Development of a Robotic Lower-Limb Exoskeleton for Gait Rehabilitation: AGoRA Exoskeleton

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***Abstract*—Stroke significantly affects millions of individuals around the world every year, leading to considerable physical impairment and serious long-term disability. Gait is one of the most important daily-life activities affected in stroke victims. The development of an ambulatory lower-limb exoskeleton intended for use in stroke survivors is presented in this paper. It is envisioned as an actuated device in the sagittal plane, capable of producing the necessary torque to move the hip, knee and ankle joints (this latter by means of a variable-stiffness ankle-foot orthosis). An additional passive add/abduction degree of freedom at the hip joint is included, as a way to improve walking balance. A control approach for the actuated joints, which aims to assist the subject only when needed, is also proposed. The main goal of this assistive device is to promote the early incorporation of stroke patients with mobility impairments to a feasible rehabilitation treatment. Such device opens the possibility to study means that might optimize conventional rehabilitation treatment.**

***Index Terms*—Stroke; Gait impairment; Lower-limb exoskeleton; Variable-stiffness; Ankle-foot orthosis; Assistance-as-needed.**

I. INTRODUCTION

Stroke can be defined as an occlusion of an artery in the brain that, unless treated quickly, produces tissue infarction [1]. Approximately 795,000 people suffer stroke in the US each year [2] and the reported incidence rate of stroke for Colombia in 2014 was 1.31 in 1000 inhabitants, many of which end up with motor disabilities [3].

The emergence of a subsequent musculoeskeletal pathology can lead to loss of function, anormal gait pattern, and fatigue. In order to help patients overcome these after-effects, several complementary technologies have been developed to be used along with conventional therapeutic interventions. Among these new technological advances, powered exoskeletons have been broadly used in the past years as both practical devices for assisting individuals with post-stroke lower limb impairments and as devices to support the work of physiotherapists [4].

Based on the state of the art of the design of assistive technologies, such mechanisms are considered metabolically beneficial if they are able to apply the right amount of assistance to user's body at the right time, as well as maintain the normal biomechanics of motion [5]. Taking these requirements into account, assisting only the ankle joint seems to be a reasonable strategy, since it contributes more power than either the hip or knee [6]. However, the support of the hip joint is also seen as a significant contribution to the energy costs reduction [7], and maintaining unrestricted hip motion is considered important for the energy efficiency of gait [8].

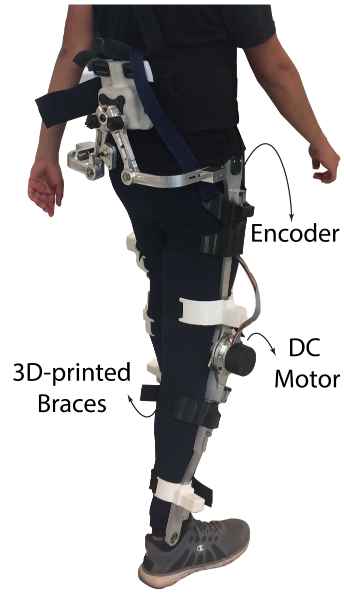

Fig. 1. *Hip and knee joints of the AGoRA exoskeleton.* The four joints are powered by brushless DC motors coupled to Harmonic Drive gearboxes.

In this paper, we propose a wearable robotic lower limb exoskeleton designed based on these premises. This device is meant to make part of an adaptable robotic platform for gait rehabilitation and assistance (AGoRA) designed by the Colombian School of Engineering Julio Garavito (CSEJV), which also comprises a smart walker. The AGoRA exoskeleton has six actuated degrees of freedom (DOF) (hip, knee and ankle joints along the sagittal plane) and one passive DOF (hip joint along the frontal plane).

Concerning the ankle joint, the device is aimed primarily at drop foot patients, which is the most common ankle-related post-stroke impairment. The drop foot is a neuromuscular disorder that deteriorates the patients' walking ability to move their foot along the sagittal plane [9], and its most commonly used treatment option is the ankle-foot orthosis (AFO). An AFO is defined as a mechanical device used to prevent or correct ankle and foot deformities and to improve their functions [10]. Due to the fact that conventional passive AFOs present

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some stability issues [11] and there is evidence indicating that an optimal match exists between patient's gait related problems and AFO ankle stiffness [12], variable-impedance orthoses present themselves as a suitable treatment of drop foot gait. Taking this into account, it was decided that the best way to achieve an effective ankle rehabilitation option within the development of the AGoRA exoskeleton was to include an active AFO based on variable stiffness actuators.

