Design and Experimental Evaluation of a Low-Cost Robotic Orthosis for Gait Assistance in Subjects with Spinal Cord Injury

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Abstract Robotic gait training after spinal cord injury (SCI) is of high priority to maximize independence and improve the living conditions of these patients. Current rehabilitation robots are expensive and heavy, and are generally found only in the clinic. To overcome these issues, we present the design of a low-cost, low-weight robotic orthosis for subjects with SCI. The paper also presents a preliminary experimental evaluation of the assistive device on a subject with SCI. Results show that 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 standard passive orthoses.

1 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 other serious health conditions, and carries substantial health care costs. Locomotor rehabilitation is reported as a high priority issue for subjects with SCI independent of severity, time after injury, and age [2].

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Current gait rehabilitation robots are machines that support the patient's weight and train the walking motion over a treadmill or feet supports; or lower limb exoskeletons that assist over-ground walking. These robots 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. Moreover, they are adapted to the patient before the treatment, increasing time and health care costs; and, in general, they impose a motion pattern rather than complementing patient's capabilities.

With the aim of overcoming these limitations, this work presents the design, control and experimental evaluation of a low-cost, low-weight and simple robotic orthosis for gait assistance in subjects with SCI. The prototype is intended for patients that can control hip flexion/extension to a certain extent, 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).

The robotic orthosis presented here improves the passive devices by adding a motor at the knee, that can move or lock the joint, and an inertial measurement unit (IMU) at the shank to detect gait events. The aim of this work is two-fold: first, we present the design of the robotic orthosis; and second, we perform a preliminary experimental evaluation on a subject with SCI. In this case study, the kinematics of walking with passive orthoses is compared with that obtained with the robotic device.

2 Robotic Orthosis Design

The proposed lower limb 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 mentioned dorsiflexion torque (*klenzak* joint). A preliminary design of the orthosis was reported in [3].

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 hinge 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, which allows an ankle range of motion between 0º and 20º (dorsiflexion). The orthosis structure is specifically tailored to the patient to avoid adapting the same design to the wide range of morphologies found among subjects with SCI. Figure 1a shows the right robotic orthosis with the elements described later.

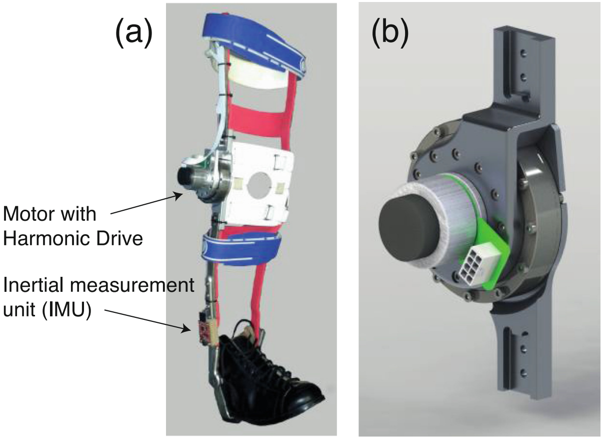

Fig. 1 Robotic orthosis design: **a** general view showing the knee actuation system and the IMU; **b** CAD design of the actuation system

2.1 Knee Actuation System

The design and selection of the orthosis actuation system were based on kinematic and kinetic data of the knee joint during normal gait at a normal speed [4]. The most significant criteria for the actuation system selection were specific power (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.

2.2 Sensors and 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 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 triple-axis gyro, a triple-axis accelerometer and a triple-axis 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.

3 Experimental Evaluation

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, 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 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).

Table 1 shows kinematic descriptors for one gait cycle during the first experiment and another gait cycle during the second experiment. Gait velocity, stride length and cadence of walking increased (24.11, 7.41 and 15.56 %, respectively)

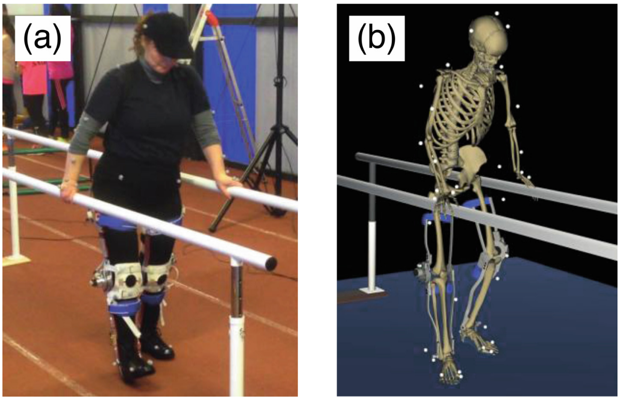

Fig. 2 Gait of spinal cord injured subject assisted by active orthoses and parallel bars: **a** acquired motion; **b** computational model

Table 1 Kinematic data with passive and active orthoses

	Ex.1: passive	Ex.2: active	% 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. displ. (cm)	7.89	6.37	−19.31

when wearing active orthoses compared to the case with passive orthoses. Furthermore, the lateral displacement of the subject's centre of mass (COM) decreased in 19.31 % when the subject walked with active orthoses.

4 Conclusion

This paper presents the design and control of a patient-tailored low-cost knee-ankle-foot robotic 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 evaluation of this assistive device on a subject with SCI shows that the subject walked faster, and in a more natural and stable way when wearing the designed active orthoses. While the experiments provided promising results, more tests with a larger sample of subjects are needed in order to confirm the improvements when walking with the designed orthosis.

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