Robotic system for gait rehabilitations of stroke patients during the acute phase

V. Monaco, J. H. Jung, G. Macrì, S. Bagnato, S. Micera, M. C. Carrozza, G. Galardi

***Abstract*— Stroke involves several modifications on walking performance due to the damages occurred in the Central Nervous System. Adaptive plasticity and favorable recovery could result from an early, intensive and task-oriented neuro-motor rehabilitation aimed at preventing abnormal posture, training muscle performance and allowing re-learning of motor skills. To this aim, a new robotic platform, called NEUROBike, is presented. It has been designed in order to overcome limits of the commercial rehabilitative robots. In particular, its main advantages are: i. the movability; ii. the ability to manipulate position and orientation of the feet in the sagittal plane, in order to control all the three degrees of freedom of the leg; iii. the ability to provide cognitive stimuli according to the timing of the gait cycle.**

I. Introduction

Stroke is a leading cause of chronic physical disability such as locomotion [1-4]. Impaired walking is common in stroke patients depending not only on the disease associated with the lesion, but also to the cardiovascular and the musculoskeletal consequences of physical inactivity.

People who experienced a stroke show several modifications in the motor performance due to the trauma as well as its consequences [2-6]. Muscle weakness and paralysis, poor motor control and soft tissue contracture [7] are the major contributors to walking dysfunctions after the disease. Deficits induced by stroke frequently impose excessive energy cost during walking, limiting type and duration of activities such that stroke patients, particularly those of advanced age, are often unable to maintain their most efficient gait speed comfortably for more than a very short distance[2-6].

Despite reports stating that 60-70% of stroke patients have regained function at the end of the rehabilitation in the hospital [8-9], there is also the evidence that only 15% of them walk outside their houses two years later [10]. Such individuals are constrained to a very limited activity in their home environment and have a strong need to exercise and increase their walking performance.

As far as the Central Nervous System (CNS) is concerned, after the trauma CNS is continuously remodeled, from the acute phase of diaschisis to the subsequent phases of cerebral reorganization, in response to the physical activity and the behavior of the subjects. During this phase abnormal inputs related to muscular hyposthenia and sensitivity disorders could be sent to the CNS as far as a number of pre-stroke motor schemes could be missed and some medullar reorganization processes could arise.

The conventional rehabilitation, during the acute phase after the trauma, involves: i. passive mobilization of the leg in order to prevent complications due to immobility; ii. exercises for the control of the trunk; iii. training of the postural transitions. These exercises have an important role on the welfare plane but they are not very useful for the motor learning, because they do not have task-oriented meaning and are of doubt motivational impact for the patients.

Therefore, adaptive plasticity and favorable recovery could result from an early, intensive and task-oriented neuro-motor rehabilitation aimed at preventing abnormal posture, training muscle performance and allowing re-learning of motor skills. Conversely, late, sporadic, passive and not task-oriented exercises may not be adequate to control abnormal posture and to prevent not correct adaptive cerebral reorganization due to abnormal information from the periphery.

The goal of this paper is to introduce a new robotic platform, called NEUROBike, aimed at providing neuro-motor rehabilitation therapy in order to favorite the recovery of walking abilities in patients post stroke. It has been designed to provide a suitable treatment, able to balance the inter-hemispheric competition by a re-education of the CNS wich might involve the recovery of the global motor action, rather than only the paretic limb.

II. Motivation and objective of Neurobike

The NEUROBike system is a robotic device dedicated to the recovery of walking skills in stroke patients during the acute phase, when they are on bed, not yet able to keep a safe upright posture and walking. The system has been designed in order to provide, as soon as possible, rehabilitation therapy, in order to prevent further damages of the cortical tissues due to their non-use [11], and to facilitate neural function recovery with repetitive exercises [12].

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Following, the motivation leading the design of NEUROBike are presented:

1. to aid clinicians during the passive therapy sessions when patients are plegic;
2. to assist their leg movements when non-functional voluntary muscular contractions are present;
3. to perform motor training when the voluntary motor activity become more consistent.

NEUROBike is not alternative but prodromic to traditional therapy, helping clinicians to limit undesired phenomena happening in the acute phase, such complications due to the immobility. Moreover, a timely physical therapy could motivate the patients to an intense functional recovery of the locomotion and to overcome depression troubles due to the consciousness regarding their post stroke state.

