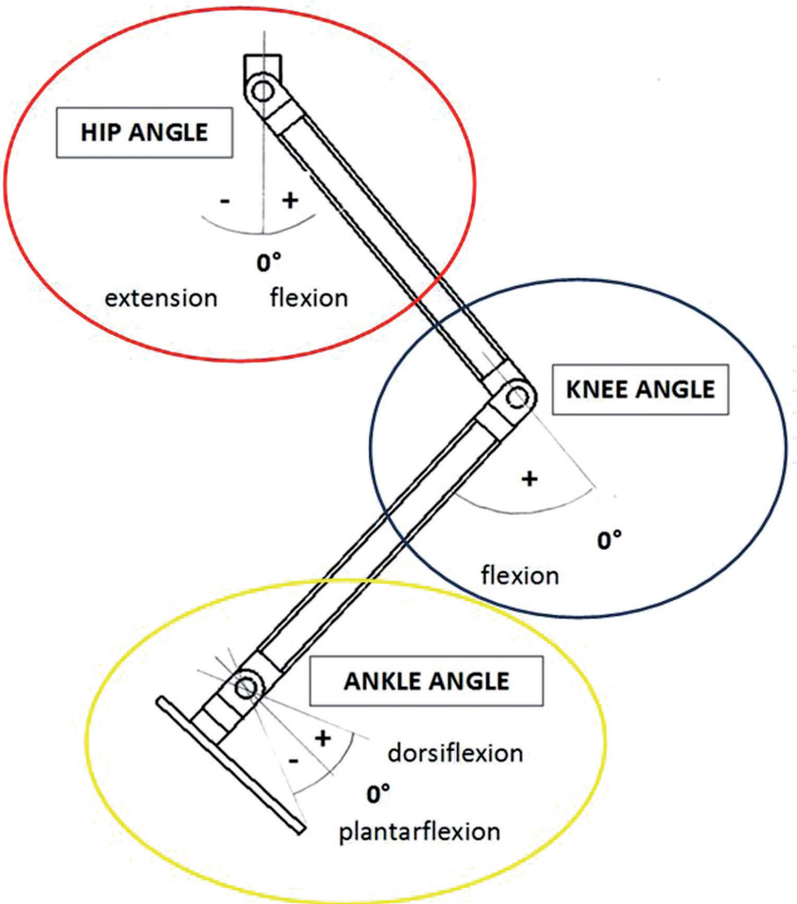


Figure 6.
P.I.G.R.O. main reference system.

