Design of a Patient-Tailored Active Knee-Ankle-Foot Orthosis to Assist the Gait of Spinal Cord Injured Subjects

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***Abstract*—This paper presents the main design steps in the development of an active knee-ankle-foot orthosis (KAFO) conceived to assist the gait of incomplete spinal cord injured (SCI) subjects. The design approach is based on the idea of modifying the available passive orthoses by adding adaptable mechatronic modules at the joints. This approach has resulted in a prototype that has been tested on SCI patients. The design and control problems found and their adopted solutions are thoroughly described.**

I. Introduction

THE design of powered orthoses and exoskeletons that assist human gait is an open field of research that covers several areas such as biomechanics, mechanical design, robotics and neurorehabilitation. Those active devices are designed to help patients with disabilities, caused for example by a spinal cord injury (SCI) or acquired brain damage, and have shown to be useful for recovering locomotor function after the injury [1], and for favouring physical activity later, thus improving the patients' health and quality of life after rehabilitation.

In the last years, a number of robotic devices aimed at assisting human gait have been developed [2]. The objective of this work is to present the progress of an ongoing project aimed at designing a patient-tailored active orthosis to assist the gait of incomplete SCI subjects. A pair of orthoses have been built so far and they are now being tested on patients of the SCI Unit of the "Complejo Hospitalario Universitario de A Coruña" (CHUAC).

The design of the orthosis is based on the ideas of the Head of the SCI Unit of the CHUAC, who wanted to improve the commercial passive orthoses that SCI patients of this unit are using at present. It must be noted that the target patients are able to control hip flexor muscles, being classified under levels C or D in the ASIA impairment scale (AIS). The current commercial orthoses include two basic parts: a) a knee locking system, which is essential to bear the patient's weight during the stance phase due to the lack of force at the quadriceps muscle; and b) a passive ankle joint (*klenzak* joint) that constrains ankle plantar flexion during the swing phase, thus avoiding drop-foot gait. Commercial knee-locking systems are shape or friction-based, being activated upon heel strike detection, usually by means of an on-off contact sensor. The *klenzak* joint consists of a spring that applies an external dorsiflexion torque. Those devices are essentially passive, being the only semi-active system that formed by the knee locking mechanism and the on-off contact sensor.

Those current orthoses represent the starting point of the prototypes that have been developed in the project. With the aim of obtaining a patient-tailored, low-cost and low-weight product, our design approach is based on using as much as possible the existing orthopaedic devices and developing mechatronic modules that can be attached to them.

The following section presents the mechanical design and sensors of the built active orthoses, highlighting the design problems found and solutions adopted. Finally, the main future developments of the project are outlined.

II. Mechanical Design and Sensors

The main modifications to the current devices suggested by the medical staff of the SCI Unit at CHUAC were the following ones: a) introducing, besides the locking system, actuation at the knee joint because the considered subjects do not have enough muscle force to flex and extend the lower limb during the swing phase; and b) including some additional sensors on the prototype or the body in order to better control the knee-locking system and actuation.

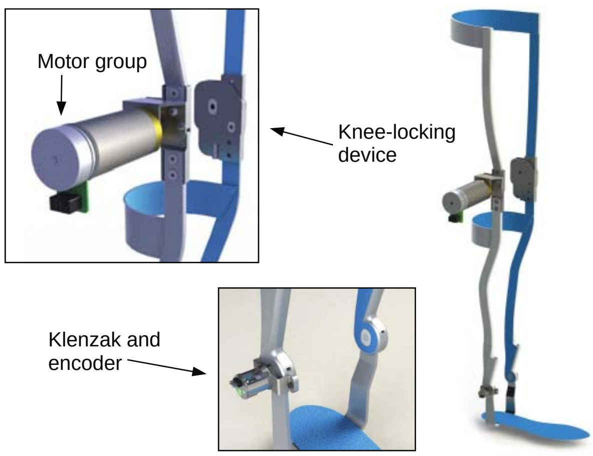

Fig. 1. CAD design of the first prototype of active KAFO.