Even if it lacks of the main aim of walking, which is to lead the body in the desired direction, the rehabilitation process involving physiological walking pattern at the leg joint, in supine position has the advantage to induce a recovery of the impaired motor abilities with the lowest effort, without increasing the cardiovascular work. The restore of the gait cycle, although done with passive modalities could facilitate the cognitive relearning of the walking functions, by using appropriate feedback from the patients (counting the number of cycles, counting the cycles signed by a luminous led, or activating with a vocal message the action of the right and left feet). The cognitive relearning and the proprioceptive inputs evoked from the gait cycle, may likely affect, in adaptive way, the cerebral reorganization mechanisms. The NEUROBike functioning principle in fact is based on the rehabilitative need to send bilateral and alternate inputs to the Central Nervous System (CNS), as soon as possible after the trauma or lesion, in order to address the brain plasticity towards the recovery of the physiological motor abilities. This issue represents the deepest difference between NEUROBike and the cyclic rehabilitation operating in a phase subsequent to the acute one, as in the cases provided by Lokomat or AutoAmbulator. In these cases, in fact, the therapy acts on the mechanisms of inter-hemispheric competition when poor adaptive mechanisms of plasticity could have been already established.

NEUROBike has the following objectives:

1) to provide neuro-physical therapy for long period depending on the impairment of the patients;
2) to prevent modifications in musculo-skeletal proprieties due to inactivity;
3) to promote synergistic muscle activations according to the physiological patterns;
4) to train the motor coordination and muscular activities according to the desired walking speeds;
5) to increase the cardiovascular endurance.

Because of its intrinsic multidisciplinary features, NEUROBike has been designed to address clinical issues, as physiological biomechanics and neurological aspects, through a suitable mechanical design and an advanced control strategy. Combination of these expertises will allow the authors to develop a device strongly consistent with the clinical constraints of patients, open and versatile, in order to provide neuro-physical therapy as close as possible to the patients' needs.

III. Comparison with some commercial robotic devices

Robotic platform aimed at providing rehabilitation therapy in patients post stroke have been already introduced in the last years. *Haptic Walker* [13], *Lokomat* [14] and *Erigo* [15] are among the most advanced and also the most similar systems to NEUROBike.

Haptic Walker consists in a system in which the subjects are placed on a harness, their feet stay on two different platforms, and a supporting mechanical structure embeds all the devices. It has been design both for gait rehabilitation and virtual reality application[1]. The kinematic of the leg joints depends on the movement provided by the two platforms under the feet.

Lokomat consists of an exoskeleton accounting thighs and shanks, allocated on a treadmill. Subjects are placed on a harness, the kinematic of the proximal links of the legs is driven by the exoskeleton and all the devices are embedded in a metallic structure. In this case, kinematics of knee and hip depends on the exoskeleton, according to the desired speed, whereas the kinematic of the ankle depends on the contact between treadmill and foot [14][2].

Erigo is a mobile platform consisting of a tilting bed, accounting a foot manipulator, bike like, and a system under the shank helping in flexing the knee [15]. The cyclic movement of the "bike like" mechanism provides cyclic movement of the leg while the thigh supporters help the knee to be flexed[3].

All the described devices manipulate the legs, according to the kinematics provided by each mechanism and the speed desired. The first two robots, which can be considered similar to NEUROBike in term of degree of freedom managed, need to be permanently installed in a room. They require that patients have to be moved from their beds to that room to experience the robotic rehabilitation. Unfortunately, depending on the healthy state of the patients, it could be not possible in all the cases inducing a shift of the beginning of the rehabilitation therapy.

On the other hand, Erigo represents a mobile platform, hence it over crosses the limit of the previous robots. Moreover it is comparable with the ones obtained during locomotion.

NEUROBike has been designed in order to overcome the mentioned limits. In particular, it is a mobile platform and the manipulation of the legs will be provided keeping the leg joint angular excursions as close as possible the ones obtained during the walking. Moreover, the development of systems providing cognitive inputs, absent in the previous robots, as well as described in the paragraph *II*, could increase the positive effects of the rehabilitation therapy.

IV. Design of Neurobike

The basic idea of NEUROBike is to manipulate position and orientation of the feet in the sagittal plane, in order to

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1 More information available on line: http://www.hapticwalker.com/

2 More information available on line: http://www.hocoma.ch/web/en/products/prd_lokomat.html

3 More information available on line: http://www.hocoma.ch/web/en/products/erigo.html

obtain leg joint angular excursions similar than the one obtained during the natural walking, as shown in Figure 1.

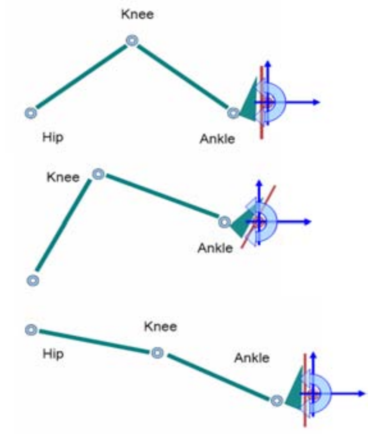


Figure 1: Basic idea regarding NEUROBike.