In regards of the hip joint, the DOF of hip add/abduction is part of the originality of the present design as most devices hinder this particular move [4]. Despite the fact that its angular range of motion (ROM) during walking is small (about $10°$) [13], the hip add/abduction exposes a high correlation between its strength and the human gait velocity at comfortable speed [14]. In order to maximize kinematic compatibility, an exoskeleton with a variable-stiffness 2 DOF hip joint with intersecting axes was developed, thus making it possible to reduce but not eliminate misalignment of the hip DOFs. With this assistive device we seek to contribute to the reduction of the clinician's effort and the therapy time, by including the implementation of different sensors to improve the rehabilitation outcomes.

This paper presents the development of such exoskeleton. Next section introduces various aspects related to the conceptual design and the description of different components of the AGoRA exoskeleton. In Section 3, the elemental control strategies proposed for the device are given. The control architecture and the communication among its components are presented in Section 4. Finally, Section 5 includes the conclusions of the work.

II. DESIGN OF AGoRA EXOSKELETON

The exoskeleton presented here is mainly intended as a rehabilitation approach for stroke patients, but it can also be used for gait compensation in patients who have suffered a spinal cord injury and present a lower-limb paralysis as a consequence of it. It is conceived for treadmill gait training in a clinical environment as a bilateral wearable device. The AGoRA exoskeleton has six active DOFs, in which hip, knee and ankle are powered along the sagittal plane. The hip joint has an additional passive add-abduction DOF, which plays an important role in the lateral balance control [15].

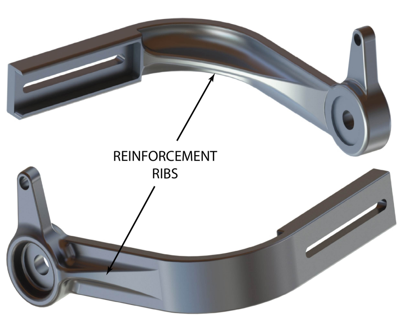

Fig. 2. *Reinforcement ribs.* The implementation of reinforcement ribs within the exoskeleton design allows this structure to increase its resistance without significantly gaining weight.

As weight is a crucial aspect in the design and fabrication of wearable devices [16], selecting a light but high-resistant material is critical. In the particular case of this exoskeleton, most pieces are made of duralumin, a material with both the mentioned properties and low corrosion (attribute of great importance in clinical settings). The whole design of the exoskeleton is rigid on the hip and knee joints, and flexible on the ankle joint. The different rigid parts possess a soft geometry, i.e. sharp points, sharp edges, and protrusions are avoided, so that stress risers disappear and aesthetics improves. Likewise, adding reinforcement ribs allows the device to be more resistant without significantly increasing its weight (see Fig. 2).

These design criteria allow the device to have a weight of about 12kg without including its battery pack. The exoskeleton is being powered by the moment as a tethered device, as it is at present still in the development stage. However, in a further stage, it is necessary to include an autonomous power supply to prevent drawbacks when performing gait training in clinical environments.

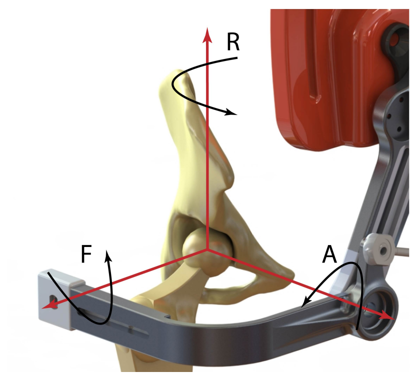

Fig. 3. Alignment of exoskeleton hinges with hip joint center so that flexion/extension (F) and add/abduction (A) are performed as natural as possible, while internal/external rotation (R) remains fixed.

