Low-cost active orthosis for gait assistance of subjects with spinal cord injury

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Introduction

Spinal cord injury (SCI) is prevalent in society. Worldwide each year more than 250.000 individuals suffer SCI [1]. Walking impairment after injury leads to a decreased quality of life and carries substantial health care costs. Current gait rehabilitation robots are machines that support the patient's weight and train walking over a treadmill, or lower limb exoskeletons that assist over-ground gait. These machines are generally heavy and expensive, and are only found in the clinic because skilled personnel have to manually fit the robot to the patient and operate it.

With the aim of overcoming these limitations, this abstract presents the design and evaluation of a low-cost active orthosis for walking assistance of subjects with SCI. The prototype is intended for patients that can control hip flexion/extension, but lack control of knee and ankle muscles. The design is based on the current passive knee-ankle-foot orthoses that these patients use after rehabilitation. The latter include a knee locking system, which is essential to bear the patient's weight during stance due to the lack of quadriceps force; and a compliant system that applies a dorsiflexion torque at the ankle to avoid drop-foot gait (*klenzak* joint).

Active orthosis design

The proposed lower limb active orthosis has two degrees of freedom. The knee joint is powered by an electrical motor in series with a Harmonic Drive gearbox. The ankle is passively actuated by a mechanism that applies the above-mentioned dorsiflexion torque. A preliminary design of the orthosis was reported in [2].

The current device weights 2.7 kg per leg, along with a 1.7 kg backpack containing a BeagleBone Black board, the motor drivers and the battery. The bilateral thigh and shank uprights are articulated at the knee, using a standard revolute joint at the medial side and the motor-gearbox set at the lateral side. A footplate with a shoe is hinged to the shank uprights by the compliant *klenzak* joint. The orthosis structure is specifically tailored to the patient at the orthopaedic workshop to avoid adapting the same design to the wide range of morphologies found among subjects with SCI. Fig. 1a shows the right active orthosis with the elements that are going to be described later.

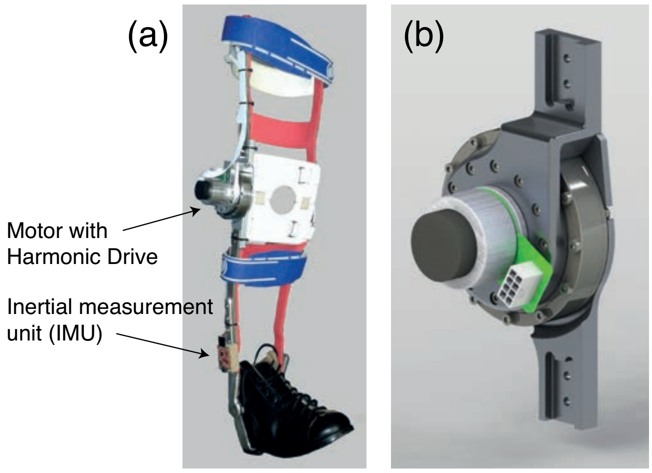

Fig. 1: Orthosis design: (a) general view showing the motor-gearbox set and the IMU; (b) CAD design of the knee set.

The design and selection of the orthosis actuation system were based on kinematic and dynamic data of the knee joint during walking at a normal speed [3]. The most significant criteria for the actuation system selection were power to weight ratio, system dimensions, and portability of the power supply system.

Based on these considerations, a 70 W brushless DC motor (Maxon Motor, Sachseln, Switzerland) was selected, which has a nominal voltage of 24 V and a nominal torque of 128 mNm. A Harmonic Drive gearbox (Harmonic Drive, Limburg-Lahn, Germany) is coupled to the motor to increase torque and reduce velocity, which offers a large gear ratio with a reduced space (Fig. 1b). The selected gear ratio of 160:1 allows a continuous net torque at the knee of 20.5 Nm and peak torques of 60 Nm (according to the driver current limit).

Regarding the control, all the sensors are placed on the orthosis mechanical structure in order to avoid issues related to safety, comfort, reliability and donning/doffing process. The sensors used are one inertial measurement unit (IMU) and one angular encoder per orthosis. The low-cost 9-DOF IMU (SparkFun Electronics, Niwot, USA) is attached to the shank upright; and incorporates a gyro, an accelerometer and a magnetometer. The orientation and acceleration measurements are sent to the BeagleBone board through a serial interface. The angular encoder is coupled to the knee motor.

