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A light-weight active orthosis for hip movement assistance

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HIGHLIGHTS

- Development of a novel light-weight wearable powered bilateral pelvis orthosis.
- Design of a novel compact, light-weight series-elastic actuator (SEA).
- SEA closed-loop torque control bandwidth equal to 15 Hz.
- SEA output impedance ranges from 1 to 35 N m /rad in human gait frequency spectrum.
- The overall system usability was proved by tests with a healthy subject.

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ABSTRACT

In the last decades, wearable powered orthoses have been developed with the aim of augmenting or assisting motor activities. In particular, among many applications, wearable powered orthoses have been also introduced in the state of the art with the goal of providing lower-limb movement assistance in locomotion-related tasks (e.g.: walking, ascending/descending stairs) in scenarios of activities of daily living. In this paper we present a light-weight active orthosis endowed with two series elastic actuators for hip flexion–extension assistance. Along with the description of its mechatronic modules, we report the experimental characterization of the performance of the actuation and control system, as well as the usability test carried out with a healthy subject. Results showed a suitable dynamic behavior of the actuation unit: the closed-loop torque control bandwidth is about 15 Hz and the output impedance ranges from about 1 N m/rad to 35 N m/rad in the frequency spectrum between 0.2 and 3.2 Hz. Results from the tests with the healthy subject proved the overall system usability: the subject could walk with the device without being hindered and while he received a smooth assistive flexion–extension torque profile on both hip articulations.

1. Introduction

Aging of the population is one of the most critical challenges current industrialized societies, characterized by a low birth rate and long life expectation, will face in the next years, and threatens the sustainability of our social welfare. In 40 years from now, nearly 35% of the European population will be over 60 year-old, resulting in the urgency to provide solutions enabling our aging society to remain active, creative, productive, and – above all – independent [1,2].

Aging may cause reduced mobility, which leads to loss of independence [3–5]. According to the investigation accounted in [6], the spontaneous walking speed decreases by about 1% per year from age 60 onward, and the observed decline of maximum walking speed is even greater. Gait disorders and lower-limb impairments are also common and often devastating companions of aging [1–3]: several population-based studies showed a 35% prevalence of gait disorders among persons over age 70, and 80% over 85 years of age [4]. Gait disturbances have major consequences, including falls (leading to major fractures or head trauma), the number of which is expected to reach 500,000 by the year 2040 in US, representing a total annual cost of 16 billion dollars [7]. Senile gait disorders could also be an early manifestation of underlying pathologies, which might not only alter gait directly, but may also indirectly cause a subjective

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sensation of instability and insecurity, forcing individuals to adopt a more cautious gait [8–15].

A possible scenario for the next years is that aging-related gait syndromes will lead to an increase of the number of people needing assistance in their daily living activities, e.g. basic mobility, personal hygiene and safety awareness. In this scenario, it is plausible that people will become progressively more reliant on technology to meet their desire to live independently, actively and satisfactorily. Among all the assistive devices springing up, wearable robotic orthoses (namely "exoskeletons") were proposed as a solution by many research teams active in the field of medical robotics to assist people (mostly elderly) affected by gait disorders [16–18].

An exoskeleton for gait assistance is generally anthropomorphic in nature, "worn" by the user, and fits closely to his or her body [19]. Given the close interaction with the user, the robot should be light-weight and take into account the user's joints range of motion (RoM), anthropometry, and kinematics to provide a comfortable physical human–robot interface (pHRI) [20–22]. Furthermore, the actuation and control of the robot should allow the user to implement his or her own movement without hindrance while receiving a certain assistance safely: in this framework, a very efficient and often adopted design methodology foresees the endowing of a mechanical compliance between the exoskeleton actuators and the user/robot interface, the so-called Series Elastic Actuator (SEA) strategy [23].