The design of NEUROBike is based on the following requirements:

1. position and orientation of each foot controlled, in order to induce all the desired configurations of the leg joints the sagittal plane;
2. avoid motion of the leg in the frontal plane;
3. avoid hyper-extension of the knee;
4. usable on a bed, with patients in lying position.

To meet the above requirements, NEUROBike consists of four parts as shown in Figure 2:

- 1st part: a foot-moving platform;
- 2nd part: four walls;
- 3rd part: wrappers for the knees;
- 4th part: hip support.

A. Foot-moving platforms

The first part (Figure 3a) consists of an orthogonal manipulator and a foot rotating mechanism. This manipulator is the most important component of NEUROBike because it pushes or pulls the sole of patient's foot. The sole of patient's foot is located on a plate (Figure 3b, n.10) which is connected with a vertical saddle (Figure 3a, n.6). A motor (Figure 3a, n.1) leads a horizontal saddle (Figure 3a, n.3) which moves on the rail of the horizontal linear guide

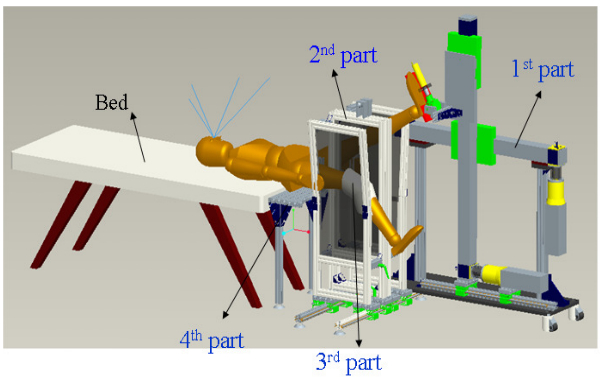
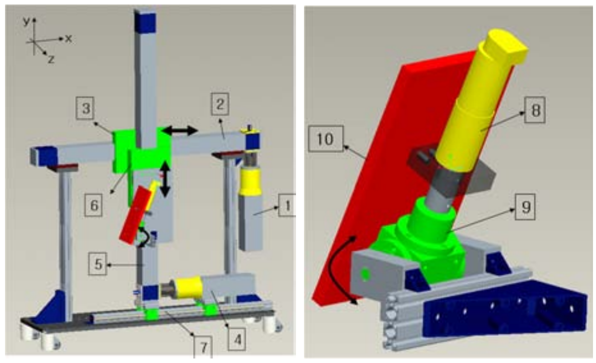


Figure 2: Overall structure of NEUROBike. In order to make easy the reading, the manipulator regarding the right leg was removed.

(Figure 3a, n.2) along the X direction. The vertical linear guide (Figure 3a, n.5) is linked to the horizontal saddle (Figure 3a, n.3) and positioned vertically. The vertical saddle (Figure 3a, n.6) is moved on the rail of the vertical linear guide (Figure 3a, n.5) along the Y direction, by a motor (Figure 3a, n.4). Hence, the foot plate (Figure 3a, n.10) can move in X and Y directions simultaneously. In addition, by a motor (Figure 3b, n.8) and a right-angle gear (Figure 3b, n.9), the foot plate (Figure 3b, n.10) is rotated about the z-axis. To sustain the weight of the linear guide (Figure 3a, n.5) and motor (Figure 3a, n.4), a sliding guide device (Figure 3a, n.7) is applied.



(a) (b)

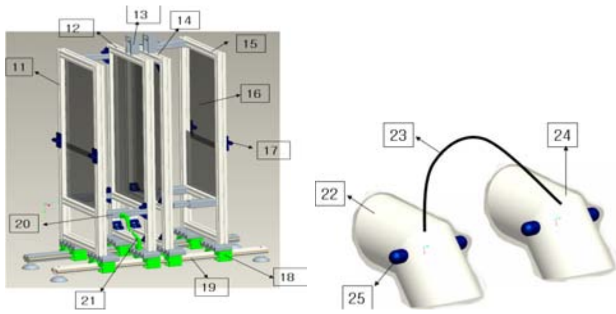
Figure 3: (a) Foot-moving device and (b) magnification of foot rotating mechanism.

B. Walls and knee wrappers

Form the kinematic point of view, gait rehabilitation is provided mainly in the sagittal plane, managed by four lateral walls (Figure 4a). Moreover, knee hyper-extension is avoided by using wrapping devices connecting the knees together as shown in Figure 4b.

