Development of a Robotic Platform for Human Gait Rehabilitation and Training: EksoWalker

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Abstract

Mobility is an important faculty that affects the life of an individual at different levels. Lack of mobility can condition the physical and cognitive maturation in the early years of development. Recently, neuroscience found that specific, repetitive and intensive training induces neuronal plasticity and, consequently, a cortical reorganization of brain damage. To improve the locomotor training of patients with reduced mobility, several robotic assistance technologies have been proposed as exoskeletons and smart walkers, and several studies have demonstrated its functional benefits. The main objective of the EksoWalker is to develop and validate a robotic platform that will support patient rehabilitation therapies, composed of an active lower limb exoskeleton and smart walker. The proposed multimodal interface to support both the cognitive and physical interaction and the bio-inspiration concepts included in the design of the platform, are promising features in the human gait rehabilitation and training therapies. The development and preliminary biomechanical validation of the EksoWalker are being conducted at the Colombian School of Engineering Julio Garavito.

Keywords: Exoskeleton, Human Robot Interaction, Human Gait, Rehabilitation, Smart Walker

1. Introduction

Mobility is one of the most important human faculties and can be defined as the ability of an individual to move freely through multiple environments and perform daily personal tasks with ease (Winter, 2009). In this way, mobility is directly related to independence, people's quality of life, and certainly, any condition that affects it is directly affecting the person's well-being. Among these conditions are cerebral palsy, stroke and spinal cord injury, that cause partial or total loss of locomotion capacities. In addition, it is known that mobility is related to age and decreases with the natural deterioration of the human locomotion systems. Cerebral Palsy (CP) is a disorder of posture and movement caused by injuries in the premature brain (Bax et al, 2005). This disability is the most common of all childhood diseases and it is estimated approximately 8,000 to 10,000 babies born each year will develop CP (Kenneth A. Stern, 2017). Stroke is considered the main cause of long-term disability in the adult population (Dobkin, 2004). This condition is caused by the cell death in a brain area, due to internal bleeding or blockage in the main arteries (Harwin et al, 2006). According to the World Health Organization, 15 million people suffer stroke worldwide each year, among these 5 million are permanently disabled (World Health Report, 2010). Spinal Cord Injury (SCI) consist of any type of alterations in the spinal cord, which affect sensory-motor and autonomous systems, leading to an injury. According to the International Campaign for Cures of SCI, based on the average annual incidence of 22 people per million in developed countries, it is estimated that more than 130,000 people survive each year to a traumatic SCI and begin "*a new and different life*" in a wheelchair (International Campaign for Cures of SCI, 2011). Also, as previously mentioned, the elderly population presents a progressive degradation of the musculoskeletal system, because of age, which limits the capacities of the locomotor system. In fact, this population (people over 60 years worldwide) will triple from 600 million to 2 billion by year 2050 (World Health Organization, 2011). This increase will be mainly presented in the least developed countries (Carlos A Cifuentes, 2015).

In Colombia, the number of people with these kinds of conditions in their mobility is significant. According to the National Administrative Department of Statistics (DANE, for its acronym in Spanish) in its last census of disability, the number of people with a disability is 2'652,000 inhabitants and it is estimated that a large percentage corresponds to people with mobility impairments.

Recently, neuroscience found that specific, repetitive and intensive training induces neuronal plasticity and, consequently, a cortical reorganization of the brain damage. This effect is a step forward in the rehabilitation of the locomotor system of patients with gait disability, and has been considered in the proposal of several robotic assistance technologies, as alternatives to therapeutic interventions. Among these technologies, two major trends of development are the focus of research nowadays, as several studies have demonstrated its functional benefits: walkers (Carlos A Cifuentes, 2015) and exoskeletons (Contreras-Vidal et al., 2016).