Many robotic exoskeletons can be found in the current state of the art: the broad variability in mechatronic design, control and human–robot interface [19] of these devices is due to differences in the targeted end users and expected usage. Some of them have been designed as unilateral support, in order to assist post-stroke patients. ALEX is a leg exoskeleton whose hip and knee joints are powered by linear actuators [24], controlled by means of an adaptive impedance controller: it is worth to note that ALEX is the only lower-limb exoskeleton which provides passive degrees of freedom (DoFs) allowing vertical and lateral movement of the pelvis, thus a more natural gait pattern. Sawicki et al. [25] investigated on ankle–foot and knee–ankle–foot orthoses powered by McKibben-type pneumatic muscles, which provide an inherent transmission compliance, but with the drawback of requiring a double actuation (antagonistic actuators arrangement). Recently, at Vrije Universiteit Brussel (Brussels, Belgium), a knee–ankle foot orthosis has been developed and tested [26]: in this case pleated pneumatic artificial muscles were used as actuators and a proxy-based sliding mode strategy ensured a safe human–robot interaction. A huge number of bilateral active orthoses have been presented, as well. Relevant bilateral orthoses for post-stroke patients are the LOKOMAT [27] and the LOPES [28], the latter being introduced as the first lower-limb exoskeleton with inherently compliant joints. The LOPES is indeed capable of a high assistance while keeping a low output impedance, thanks to its SEA actuation strategy [28]. Wearable devices for paraplegic or hemiplegic rehabilitation, aiming at replacing locomotion in case of no residual mobility, are the Vanderbilt powered limb orthosis [29] and HAL, an active suit for motion assistance commercialized by Cyberdyne (Tsukuba, Japan) [30]. Other exoskeletons have been specifically designed for assisting the cautious gait of elderly people, such as the exoskeleton EXPOS reported in [31], while other researches focused on devices for body weight support, such as the Moonwalker [32] and the Bodyweight Support Assist by Honda (Honda, Tokyo, Japan). Furthermore, lower-limb exoskeletons were also designed for augmenting human strength, enabling to carry heavy loads, mainly for military purposes: well-known examples are the BLEEX [33], the SARCOS exoskeleton (Sarcos, US) and the MIT passive exoskeleton [34], all developed within the frame of the DARPA program Exoskeletons for Human Performance Augmentation (EHPA, [19]).

It is worth to cite also single-joint active orthoses, such as the SERKA, an active knee orthosis addressing stiff knee gait in stroke patients [35] actuated by a cable-driven rotational SEA, the Dynamically Controlled Ankle–Foot Orthosis [36] and the Adaptive Ankle–Foot Orthosis by Blaya et al. [37], which are examples of simpler active orthoses making use of SEAs to assist push-off or to correct dropped foot gait. Examples of active orthoses for the hip flexion–extension assistance are the devices introduced by do Nascimento et al. [38] and the hip exoskeleton designed by Ferris et al. [39], both powered by artificial pneumatic muscles, and the Stride Management Assist by Honda (Honda, Tokyo, Japan).

In this paper, we introduce the design of a light-weight active pelvis orthosis (APO), which was preliminary presented in [40], for assisting hip flexion–extension (Fig. 1). The device was conceived with two innovative solutions. Firstly, it has a novel, compact and light-weight SEA unit which exploits a custom torsional spring. Secondly, we proposed an optimized design based on extremely light-weight carbon-fiber linkages, embedding manual adjustments for fitting the orthosis to a wide range of user sizes, and passive DoFs which follow the gait motions out of the flexion/extension plane (pelvis tilting, thigh abduction). The device hence ensures good kinematics compatibility, enhancing the comfort of the human–robot physical interaction, avoiding limitations and constrains to user's gait pattern, and addressing the match of intra- and inter-subject anthropometric variability.

Along with the description of the mechatronic modules of APO, this paper also reports its experimental characterizations. In particular, the performance of dynamic response of SEA, and overall usability of the system in a gait assistance task. The usability is tested by controlling APO with an adaptive motion control strategy which was early introduced in [17,18].

The paper is structured as follows: Section 2 describes the design of the light-weight active orthosis. Results of the experimental characterization are reported in Section 3 and discussed in Section 4. Finally, Section 5 draws the conclusions.

2. Mechatronic design

This section presents the main technical solutions of the active orthosis we conceived for the APO system. Hereafter we describe the three subsystems we developed: namely the mechanical structure, the actuation unit and the control system.

2.1. Mechanical structure

The device is sustained by an horizontal C-shaped frame, surrounding the user hips and the back of the pelvis, and interfaced to the trunk by means of three orthotic shells (two lateral and one rear); the frame carries the two actuation units. The structure is realized in two 2.5 mm thickness carbon-fiber lateral arms, connected through a rear straight bar. The rear bar is composed by an external guide in which two internal rods can slide: the bar length can then be adjusted in order to match the distance between the two lateral shells, ensuring the frame to be tightly attached to the upper body in the medial–lateral direction (Fig. 2(a)). One of the two sliding rods can be locked by a fast-detach pin (for coarse regulation and fast don–doff procedure), and finely adjusted thanks to a leadscrew mechanism. In order to further make easier the wearing procedure the structure can be also completely separated into two parts (right and left).

The human and robot hip flexion–extension axes are aligned in the sagittal plane thanks to the adjustment of the horizontal and vertical positions of the rails in the cuff-frame interface. Furthermore the back orthotic shell is fixed on the rear bar and adjusted by a screw mechanism to assess a correct and ergonomic pushing support on the lumbar region of the subject (Fig. 2(a)), for a correct transmission of the assistive torque. The entire subsystem reaches a total weight of 0.8 kg.