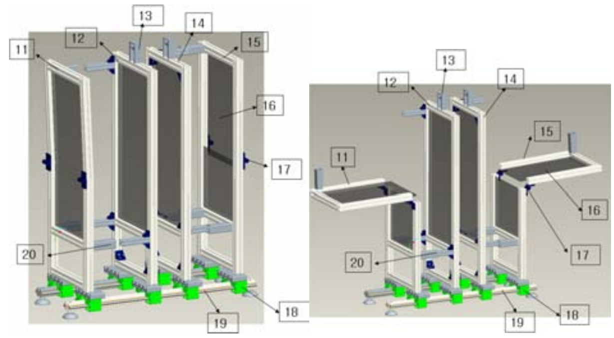
The knee wrappers comprises four beads (Figure 4b, n.25) which are in contact with the plates (Figure 4a, n.16) of the walls in order to reduce the friction between the wall and the wrapping device. A cable (Figure 4, n.23), connecting the knee wrappers passes through rollers (Figure 4a, n.13), such that, when one knee is extended, the other one is going to be lifted.

Since legs size varies among subjects, the space between the walls is adjustable by moving the saddles (Figure 5a, n.18) on the rails (Figure 5a, n.19). In addition, in order to easy install the legs into the device, walls are routable by hinges, as presented in Figure 5b.



(a) (b)

Figure 4: (a) Walls and (b) knee wrappers. In this figure, only one clamp 21 is shown but clamps are installed to all moving saddles and telescopic bars.



(a) *(b)*

Figure 5: (a) Space adjusting between walls and (b) rotating walls.

C. Hip support device.

Figure 6 shows the hip support device. Patient's hip is located on a plate (Figure 6, n.28). To allow the leg to move below the horizontal plane passing through the plate, the parts of the plate (Figure 6, n.28) that touch the thigh will be opportunely shaped. Bar (Figure 6, n.26) and belt (Figure 6, n.27) fix the hip during the rehabilitation therapy. The knuckle foot (Figure 6, n.29) allows to adjust the height of the plate.

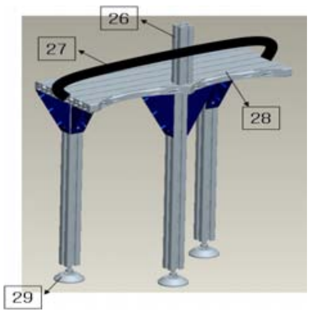


Figure 6: Hip support device and height adjustable knuckle foot

D. Control Architecture

As widely adopted in the robotics community, the control of NEUROBike is based on open-source software. In particular:

– Fedora Core, as operative system, with RTAI kernel;
– S626 Sensoray I/O boards, which drivers are included in the OS;
– control algorithm implemented in C;
– graphical interface.

Figure 7 briefly shows the control architecture designed for NEUROBike. In particular, the mechanical information concerning angular excursions and the torque at the motor are gathered by suitable sensors and sent to the motion controller, which will provide biofeedback, and suitable set up to the motor drivers.

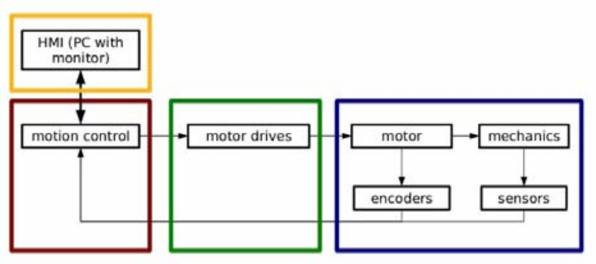


Figure 7: Control Architecture.

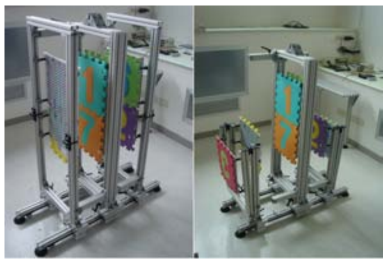
V. Realization of NEUROBike

Now, mechanical parts of NEUROBike have been almost realized. The following figures show overall structure and several parts of NEUROBike.

Figure 8: Realization of overall structure of NEUROBike

(a) *(b)*

Figure 9: (a) left foot-moving platform and (b) foot rotating part.



(a) *(b)*

Figure 10: (a) All standing walls and (b) rotated outside walls.

VI. Conclusion

In this paper, the novel robotic system, called NEUROBike, for gait rehabilitations of stroke patients during the acute phase has been addressed. Basically, NEUROBike manipulates position and orientation of the subject's feet in the sagittal plane, in order to obtain leg joint angular excursions similar than the one obtained during the natural walking. For this end, NEUROBike NEUROBike consists of four parts. In addition, NEUROBike has been designed in order to overcome the limits of the existing commercial devices.

Now we are stage of finishing realization of mechanical parts of NEUROBike. Afterward, we will develop its control system and then have clinical test in the hospital.

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