Walkers are widely used because of their simple and affordable mechanical structure. They are usually prescribed for patients in need of gait assistance, to increase static and dynamic stability and to provide partial body weight support during functional tasks. Such devices empower the residual motor capacities of the user, allowing a natural way of locomotion and, thus, preventing immobility-related changes. Additionally, evidence shows that walker-assisted gait is related to important psychological benefits, including increased confidence and safety perception during ambulation (Carlos A Cifuentes, 2015). However, several studies have shown that conventional walkers do not provide enough support and stability during gait and, therefore, the possibility of improving and enhancing their effects through the inclusion of robotic technology has arisen. Smart walkers present Human-Robot interfaces, which allow the interpreting of the user movements to provide a safer and efficient mobility.

On the other hand, exoskeletons can effectively integrate the cognitive ability of human being and the advantage of robotic devices to assist the users to accomplish their desired activities (Huo, Mohammed, Moreno, & Amirat, 2016). They are mechanical devices designed around the shape and the function of the human body, with segments and joints corresponding to those of the person it is externally coupled with (Pons, 2008). They can participate more efficiently than walkers in the learning of normal gait parameters and in the muscle strengthening of the limbs and body.

Considering the individual contributions of each of these research trends in gait assistance technologies, the integration of a smart walker and a lower limb exoskeleton into a single platform could improve the results achieved so far in conventional motor rehabilitation. The benefits of each technology together, where Partial Body Weight Support (PBWS) is provided during the gait, and the movement of the joints is controlled according to healthy gait pattern for each patient, could contribute in the establishment of a robust gait rehabilitation therapy. The main objective of the EksoWalker project, carried out at the Colombian School of Engineering Julio Garavito, is to develop and validate a robotic platform that engages in the patient´s rehabilitation therapies. The platform consists of an active lower limb exoskeleton and a smart walker.

In the second section the robotic platform is described and the different sensors involved are addressed. In the third and fourth sections the proposed Human Robot Multimodal Interface and control strategies are introduced and briefly described. Finally, in the fifth section an overview of the current stage and future work regarding the development of the platform is presented.

2. Robotic Platform

The EksoWalker is composed of two main structures: (1) a lower limb exoskeleton with six actuators (one at each joint) and (2) a smart walker (see Figure 1). The platform includes a sensory interface for each of them. To monitor the physical interaction of the exoskeleton with the user and characterize different movement trajectories, two wearable sensors will be dressed by the patient: (1) an electromyography (EMG) system for monitoring the patient's muscular activity and (2) Inertial Measurement Units (IMUs). Additionally, the exoskeleton includes: (1) strain gauges for the detection of efforts between the platform and the patient and (2) optical encoders inside and outside each joint gear, to measure the position and angle of displacement.

In the case of the smart walker, different sensors were considered to estimate different parameters of the user's gait and define control strategies for an autonomous gait: (1) a Laser Range Finder (LRF) for the detection of gait´s kinematics and (2) triaxial force sensors to measure the upper limbs physical interaction. In addition, the platform includes a social interaction module, composed of (1) a LRF and (2) a video camera. This module, is intended for environmental interaction of the platform (navigation and human detection) in order to achieve a safer and guided locomotion.

The integration of both systems, the smart walker and the exoskeleton, provides the user greater support and stability during gait. The exoskeleton provides support to the lower limbs and the walker provides support to the upper limbs, at the same time that allows the interaction with the user's intention of movement. In addition, although the exoskeleton assists the user gait, it does not provide a safe interaction with the environment. This is going to be achieved with the smart walker's social interaction and navigation modules.

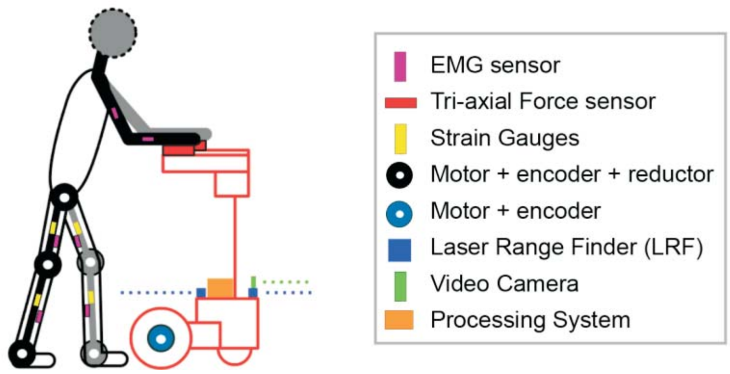

Figure 1. EksoWalker proposed platform.