Furthermore, correct alignment of exoskeleton hinges with biological axes of rotation is crucial to ensure the correct transfer of torque from exoskeleton to wearer [17]. Therefore, in order to guarantee the alignment of the exoskeleton hinges with the human joints (Fig. 3), the length of each exoskeleton segment can be adjusted to different patient's anthropometric measures without losing functionality. The length of the thigh and the shank segments can be adjusted via a mechanism of two telescopic bars that are pushed one inside the other. The setting range thus covers heights between 1.70-1.83m (which encompasses the majority of the Colombian male population [18]) and a maximum body weight of 90kg (loading capacity validated by means of 3D finite element simulations).

Moreover, another aspect that ensures proper torque transmission is the fastening system, and its design must be therefore based on compliance, comfort, adjustability, and wear resistance. Taking these design criteria into account, adjustable rounded leg braces carriers with Velcro straps (Fig. 1) were 3D printed in Nylon, which is a highly stress-resistant material.

Foam pads are also used to minimize pressure against the skin and prevent damage.

In regards of the kinematic configuration, the maximum ROM possible across all joints is shown in Table I. These values were established based on normal gait on healthy subjects [19], so that users are also able to perform sit-to-stand and stand-to-sit movements [20]. Based on these anatomical restrictions, the angular joint limitation of the AGoRA exoskeleton is kept by both software and hardware (end-stop at the exoskeleton knee joint) for safety reasons. For the exoskeleton ankle, its control architecture implements an initial calibration step, whereby the patient's ankle joint is passively moved by the therapist while their maximum ROM is being recorded and set via software for subsequent active therapy.

TABLE I
DEGREES OF FREEDOM (DOF) AND RANGE OF MOTION (ROM) ACROSS ALL JOINTS

Joint	DOF	Actuation	ROM
Hip	Flexion/Extension	Active	100° / 20°
Hip	Add/Abduction	Passive	10° / 10°
Knee	Flexion/Extension	Active	100° / 3°
Ankle	Dorsi/Plantar-Flexion	Active	Software calibrated

A. *System for the Control of Joints Movements*

- *Actuators*: Based on the fact that electric motors provide a reduction in power consumption during gait [21], and particularly, DC motors meet the criteria of necessary power with a compact and portable structure, a harmonic drive coupled with a brushless flat DC motor EC-60 flat 408057 (Maxon AG, Switzerland) were selected to be the actuation system of the hip and knee joints. The harmonic drive mechanism CSD-20-160-2AGR (Harmonic Drive LLC, USA), with a gear ratio of 160:1, was selected because it allows ensemble position accuracy with a low weight/volume ratio. This assembly (Fig. 4) gives to each joint a continuous net torque of 35 Nm and peak torques of 180 Nm, which is in accordance with the design requirements for most patients [22], [23].
  Likewise, the electric actuation mechanism of the ankle joint consists of two high-torque servomotors Dynamixel MX106T (Robotis, USA) placed on the posterior and anterior parts of user's shank (Fig. 6).
- *Sensors*: Human-robot interaction is very important for users' comfort and safety in a wearable robotic device [24]. In terms of physical interface, the AGoRA exoskeleton is designed in such a way that there are no sensors physically attached to the user's body. The sensors included in this system are:
  - *Encoders*: Besides the internal encoder of each DC motor (used for the implementation of position and impedance controls), the exoskeleton has one incremental encoder placed concentrically to each joint assembly (Fig. 4). Voltage outputs received from these encoders are converted to angle values, which provide information on the relative angular position of both hip and knee joints during passive gait training.
  - *Force sensors*: We have included strain gauges as force sensors in the metal rods of the exoskeleton, which are coupled with the joints assembly (Fig. 4), to measure the torque produced by the interaction between the user's limb and the robotic device. These strain gauges are connected in a full Wheatstone bridge with the purpose of achieving higher sensitivity and accuracy [25].
  - *Insole pressure sensors*: The footplate of the exoskeleton is equipped with two force sensing resistors (FSR) for each insole (placed on the heel and toe), which binary detect the contact of the user's foot against the ground. These sensors are mainly intended for the phase differentiation during gait segmentation, which is useful to assess the patient's gait pattern.

The exoskeleton, its actuators and sensors are shown in Fig. 1.