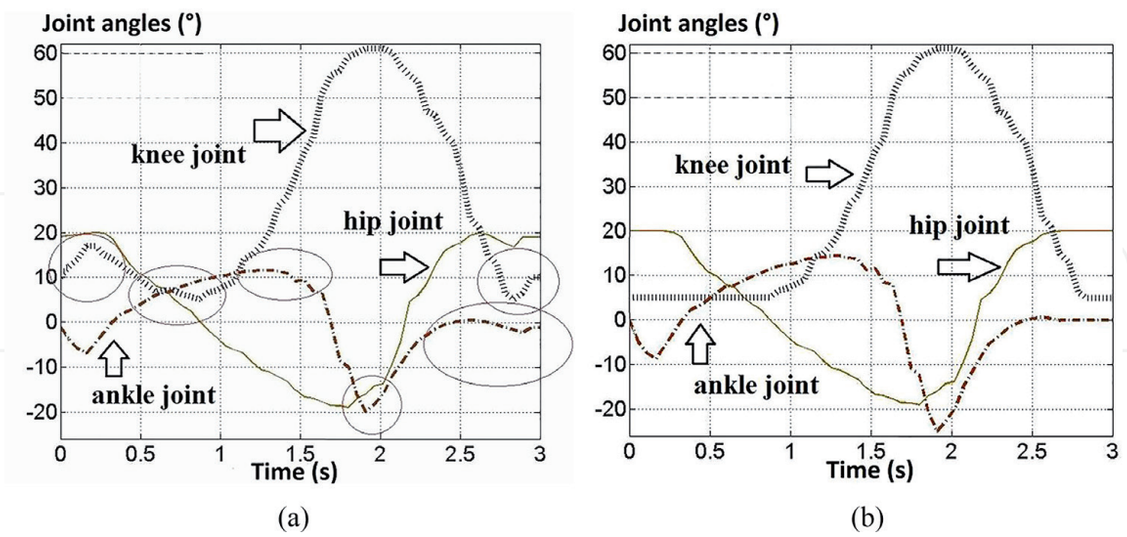


Figure 7.
(a) Curves of the physiological walking on the ground and (b) authors' unloaded walking set curves (AUWS) [17].

4.3 The definition of the structure of the P.I.G.R.O. control system for each joint

The control of P.I.G.R.O. is a real-time position control with a close loop for each joint, where a control subsystem was designed made of a PID-PWM control position structure, as shown in **Figure 8**.

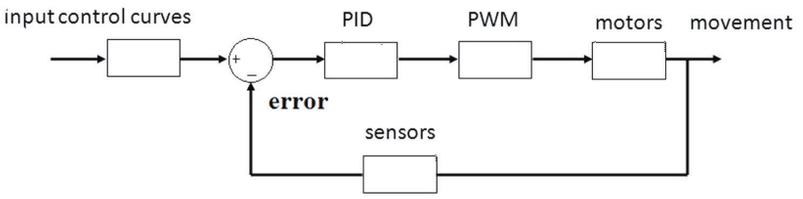


Figure 8.
P.I.G.R.O. control structure for each lower limb joint.

The input signal in each subsystem is the control curves selected and then compared with the position sensor signals (feedback) generating the "error."

The error is properly treated in order to control the electropneumatic valves.

The error sign establishes which types of electropneumatic valves (supply valves or discharge valves) have to be activated for the flexion or the extension of the joint.

The output signal of the PID controller is the input signal for the PWM part of the control system.

4.4 The definition of the parameters of the PWM and PID controller

The configuration of P.I.G.R.O. control system was carried out with a lot of experimental tests, done with a preliminary prototype of a single joint with two pneumatic actuators built with an agonistic-antagonistic structure, using cross-connected chambers and some masses to simulate the load.

Then other tests were done with a first prototype of P.I.G.R.O. made of a single leg, in particular the right leg, carrying out tests changing PWM carrier wave frequency, PID gains, tube diameters, and the number of the electropneumatic valves.

Finally the tests on the whole complete P.I.G.R.O. structure were carried out establishing the final configuration of the control system.

All of these tests allowed to establish the number of the electropneumatic valves (**Figure 5**) useful for a right control of the actuators, the tube diameters, and the parameters of the PID-PWM controller.

In particular the PWM characteristics were defined by varying the PWM carrier wave frequency and looking for its optimum values (**Figure 9a** and **b**).

The study was carried out using the exoskeleton with some healthy subjects, analyzing the effect of the carrier wave frequency values on the hip-knee-ankle