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Based on that, a first knee-ankle-foot orthosis (KAFO) prototype was designed [3], Fig. 1. In this prototype, a standard *klenzak* joint was slightly modified including an optical incremental encoder for control purposes. The knee joint incorporated two powered systems acting in parallel. In order to lock the knee during stance, the controllable shape-locking mechanism Neuro Tronic, manufactured by Fior & Gentz (Germany), was used. An on-off contact-detection sensor provided by the company controlled this system. Regarding the knee actuation, an electrical EC 45 flat motor, manufactured by Maxon Motor (Switzerland), together with a 1:156 planetary gearbox was used. The motor included an optical encoder for its position control. The objective of using the two systems was to avoid the use of the motor for locking the knee during stance, thus reducing the power consumption of the orthosis. Regarding the control, apart from the mentioned sensors, a hip electro-goniometer was also included. Since the target patients are able to control (up to a certain degree) the hip joint rotation, this angular measurement was intended to be used as a reference for the knee flexion-extension actuation during swing. It must be mentioned that this prototype had length-adaptable lateral bars, so that it could be used with different SCI subjects.

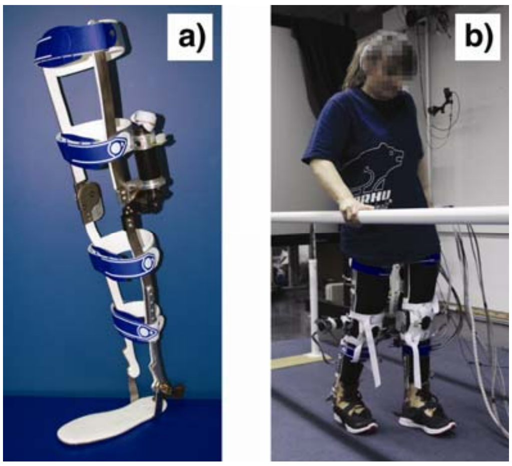

Fig. 2. (a) Prototype with femur-aligned motor. (b) Experimental test of a SCI subject wearing the active KAFO.

Laboratory testing revealed several drawbacks of the first prototype, which are described in what follows.

A first inconvenient was related to the horizontal arrangement of the motor axis, which could collide with the crutches during walking. This was amended using a 1:1 bevel gear and placing the motor axis parallel to the femur, Fig. 2(a). However, the lack of robustness of the gear set forced to return to the original horizontal layout.

Regarding the shape-locking mechanism, a considerable extension torque from the motor was required to unlock the joint in order to start the swing, thus increasing the power consumption and time of response. So it was decided to use the motor to lock the knee, since it proved to be capable of locking that joint during stance.

In what refers to the foot-ground contact detection, the on-off transducers were very unreliable, so they were replaced by continuous force-sensing resistors.

Finally, the inability of properly measuring the hip angle by means of electro-goniometers led to discard it as a control input.

The mentioned improvements led to a second prototype, illustrated in Fig. 2(b), this time specifically tailored for the target female patient, since the previous adaptable design showed to be problematic due to the wide range of morphologies found among patients. Each orthosis weights less than 2 kg, which was the initial specification of the medical staff. A PID controller is used to control the position of the knee actuator as a function of the ankle angle of the contralateral leg. A real-time GUI has been developed in order to parametrically tune this function during the tests, so that it adapts to the gait style of the patient. According to the physicians, this control has yielded a more natural gait pattern of the SCI subject, who has been so far walking with the aid of parallel bars.

III. Future Developments and Challenges

There are still several challenges to face in the project. First of all, for the patient to be able to walk long distances so that her performance can be objectively measured, portability of the system is being addressed. The objective is to integrate power and control devices inside a 2 kg backpack carried by the patient. As for the mechanical design, a novel actuation system is under development and the use of series elastic systems to reduce energy consumption is being investigated. Moreover, the use of electromyography (EMG) of active muscles for control, and the use of functional electrical stimulation (FES) together with the current actuation (hybrid active orthosis) are also being explored.

IV. Conclusion

This extended abstract presents the work being done in a project aimed at designing an affordable and patient-tailored active orthosis for gait rehabilitation of SCI subjects. The main features of the prototypes and the decisions made during the design stage, which are based on practical experience on actual SCI patients, are outlined. From this experience, several design and control challenges are currently faced in order to obtain a product that could be introduced in hospitals and rehabilitation centers.

References

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