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Review Article

Wearable lower limb robotics: A review

Slavka Viteckova *, *Patrik Kutilek*, *Marcel Jirina*

Faculty of Biomedical Engineering, Czech Technical University in Prague, Prague, Czech Republic

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ABSTRACT

Owing to the recent progress in the field of supportive robotic technologies, interest in the area of active orthoses and exoskeletons has increased rapidly. The first attempts to create such devices took place 40 years ago. Although many solutions have been found since then, many challenges still remain. Works concerning the lower extremities and active orthoses are listed and described in this paper. The research conducted and commercially available devices are presented, and their actuation, hardware, and movements they make possible are described. In addition, possible challenges and improvements are outlined.

1. Introduction

Over the past few years there have been many attempts to integrate the human body and a robot into a single system. The opportunity to develop robots that can serve humans and that can be applied in the field of biomedicine is increasingly being inspired by other disciplines, such as those in industrial fields, for example, systems in which people contribute in the form of intelligence, and then benefit from robotic system's performance, power, and precision, are called user-oriented robots.

Here, we limit the scope of our review of user-oriented robots to those that run parallel to the wearer's lower limbs, which implies robotic leg exoskeletons and active orthoses. Although the described devices are different in terms of their construction, they are made of elements and kinematic coupling engines that either reflect the structure of the human body whose structure is designed around that structure, without containing all of its degrees of freedom.

The aim of this paper is provide an overview of all the efforts that have been made to build lower extremity exoskeletons and active orthoses, which have a wide range of possible applications. These uses include helping patients to guide the trajectory of their movements or repetitive training, providing physical support to ADL (Activities of Daily Living), and facilitating labor-intensiveness by decreasing the load action on the operator. These fields of application form three main groups of powered lower-limb devices: rehabilitative, assistive, and empowering devices.

This paper is organized as follows. Assistive exoskeletons and orthoses are presented in Section 2. Rehabilitative devices for musculoskeletal therapy are discussed in Section 3. Finally, a summary and concluding remarks are given in Section 4.

2. Assistive exoskeletons

The aim of assistive robotics is the production of exoskeletons that have sufficient flexibility (both mechanical and control) for performing the wide range movements encompassed in ADL, such as walking, walking up and down stairs, sitting and

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* *Corresponding author at:* Faculty of Biomedical Engineering, Czech Technical University in Prague, Prague, Czech Republic.
E-mail address: slavka.viteckova@fbmi.cvut.cz (S. Viteckova).

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standing up. These devices are intended to be worn by the elderly and those who are physically weak.

Assistive exoskeletons can be classified into full and partial lower limb exoskeletons. The distinguishing criterion is the number of human joints that a device runs parallel to. For example, a full lower limb exoskeleton contains joints located alongside the hip, knee, and ankle joints. Partial lower limb exoskeletons mostly focus upon joints that work together with the knee or ankle joint.

2.1. *Full lower limbs*

The development of robotic orthotics began in the 1970s, when Miomir Vukobratovic of the Mihailo Pupin Institute in Belgrade constructed the active assistive lower limb exoskeleton. This hydraulic exoskeleton provided actuated flexion/extension of the hip, the knee and the ankle, as well as hip abduction/adduction. During the same time, Seireg and Grundman at the University of Wisconsin designed and implemented an exoskeleton to facilitate walking forward, sitting down, standing up, and walking up and down stairs. This exoskeleton was also hydraulic. Furthermore, it had active joints at the hips and the knees to support flexion/extension. The rest of the DoFs were either passive or controlled by springs. The desired motion was chosen by the patient by using switches on a control board. The final trajectory of a movement was preprogrammed on the basis of the trajectory of a healthy subject.