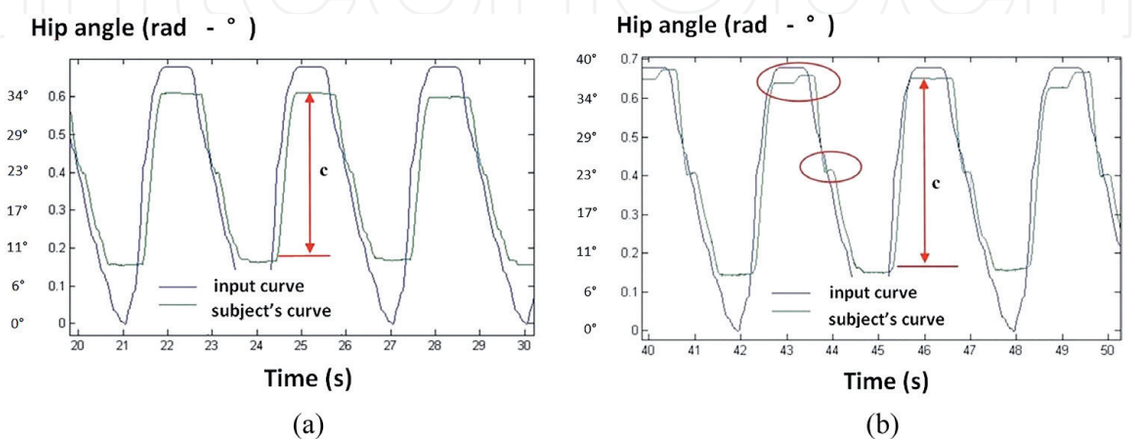


Figure 9.
Tests on the hip joint, varying the PWM carrier wave frequency (female subject with a body mass of 58 kg; supply pressure, 6 bar; (a) PWM carrier wave frequency = 10 Hz and (b) PWM carrier wave frequency = 50 Hz).

joint curves versus time, in comparison with the input trajectories. In this way, the optimum value for this frequency was defined.

In this step, the PID controller gains were not varied. As can be seen in **Figure 9a**, for the hip joint, for example, a low carrier wave frequency limits the actuator strokes and causes some oscillations in the subject curve.

On the other hand, a too much high carrier wave frequency (**Figure 9b**) improves the movement of the cylinders, but the subject's curve becomes less stable, and the oscillations increase.

After several experimental tests with healthy female and male volunteers, the optimum values of the PWM carrier wave frequency were defined for the hip-knee-ankle joints, obtaining a proper and stable movement of the actuators [11].

Then, the optimum values for the PID controller gains were investigated, testing the exoskeleton with healthy male/female subjects, with different body masses [11].

The PID controller gains are obtained, analyzing the kp proportional component, the ki integrative component (here always equal to zero), and the kd derivative component. Often these gains have different numerical values for the various parts of the input joint curves (initial, middle, and final part [17]).

The tests carried out allow to define the numerical values for the PID controller gains, which are values for subjects with body mass from 50 to 70 kg and values for subjects with body mass from 70 to 100 kg. In the beginning of the training, these PID controller gains are automatically selected by the software, as in the input data of the software; the patient's body mass is always required before the start of the trial.

In particular in the PID controller, the optimum values of the various components are defined as follows.

4.4.1 Proportional component (kp)

This component gives more or less reaction in the response of the system, so the authors used this component with different values in the various parts of each joint input control curves (i.e., hip-knee-ankle joints). The value of kp is higher when the inclination of the curve is higher. In particular the meaning of the kp in the parts of the curves of each joint is hip joint (increasing part of the hip input control curve kp_Ah, decreasing part of the hip input control curve kp_Al, constant part of the hip input control curve kp_Avl), knee joint (increasing and decreasing part of the knee input control curve kp_Gh, constant part of the knee input control curve kp_Gl), and ankle joint (increasing part of the ankle input control curve kp_Cl; decreasing part of the ankle input control curve kp_Ch).

4.4.2 Integrative component (ki)

In this system ki is always equal to zero because it can produce a block of the joint due to a saturation condition in the control.

4.4.3 Derivative component (kd)

kd increases the speed of the response of the system, but it can produce some oscillations. The authors decided to use for it a constant value for each curve (kd_A for the hip curve, kg_G for the knee curve, kd_C for the ankle curve). This value was then increased slowly till reaching a proper functioning of the system.

Figure 10 show the use of some PID controller components in the hip-knee-ankle joint curves.