2.1. Exoskeleton

The design of the exoskeleton was based on the Articular Centers of Rotation (ACR) and axes of the ankle, knee and hip, where actuators were placed. One of the main concepts involved in the process was the bio-inspiration and it was approached through the creation of curve segments (links) that could be adaptable to the length of the patient's legs (based on typical anthropometric measurements of Colombian adult men). The design was contemplated in three modules; first, the lower limbs, second, the hip and finally, the fastener system. Table 1 shows the main characteristics of the exoskeleton.

Table 1. Exoskeleton-user's characteristics

Parameter	Detail
Degrees of freedom	Hip, knee and ankle sagittal*
User's weight	Up to 100 Kg
User's height	From 170 to 188 cm

*Hip ab/dduction will be included.

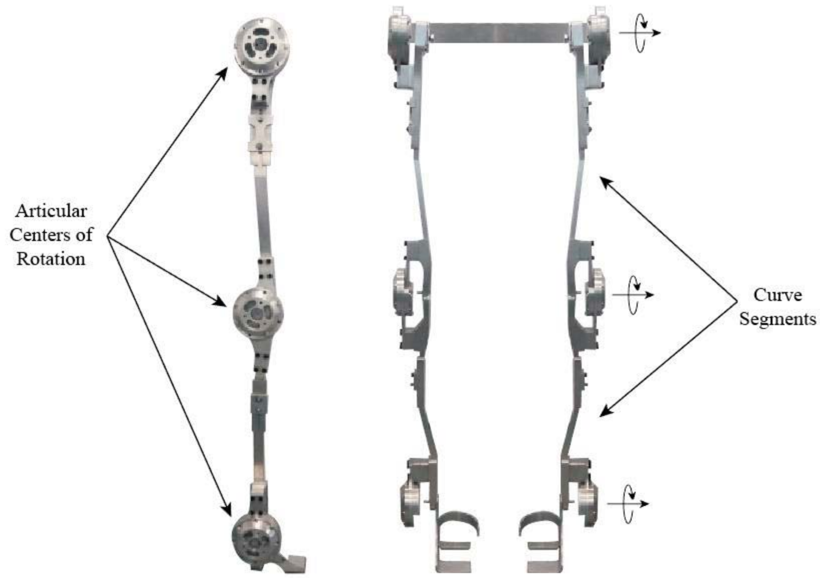

Figure 2. EksoWalker's lower limb exoskeleton.

The lower limbs were modeled as rigid segments that are attached to the ACR. The design is intended to maintain the center of rotation of the exoskeleton joints coincident with the ACR of the human body. It contemplates a completely adaptable structure for patients between 1.70m and 1.88m (range in which most of the Colombian male population is concentrated) with a continuous telescopic system, both for the femur and for the tibia and fibula´s length. In addition, the segments adapt to the curvature of the legs, so that the points of the device articulation are close to the ACR (see Figure 2).

Currently, the exoskeleton has an adjustable width and length hip, suitable for the target population, with a single degree of freedom: flexion-extension of the legs. However, a version with two degrees of freedom is in designing process in which the abduction-adduction is allowed. In this order, a greater freedom of movement can be provided during the gait. Two attachment points were selected for each exoskeleton segment and several materials were integrated. Through this integration, the attachment to each point is rigid enough to translate the action of movement, but soft to avoid hurting the user.

2.2. Smart Walker

The design of the smart walker was performed considering the need of ergonomics and healthy postures during gait, body weight support, balance and stability. A differentiation and innovation aspect was introduced by applying sizing concepts that make it an empowering structure in rehabilitation environments. On the one hand, it has a forearm support, which increases the patients support in the device and facilitates the detection of the movement´s intention. In addition, the user´s location was an important designing criterion. The user's center of gravity was located between the rear wheels for better locomotion and steering of the platform. On the other hand, anthropometric measures were considered to make the walker an adjustable structure through the implementation of a telescope at its height.