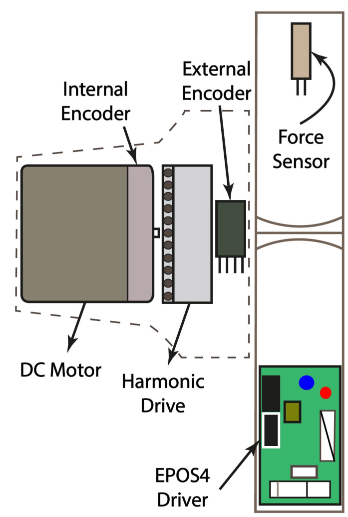

Fig. 4. Schematic drawing of knee joint assembly of the AGoRA exoskeleton.

B. *Add-Abduction DOF of Hip Exoskeleton*

Considering the hip joint as a ball joint, three DOFs must be considered. However, for purposes of simplicity, the design of the present device does not involve the hip internal/external rotation, as enabling all DOFs would cause more instability and would therefore require a more complex misalignment-compensating system [8].

The flexo-extension axis consists of a single hinge and need to be manually aligned with the human axes, whereas the add/abduction axis consists of a self-aligning hinge that, in conjunction with a composite material, conditions the user's hip ROM. The assistance provided by the AGoRA exoskeleton along the add/abduction DOF is based on a variable-stiffness system (Fig. 5), so that the patient's stability enhances regardless of their level of disability. This variable system tenses two bio-inspired tendons (fishing rod coiled around a 2.85mm Filaflex thread), which are connected to a steel link for load transmission to the lateral structures, restricting the add/abduction movement within a normal human range (see Table I).

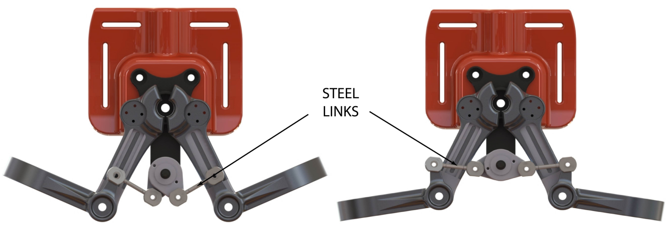

Fig. 5. *Add/abduction DOF of the AGoRA exoskeleton.* A variable-stiffness system, which involves composite tendons, enables the hip Add/abduction DOF with a determined stiffness level.

C. Powered Ankle-Foot Orthosis

As already mentioned, considering too many actuated joints on an exoskeleton design can result in a bulky device with a much more complex control system. However, lack of actuation in some important joints can lead to some drawbacks. Actuation on the ankle joint, for instance, is clinically relevant for stroke patients, some of which suffer from drop foot [25].

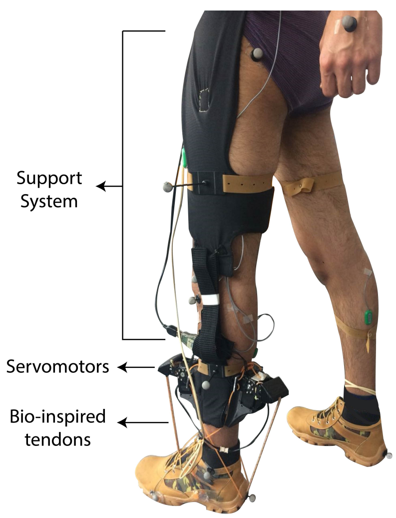

Fig. 6. *Ankle-foot orthosis of the AGoRA exoskeleton.* A variable-stiffness actuation mechanism, which involves bio-inspired tendons, enables the ankle dorsi/plantar-flexion DOF based on gait phase detection.

For the AGoRA exoskeleton, the actuation system used on the ankle joint is formed by servomotors attached in series with two bio-inspired tendons (with the same composition as those on the hip assembly). These tendons are secured to the patient's heel and forefoot by means of a customized insole, as shown in Fig. 6.

The primary goal of this design is to reproduce a variable stiffness profile by manipulating the bio-inspired tendons. These tendons are handled in such a way that they resemble the behavior of two antagonist muscles, as ankle impedance is varied in response to walking phase and step-to-step gait variations. To the best of the authors' knowledge, there are few ambulatory exoskeletons used for rehabilitation that have the ankle joint actuated based on a flexible structure [20].