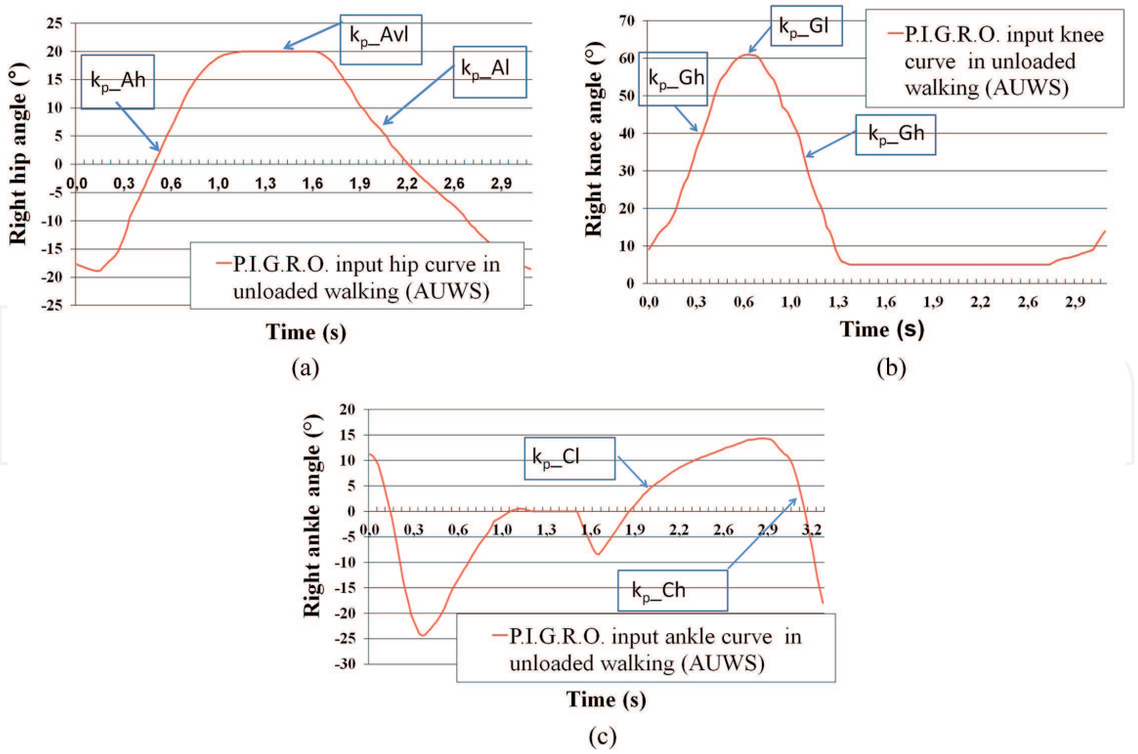


Figure 10.
Details of some components of the PID controller referred to the hip (a) knee, (b) ankle, and (c) input control curves defined by the authors for the unloaded walking [17].

5. The human machine interface of P.I.G.R.O.

P.I.G.R.O. has a useful human machine interface, which was properly developed. In particular there are two monitors, one for the operator and the other one for the patient's biofeedback.

In the human machine interface of P.I.G.R.O., it is possible to create and to save a file for each patient with all the patient's parameters; to start or to stop the system at the end of the training or during the training, if it is necessary; to change the input control curves, selecting them from a database created under the Doctors requirements; to show and to save the graphs obtained; to change the pressure in each leg, in the beginning of the training or during it; to save the time when this variation is done; and to have a proper biofeedback for the patient.

In particular, in the monitor for the operator (**Figure 11**), the behavior of the three joints of each leg (hip, knee, and ankle joint) can be analyzed during the trial by the clinicians. The graphs on the operator monitor can be saved.

In the panel of the operator, there are various buttons used to regulate the pressure in each leg independently and to stop the system at the end of the training, during the training, or in a possible emergency situation.

The supply pressure can be changed and its value in the two legs of P.I.G.R.O. can be different or equal, as the doctors require.

In fact a different value of pressure in the two legs of P.I.G.R.O. can be useful when the patient's pathology gives an asymmetric condition between the right and the left part of his body.

The time when the supply pressure is changed during the training can be saved.