The control algorithm uses both IMUs measurements to detect the stance-to-swing transition within the gait cycle. During stance, the knee is fully extended and the motor acts as a brake. When the stance-to-swing transition is detected, based on vertical acceleration and pitch angle of both shanks, the knee motor launches a fixed flexion-extension cycle using a PID position controller with feedforward. This cycle is personalized to the subject in terms of duration, shape and maximum flexion angle.

Experimental tests

The subject was an adult female 41 years old, mass 65 kg and height 1.52 m; with SCI at T11. In the first experiment (Experiment A), she walked with her usual pair of passive knee-ankle-foot orthoses with the help of two parallel bars. Then, the subject carried out 6 one-hour training sessions wearing the active orthoses and did some specific exercises at home to facilitate adaptation. After this period, a second experiment (Experiment B) walking with the active orthoses, also with the help of parallel bars, was performed (Fig. 2a).

In order to compare the walking kinematics in the two experiments, 4 consecutive gait cycles were captured each time by 6 optical infrared cameras (Natural Point, Corvallis, USA) that measured the position of 37 optical markers. Then, a computational 3D skeletal model with 18 anatomical segments and 57 degrees of freedom was used to determine the kinematic characteristics of the subject's gait (Fig. 2b).

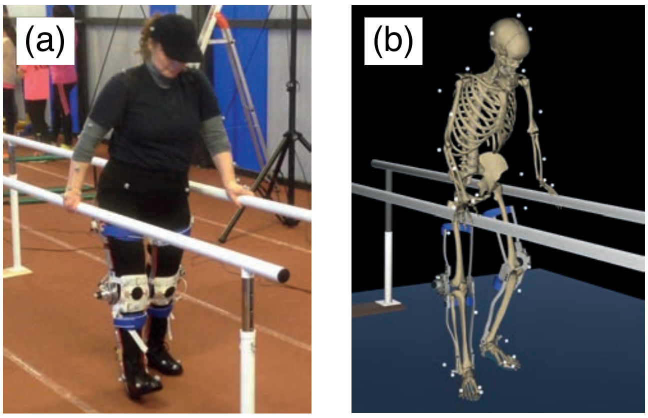

Fig. 2: Gait of SCI subject assisted by active orthoses and parallel bars: (a) motion capture; (b) computational model.

Table 1 shows kinematic results for one gait cycle during Experiment A and another gait cycle during Experiment B. Gait velocity, stride length and cadence of walking increased (24.11%, 7.41% and 15.56%, respectively) when wearing active orthoses compared to the case with passive orthoses. Moreover, the lateral displacement of the subject's centre of mass (COM) decreased in 19.31% when the subject walked with active orthoses.

Table 1: Kinematic data obtained with passive orthoses (Experiment A) and active orthoses (Experiment B).

	Experiment A	Experiment B	% change
Gait velocity (m/s)	0.17	0.21	+24.11
Stride length (m)	0.53	0.57	+7.41
Cadence (step/min)	38.46	44.44	+15.56
COM lat. dis. (cm)	7.89	6.37	–19.31

Conclusion

This paper presents the design and control of a patient-tailored low-cost active orthosis for subjects with SCI. This orthosis is equipped with a compact knee actuation system and an IMU at the shank to detect gait events. Preliminary experimental tests of this device on a subject with SCI show that the subject walks faster, and in a more natural and stable way when wearing the designed active orthoses. While the experiments provide promising results, more tests with a larger sample of subjects are needed in order to confirm the improvements when walking with the designed orthosis. Future research will be devoted to the design of more efficient and comfortable actuation systems based on elastic elements; and to the use of functional electrical stimulation (FES) in parallel with the current motor actuation, with the aim of improving the health condition of the patient and increasing device autonomy.

Acknowledgements

This work was funded by the Spanish Ministry of Economy and Competitiveness (MINECO) under Project No. DPI2015- 65959-C3-2-R, co-funded by the European Union through the European Regional Development Fund (ERDF). The support is gratefully acknowledged.

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