The design contemplated two main modules (see Figure 3a). The first one is the weight support module, characterized by the user's forearm support in the walker. Some approaches had been made into this type of support, placing triaxial force sensors and have presented a more natural way to command the walker motion without previous training (Frizera-neto, Ceres, Rocon, & Pons, 2011). The second, is the locomotion module, where a rollator configuration was chosen with free front wheels and motorized rear wheels.

As previously mentioned, the smart walker includes a social interaction module. At the time, this module is being developed and integrated on a Pioneer LX (PLX) research platform by Omron Adept Mobilerobots (see Figure 3b), and once it is completed it will be transferred to the smart walker. The module is composed of: (1) a human detection and social interaction layer, based on the information provided by the LRF and the HD camera; (2) a motion planning and navigation layer, based on the Robot Operating System (ROS) built in navigation stack; and (3) a user interaction layer, based on the triaxial force sensors, intended to introduce the user's intention of movement.

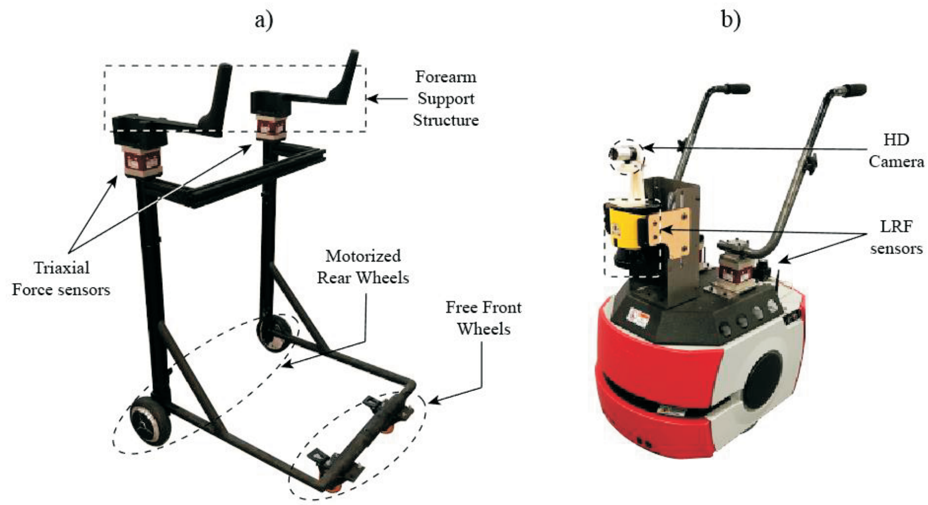

Figure 3. a) EksoWalker's Smart Walker. b) Pioneer LX Smart Walker for social interaction strategies development.

3. Human-Robot Multimodal Interface (HRMi)

The Human-Robot Interaction (HRI) is presented through two types of interactions: (1) the cognitive HRI (cHRI) and (2) the physical HRI (pHRI), that are not independent of each other. The cHRI is a two-way interaction, where the user guides the robot through his movements and intentions while receiving feedback. It is based on the acquisitions of data by sensors that measure bioelectrical and biomechanical variables. The pHRI is characterized by an exchange of forces between the two actors, considering the nature of the contact during the assistance or rehabilitation process. Both interactions are supported by a Human Robot interface (HRi), that are any hardware and software linking two dissimilar systems, e.g. robot and human. (Pons, 2008). The Human-Robot Multimodal interface (HRMi) proposed, is an interface designed to integrate these interactions, based on the sensor and design criteria previously mentioned (see Figure 4).