Through the monitor for the operator, the duration of the whole training or of one part of the training can be registered and saved. In the program elaborated for P.I.G.R.O., there is the possibility to stop the patient's leg movement during the

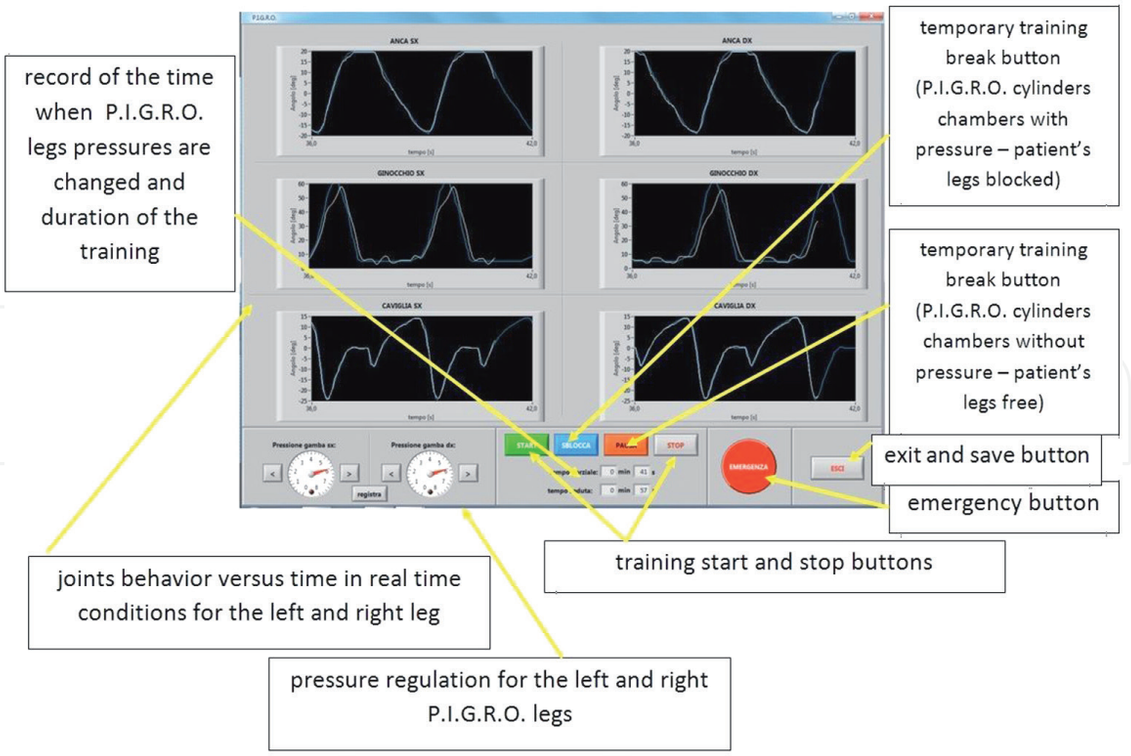


Figure 11.
Some details of the HMI of P.I.G.R.O.

training, closing the vent valves ports of all the actuators and having a pressure level in all the chambers of the actuators.

The possibility to stop the patient's legs in a specific position is useful for the doctors to investigate the cognitive status of the patient, for example, asking him the position of one or both of the stopped legs.

The patient's biofeedback has a monitor and the possibility of selecting one joint for one leg or the same two joints of the two legs.

In particular the biofeedback monitor shows, for each joint, that the patient's curve is within a certain range, if he is performing well.

P.I.G.R.O. has three emergency buttons: one on the monitor (for the operator), one on the fixed box (for the operator), and one to put in the hand of the patient.

During an emergency situation, all the electropneumatic valves of P.I.G.R.O. are switched to a vent configuration, with the possibility to immediately discharge all of the chambers of the actuators.

In this way, the patient can move autonomously his legs, while the training is immediately stopped.

Furthermore, the program allows to save all the data in files capable of being elaborated using many types of software.

6. The harness system for the patient and the textile corset of P.I.G.R.O.

As in this step of the research, P.I.G.R.O. is designed and used in unloaded training; a comfortable harness system for the patient was studied by the authors.

In fact, during the unloaded training, the patient is suspended by means of a harness system connected to the body weight support.

The exoskeleton P.I.G.R.O. is also connected to the body weight support by means of some proper belts and wore by the patient.

Figure 12 shows the harness system for the unloaded training.