Kawamoto and Sankai et al. began developing the exoskeleton HAL (Hybrid Assistive Leg) in the mid 1990s [1]. Their first prototype had active joints with 1 DoF at the hips and the knees, as well as a passive joint at the ankles. This model was followed by other versions of HAL. The most recent commercially available is version HAL-5, which offers improvement in the upper limbs of the exoskeleton (CYBERDYNE Inc., Japan). This modification enables an operator to lift loads that are up to 40 kg heavier than it is possible without HAL. The latest version of HAL-5 is intended for wearing on only one side of the body [2]. Unlike the first prototype, which had a passive ankle joint, in the latest version of HAL, the ankle dorsi-plantar flexion is driven also. Control is achieved by means of two cooperative systems: one triggers the activity of the actuators, and the other stores the operator's walking patterns in the memory. The functioning of the control system is based on data obtained from EMG sensors, GRF sensors, potentiometers, gyroscopes, and accelerometers.

Mori et al. presented a different assistive concept with a combination of active orthosis, mobile platforms, and telescopic crutches, called ABLE [3]. The transfer principle of its shoe-sized platforms is a crawler mechanism that can transport the operator not only on flat floors, but on uneven ground and outdoors as well. The platforms' upper layers are rotational, and thus allow the operator to turn. Orthoses are actuated at the hip and knee joints. To maintain balance, which is a key task of assistive devices, the telescopic crutches are equipped with an inclinometer. Through appropriate coordination of these parts, the patient is able to walk up/down stairs as well as stand up/sit down.

Researchers at Saga University (Japan) developed a robotic exoskeleton with 8 DoFs (four per leg) [11]. Its active joints reflect the hip and knee joints, where movement is actuated in the sagittal plane. The ankle joints are passive. A neuro-fuzzy controller receives EMG signals as well as signals from force sensors.

Another robotic system for special groups, such as the old and the disabled, is WPAL (Walking Power Assist Leg). WPAL has 6 DoFs per lower limb (three at the hips, one at the knees, one at the ankles, and one at the metatarso-phalangeal joint) [10]. In WPAL, only DoFs that are frequently used are actuated. In this case, it actuates only the hip joint and the knee joint to provide flexion/extension. Coupling between the operator and WPAL is provided by force sensors located on the thigh and in the soles of the feet.

A new approach to achieve portability of assistive robotic devices was demonstrated at Sogang University (Korea). Researchers there created EXPOS (EXoskeleton for Patients and Old by Sogang), which consists of two parts: lower limb exoskeletons and an active walker [15]. The active walker has a handle and moves on wheels, thereby providing support and maintaining the patient's balance. Taking out the batteries, motors, and control unit and placing them into the walker reduce the weight of the orthosis. Power is transmitted from the motor to the exoskeletons in wires. Along with the rotation of the motor, the wires also rotate, thus causing pulleys that are placed parallel to the joint connections to rotate as well. In this way, the motor's rotation leads to the movement of the exoskeleton. Each orthosis has a 1-DoF active joint at both the hips and the knees. Fuzzy control is produced on the basis of information from potentiometers and pressure sensors that sense the contraction of the thigh muscles. To allow the patient to comfortably sit/stand up, the handle height varies according to the angle of the knees.

Later, SUBAR (Sogang University's Biomedical Assistive Robot), an advanced version of EXPOS, was developed. SUBAR has an improved actuating power and a transmission mechanism for minimizing impedance, which enable it to provide more effective assistance [9]. A control algorithm inspired by aquatic therapy was introduced and implemented in SUBAR; this algorithm was experimentally verified [16]. The proposed method of therapy is now being prepared for clinical verification.

A second-generation IHMC [12] lower extremity robotic gait orthosis is called Mina. Mina has two actuated DoFs per leg, hip flexion/extension, and knee flexion/extension, for a total of four actuators. Mina does not provide hip ab-/adduction or medial/lateral rotation of the leg, and it employs a rigid ankle joint with a compliant carbon fiber footplate [17].

Argo Medical Technologies (Israel) unveiled the assistive exoskeleton ReWalk in 2008 [4]. ReWalk actuates the knee and hip flexion/extension. Patients must use crutches to maintain their balance. Sensors located on the chest determine the angle of the torso and measure the patient's shift in gravity and upper body movements. The use of this exoskeleton is limited to patients who meet certain height and weight criteria.

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