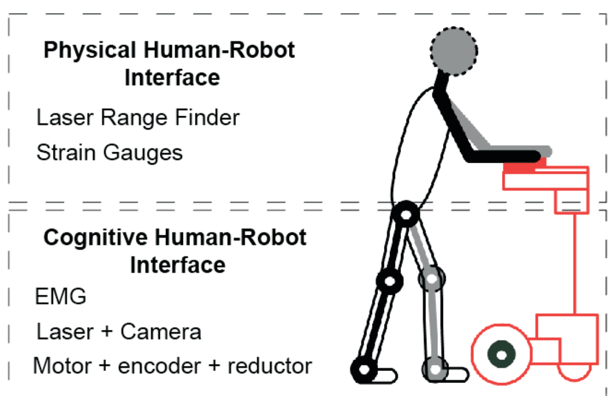

Figure 4. EksoWalker's HRMi

4. Control Strategies

Different control strategies are being evaluated with the platform. These basic control strategies, in combination with information provided by the multimodal interface and the different sensors distributed along the platform, will be the basis of the monitoring and therapy planning, which will be in accordance with the experience of the project's clinical partners. Within these strategies, for the exoskeleton the following are found: (1) A trajectory control strategy of the joints, which guides their movement with previously defined trajectories (Bayón et al., 2017) and (2) a gravity compensation control strategy, which eliminates the gravity sensation in the joint´s movements (Moubarak, Pham, Moreau, & Redarce, 2010). In the case of the smart walker, the strategies are: (1) an admittance control strategy, with which the walker´s linear and angular speeds of movement are obtained from the force measured in the forearm support (Mun, Zhu, Yu, & Cruz, 2014) and (2) a locomotion control strategy based on the LRF, with which the gait can be assisted through the extraction of gait parameters from the patient (C.A. Cifuentes, Rodriguez, Frizera, & Bastos, 2014).

5. Current Stage and Future Work

At the time, the acquisition of each signal integrated is already achieved and some of the strategies are being tested on the platform. The exoskeleton is currently coupled with a mannequin leg with the fasteners system and the knee actuation is being conducted (see Figure 5). The previously mentioned strategies will be tested with this configuration and then the actuation will be generated at the ankle and hip. Once they are mastered, the performance will be taken to healthy subjects and subsequent, to real patients.

The results regarding to navigation and people detection module are presented, as shown in Figure 6 and Figure 7. The Figure 6 presents a stationary result of the people detection module. In addition, the Figure 7 shows a navigation goal, two planned trajectories (Local and global) and a navigation cost-map, related to the navigation module. The integration of both modules is being implemented, using a social navigation layer that takes people proxemics into account. The user interaction module is also under development and is going to be modeled with an admittance controller that emulates a dynamic system and gives the user a sensation of a physical interaction during gait assistance.

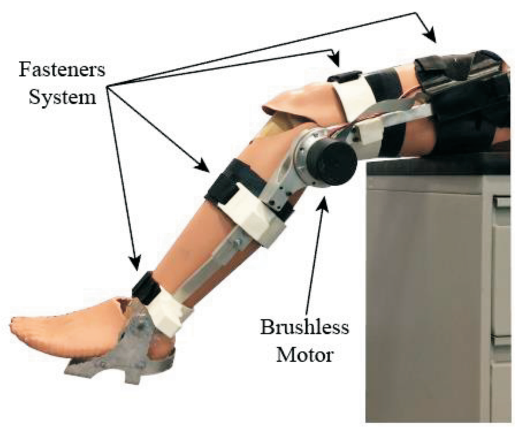

Figure 5. Exoskeleton left leg coupled with mannequin during knee actuation.

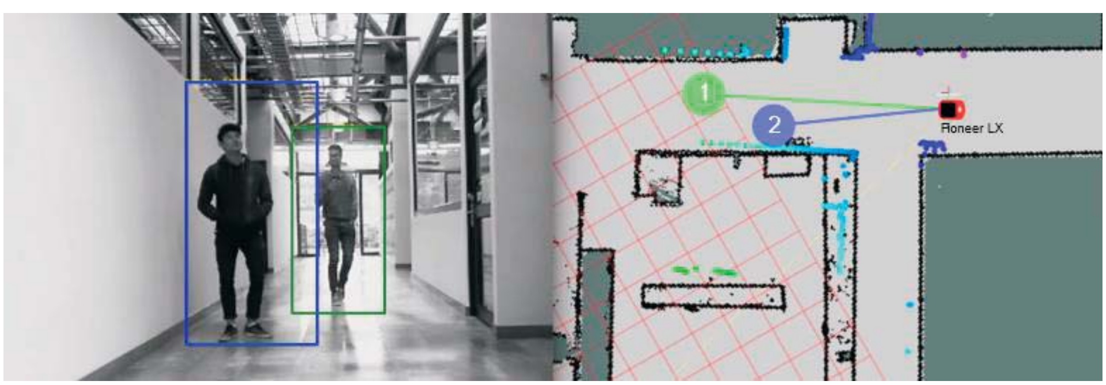

Figure 6. Two people detected by the human detection module.