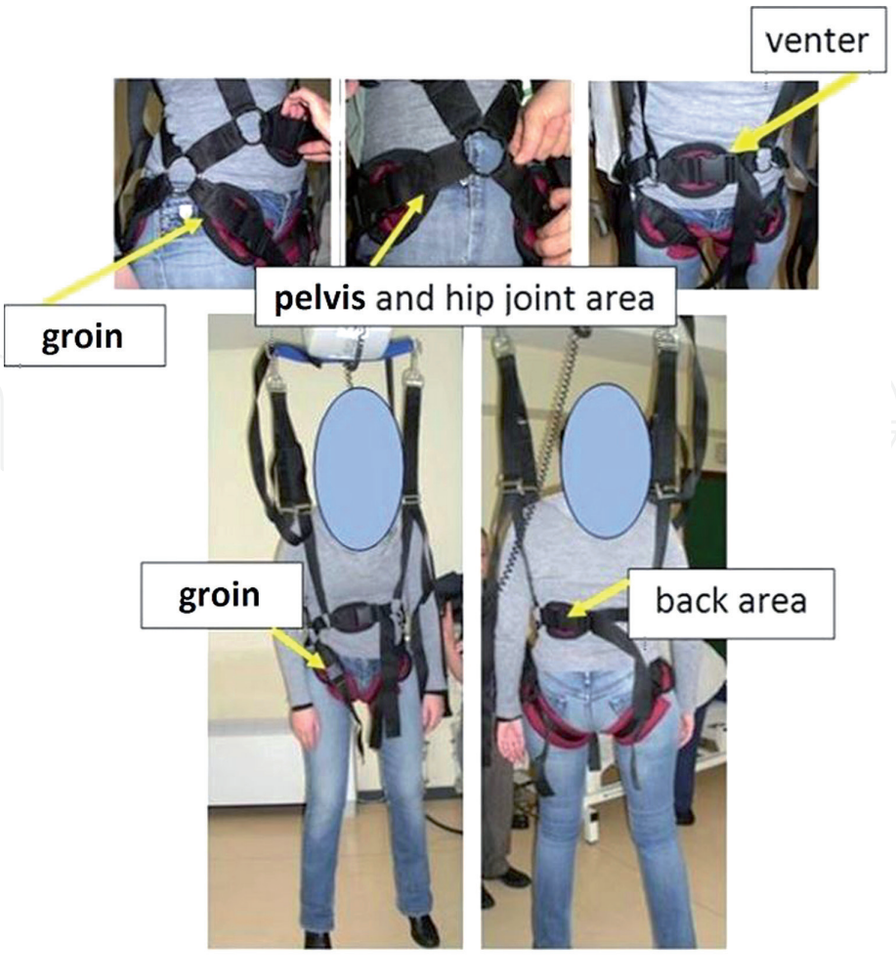


Figure 12.
P.I.G.R.O. patient harness system for unloaded training.

P.I.G.R.O. harness system supports a wide range of regulations and two specific configurations, one for men and the other for women.

This system was obtained after several studies on suspended people devices, in order to define the best design for the unloaded training done with P.I.G.R.O.

Its main characteristics are very comfortable and easy to wear; capable of suspending the patient in a vertical position, with the legs vertically extended; a proper and wide possibility of movement of the patient's legs during the unloaded training; and a construction made with safe and washable materials.

This harness system is partly made of textile parts, which are connected together by means of rigid rings, and some elements, filled of soft material, were also designed to improve the contact between the patient and the harness system and to avoid any pain for him.

In particular to define the best geometry of this harness system, a lot of considerations were done on the harness configuration in the hip joint area (**Figure 12**), where some differences from woman to man have to be foreseen, and the harness configuration on the patient's venter-groin-back area in order to obtain a very comfortable and safe design.

The purpose of this device is to sustain the patient in a vertical position for a trail duration of about 1 h, without any pain perception, which can reduce the benefit of the treatment and can cause irregularity in the movement during the trial.

A textile corset (**Figure 13**) was also studied to connect P.I.G.R.O. to the chest of the patient.