III. CONTROL STRATEGIES

This section describes the different lower-level control strategies that will be implemented for the control of basic functions of the AGoRA exoskeleton. In the future, this assistive device may use both trajectory and impedance control as the base of novel training therapies. We hypothesize that this approach will contribute to the conventional rehabilitation, since the therapy would adapt according to each subject's needs.

A. Trajectory control strategy

Trajectory or position control is a robotic strategy based on the principle of guiding the joints of the user's lower limbs along a preset reference gait trajectory, while receiving the joint angles as a feedback [25]. The reference trajectories will be generated by using an algorithm that reconstructs regular kinematic patterns based on user's height and gait speed [26]. With this simple strategy, the exoskeleton will be able to guide the patient throughout reconstructed normal reference trajectories for any given ROM.

B. Impedance control strategy

Despite the position control presents itself as an appropriate initial control approach, robot-based therapy should be optimized in order to increase the patient's involvement. For the purpose of ensuring a more compliant operation, an algorithm that takes into account the interaction torque between user and assistive device is meant to be implemented.

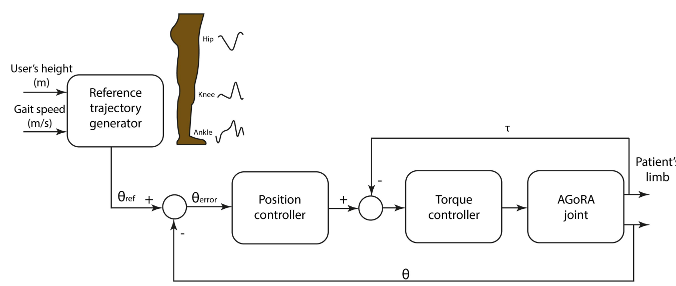

Fig. 7. *Impedance control algorithm of each actuated joint of the exoskeleton.* Adapted from [27].

To accomplish this, the output of the position controller should feed a torque controller (Fig. 7). Consequently, the AGoRA exoskeleton should provide an output torque for the actuators, which is expected to be proportional to trajectory deviations. Together, this control algorithm should guide patients' limb in a correct pattern, only assisting patient when they deviate from the trajectory. Literature suggests that this behavior can lead to better results than fixed repetitive training as it is individually personalized [28].

C. Control Strategy of Ankle-Foot Orthosis

Control strategies at the AGoRA AFO are mainly targeted towards the prevention of toe drag in swing phase and slap foot at heel strike. During midstance phase, both tendons remain at maximum tension to provide stability. Subsequently, joint impedance is minimized so as not to impede powered plantar flexion movements during late stance. Finally, during the swing phase, the posterior motor lifts the foot to provide toe clearance.

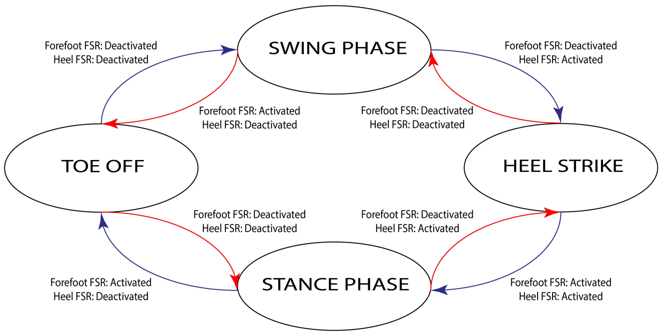

Fig. 8. *Gait phase detection by means of a pressure sensing system.* A binary detection algorithm allows for identification of each gait phase.

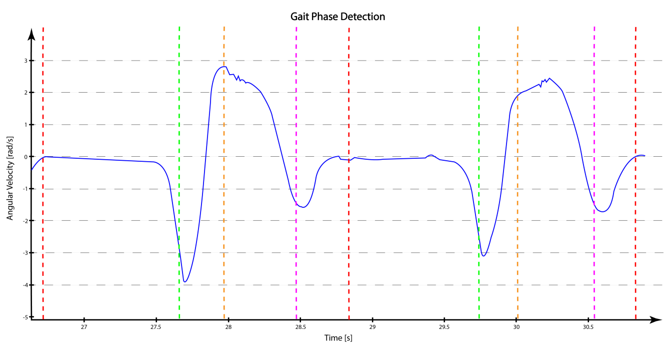

Fig. 9. *Gait phase detection by means of an inertial sensing system over two gait cycles.* A peak detection algorithm applied to the angular velocity signal allows for identification of each gait phase start: stance phase (red dashed line), toe off (green dashed line), swing phase (orange dashed line) and heel strike (pink dashed line).