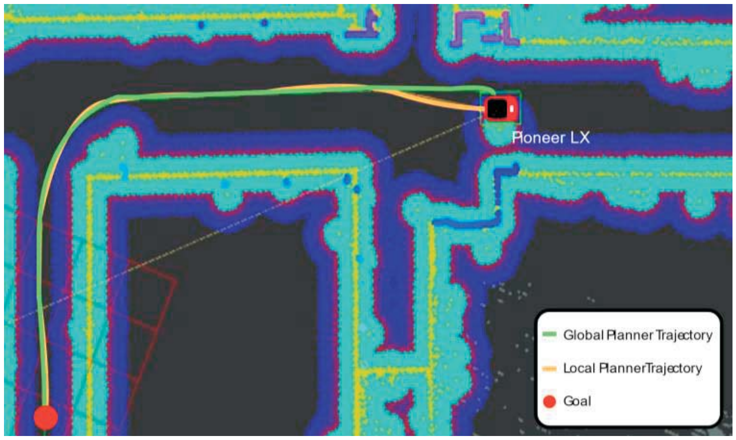

Figure 7. Simple navigation task.

At the same time, preliminary validation is being conducted in the laboratory, as biomechanical studies are performed with healthy patients and the platform at its passive mode (see Figure 8). The above mentioned biomechanical studies include tests that use both systems, smart walker and exoskeleton at the same time, as well as tests that evaluate their use separately. Different variables as EMG, gait postures, angles and orientations and floor reaction forces are being evaluated in order to quantify the degree of assistance and rehabilitation contribution when the two systems are used in a complementary way. Studies with healthy patients and the platform at its passive mode will conclude in the short term and test with the active platform will take place. In the long term, studies with impaired subjects will be conducted with the support of the project's clinical partners.

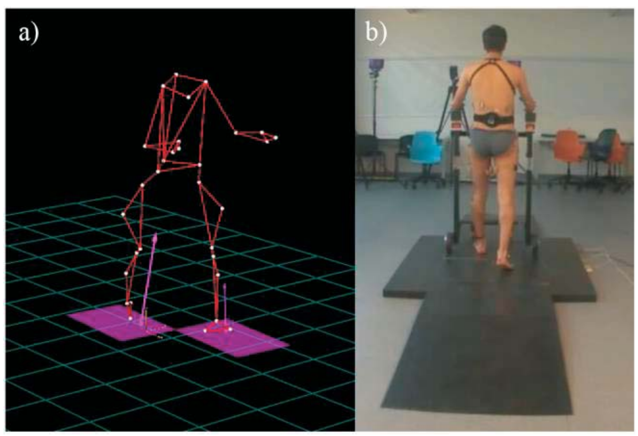

Figure 8. a) Biomechanical model implemented in the tests. b) Patient performing gait test with the walker.

6. Conclusions

This paper has presented the conceptualization and firsts stages of development of the EksoWalker, a robotic platform for human gait rehabilitation and training. The device intends to provide a PBWS based on upper and lower limbs support during the gait, and the joints movement assistance, to contribute in the establishment of a robust gait rehabilitation therapy to impaired subjects. The robotic trainer integrates an active lower limb exoskeleton and a smart walker, that will enable the patients to experience autonomous gait through the environment and social interaction, which we hypothesize will improve the outcomes of the stablished traditional therapies.

This robotic platform is equipped with kinematics (angular position and velocity) and kinetic (interaction force between limb and the exoskeleton) sensors and a social interaction module. Additionally, the communication between the user and the platform is presented through a multimodal interface based on EMG, LRF and IMUS sensors and a HD camera. Different control strategies will be tested on both the exoskeleton and the smart walker in order to have a wide range of assistance levels to each of the patient's disabilities.

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