The choice of textile structures gives wear ability and comfort to the system, as these materials allow to adapt the device easily to men and to women from 10%ile

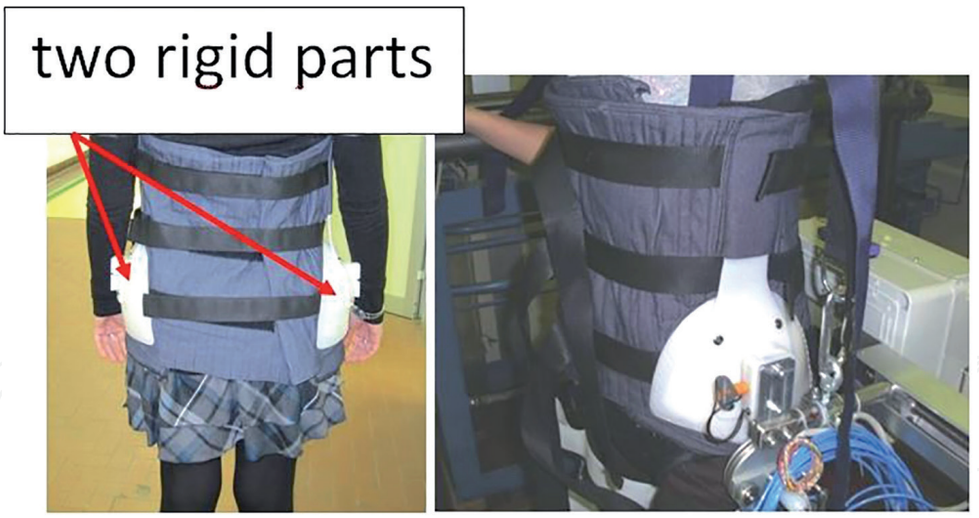


Figure 13.
Textile corset, used to connect the patient to P.I.G.R.O.

Italian woman to 95% Italian man. Furthermore a textile structure is safe and comfortable for the patient, as it avoids him any contact with rigid parts during the rehabilitation training.

This textile corset is somewhat regulated using an efficient system of straps sewed on the textile surface. The system makes it very wearable for patients with different body shapes.

In **Figure 13** some details were shown. Two lateral rigid elements, inserted in the external part of the textile corset, allow to connect it to the P.I.G.R.O. structure.

These two rigid parts can be connected or disconnected to P.I.G.R.O. legs by means of a proper lock device that allows a very quick and safe connection/disconnection, also if an emergency situation occurs.

7. Procedure defined to wear P.I.G.R.O. on the patient

The authors also defined a proper procedure to wear P.I.G.R.O. on the patient, verifying the wear ability and the comfort of the system and the possibility to wear P.I.G.R.O. on the patient in a short time.

The main steps of this procedure are measure on the distances between hip-knee and knee-ankle of the patient and the pelvic width in order to do the anthropometric regulations in the P.I.G.R.O. structure; insert these measures in the P.I.G.R.O. software, together with the patient's weight and the patient's data; wear the harness system on the patient; wear P.I.G.R.O. on the patient; verify all the system; and then unload the patient and P.I.G.R.O. using the body weight support.

In **Figure 14** a detail for the right use of the patient's harness system is shown: the unloaded walking training requires a proper vertical position of the patient.

In particular P.I.G.R.O. ankle joint has also a proper support for the patient's foot.

To guarantee that the patient's foot remains in a horizontal plane, the authors designed two screws, put in the inside part of the two P.I.G.R.O. legs, connected between the tibia blade and the foot support.

The regulation of these screws allow to have a right posture of the patient's feet during the unloaded walking cycle.

In **Figure 15** some details of this system and of its regulation were shown.

The average time to wear P.I.G.R.O. on a patient is about 20 min.

As the study is still in progress, the authors do not explain in this phase of the research more details on the tests carried out and the results obtained.