The gait phase detection is implemented by means of the in-sole pressure sensors and the inertial sensing system BNO055 (Bosch Sensortec, Germany). The FSR control system is a simple binary detection algorithm (illustrated in Fig. 8), and the inertial control system is based on the angular velocity of the gait cycle [29], as shown in Fig. 9. The integration of these control approaches enables the implementation of a real-time actuation mechanism at the ankle joint.

IV. CONTROL ARCHITECTURE

The control hardware of the exoskeleton is shown in Fig. 10. The hip and knee joints are equipped with an EPOS4 Module 50/8 (Maxon AG, Switzerland) (Fig. 4), and both ankle joints are controlled by a single-board computer Raspberry Pi 3 Model B. The main board is, for the time being, implemented on the AGoRA-Joint 1 (right hip joint). Nevertheless, as a human-robot interface is thought to be developed to provide more adaptability, the main board must be another stand-alone device in the future. Each board is in charge of data acquisition of their own joint's sensors: angular position, interaction torque and foot-ground contact.

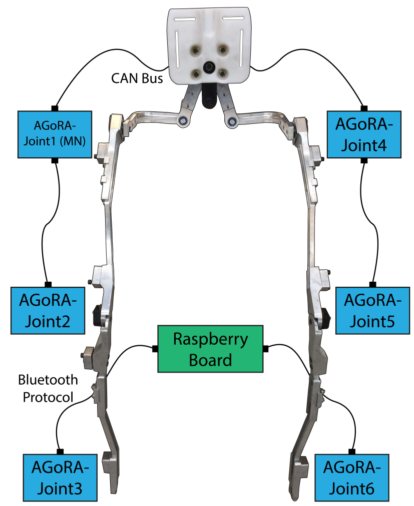

Fig. 10. *Overall control architecture of the AGoRA exoskeleton.* All sensor data in both legs are collected by the AGoRA-Joints 1∼6 boards, which communicate through CAN and Bluetooth protocols.

The communication among the different components of the hip and knee joints is based on the control architecture defined in [25]. The network structure has a deterministic real-time communication based on Control Area Network (CAN) technology running at a fixed rate (1 kHz). This communication protocol is intended for the reduction of the volume, complexity and difficulty of wiring [27]. To read the message, each driver has a CAN ID number associated to it, which allows that it can be distinguished from other by the main board. As for the case of the ankle joints, collected data is sent through bluetooth protocol to the Raspberry Pi 3 board to perform data processing and implementation of control strategies.

V. CONCLUSIONS

This paper has presented a robotic exoskeleton for gait rehabilitation in stroke survivors and similar motor disorders, which is being developed at the CSEJV in the framework of the AGoRA project. This document has been focused on the conceptualization and development of this robotic assistive device.

Notably, since each exoskeleton joint is equipped with its own controller, the AGoRA exoskeleton offers promising means of using unilateral versions of the device, enhancing modularity and therefore customizing treatment protocols to each patient's specific needs. To use these modular components, the exoskeleton's control system is based on a custom assist-as-needed algorithm that proportionally applies torque only when patient deviates from a pre-programmed correct pattern.

In summary, the developed AGoRA exoskeleton opens up an opportunity to study novel rehabilitation protocols with the capacity to deliver intensive and task-specific treatment. This type of advances may therefore have a huge clinical impact by promoting faster recovery and improving quality of life in stroke victims.

For further work, the design of the AGoRA exoskeleton is expected to become modular, which is particularly relevant for stroke patients. Mechanical design must be conceived in such a way that all segments of the device can be used independently without significantly affecting donning and setup times. Moreover, in an even further development stage, the presented lower-limb exoskeleton is meant to be integrated with a smart walker by means of a human-robot interface, so that a reliable platform for clinical application can be created.

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