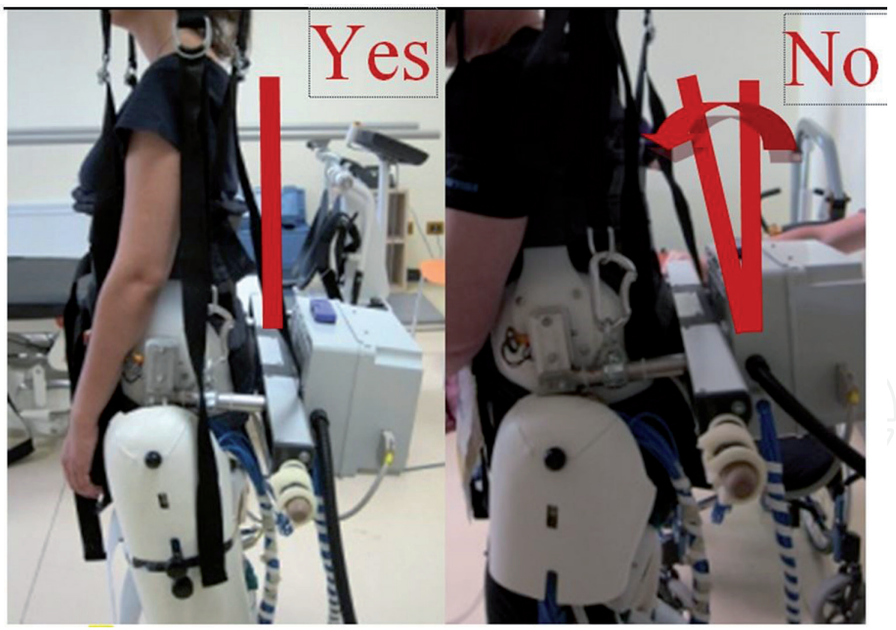


Figure 14.
Some details of the right position of the suspended patient for the unloaded training.

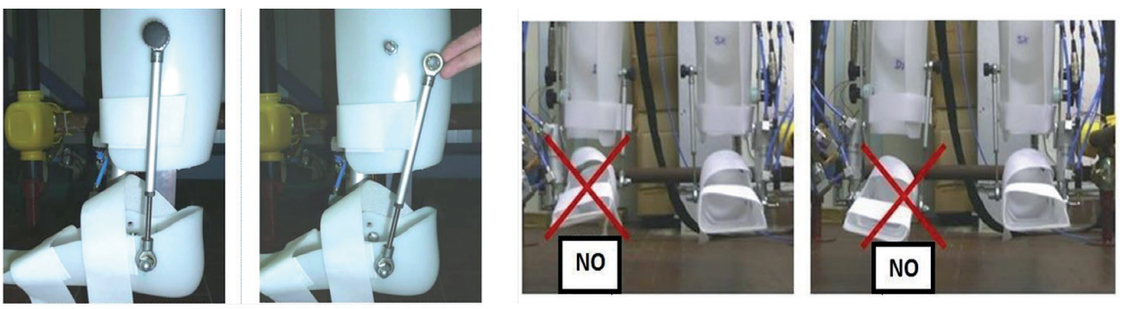


Figure 15.
(a) Screw inside each leg of P.I.G.R.O. to support the rigid part for the patient foot and (b) some details of regulation of this screw.

8. Conclusions

This article illustrates the structure and the main and innovative characteristics of P.I.G.R.O., an active electropneumatically controlled exoskeleton for unloaded robotic neurorehabilitation training. It is constructed to work without a fixed station, as this procedure is useful in the beginning of the trial to avoid the activation of the antigravity musculature.

P.I.G.R.O. has a real-time position control.

A useful human machine interface was developed: it allows P.I.G.R.O. to be easily used. It is possible to insert, to acquire, to save the patient's data, to carry out properly and safely various kinds of training, and to analyze the data. An innovative, useful, and comfortable harness system for the patients' unloaded training was studied and developed.

The preliminary tests show the reliability and the importance of this active exoskeleton that is also easy to wear.

In the future, the study of P.I.G.R.O. used in a walking training on the ground will be carried out, and some more experimental tests will be conducted in order to understand other possible improvements of this exoskeleton.

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Conflicts of interest

The Authors declare no conflict of interest.

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