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Towards Intelligent Lower Limb Wearable Robots: Challenges and Perspectives - State of the Art

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***Abstract*— Recent technological advances made necessary the use of the robots in various types of applications. Currently, the traditional robot-like scenarios dedicated to industrial applications with repetitive tasks, were replaced by applications which require human interaction. The main field of such applications concerns the rehabilitation and aid of elderly persons. In this study, we present a state-of-the-art of the main research advances in lower limbs actuated orthosis/wearable robots in the literature. This will include a review on researches covering full limb exoskeletons, lower limb exoskeletons and particularly the knee joint orthosis. Rehabilitation using treadmill based device and use of Functional Electrical Stimulation (FES) are also investigated. We discuss finally the challenges not yet solved such as issues related to portability, energy consumption, social constraints and high costs of theses devices.**

***Index Terms*— Wearable robots, knee orthosis, lower limb exoskeletons, rehabilitation robotics.**

I. INTRODUCTION

In the last five years, a big step forward in the development of robotic exoskeleton has been made relatively to the preceding 40 years [1], [2], [3], [4], [5]. In fact, recent studies show that advances in this field are very promoters [6]. On the other hand, robotics applications have been rapidly expanded from classical industrial ones with repetitive tasks to human interaction domain. These robots gained more sophisticated forms and more intelligence, they are called so far Wearable Robots (WR). By definition, a wearable robot is a mechatronic system that is designed around the shape and function of the human body, with segments and joints corresponding to those of the person it is externally coupled with [7]. They are worn by a person in such a way that the physical interface permits a direct transfer of mechanical power and exchange of information [8]. These robotic mechanisms have been applied in telemanipulation, man-amplifier, rehabilitation and to assist impaired human motor control. By using many type of sensors such as actuators, cameras, microphones, accelerometers, inertial sensors, etc., computers can observe through wearable robots our activities and the world from a privileged perspective analogous to the one they would have from a robotic body [9]. Wearable robots are expected to work closely, to interact and collaborate with people in an intelligent environment. Perception of the ambient environment is needed to better achieve the desired tasks. Regarding elderly people in Europe, in 2000, more than 60 million people (16.4% of the EU population) were aged 65 or over. The rise in life expectancy is set to continue; combined with falling birth rates, this will accelerate the ageing of the population. The EU population aged 60 and over is expected to rise by 37% by 2050[1]. This will certainly have a great impact on the development of the wearable robotic devices. Assisting handicapped and elderly people by reinforcing movement of the lower limbs has elicited particular attention. Development of lower limbs orthosis have progressed from complex mechanical design to miniaturized commercial products especially with the great technological advances in wearable sensors. For example, recently, miniaturized biosensors such ”intelligent” textile clothes can provide an assessment of someone health by monitoring its heart activity, measuring its body temperature, etc. The use of wearable robots should have also an effect on the energy expenditure, oxygen consumption, etc. Future trends will try to incorporate the wearable robots in an overall network architecture for continuous monitoring and health management system. On one side, we interconnect these smart devices constituting the wearable robot for monitoring and control purposes and on the other side it will be interconnected with the environment through high level network platforms accessed by other administrators/physicians [10]. In this paper we will review the state of the art of the lower limb wearable robots that might assist dependent/elderly persons to regain/reinforce their daily activities (standing-up, standing, walking, ambulation, rehabilitation, etc.). Even research in the development of lower limbs assistive technologies for handicapped persons has started in the late 1960; its acceptability by the public has been shown lately due to problems related to safety, portability, donning and doffing, etc. Lower limbs wearable robots have the advantage of supporting actively movements of the joints while passive exoskeletons are limited to the mechanical design that is often insufficient and demand considerable physical effort. On the other hand problems related to power, energy

[1] www.europarl.europa.eu/facts/4_8_8_en.htm

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consumption, chargeability, portability without affecting the natural movement, workspace and high costs are to be faced with actuated orthosis. We start with a brief summary of the main research work related to full lower limb exoskeletons including the hip, knee and ankles. Then, we focus on reviewing literature regarding the knee joint orthosis in a rehabilitation/assisting context, particular attention is given to the rehabilitation methods based on Functional Electrical Stimulation (FES) and finally we will discuss current research and future direction for research and development, limitations and challenges.

II. EXOSKELETONS

Exoskeletons could be viewed as armors covering the entire or a particular part of the body. Designed originally for military purposes, they are composed of actuated orthosis aiming to assist human body in its movement. These devices are applied to the outside of the body to assist the muscular, neural, or skeletal system. Depending on exoskeleton and on the given context, a physical therapist could assist patients during rehabilitation by moving their limbs and their joints in order to regain or improve their abilities to walk. In the following, three case studies of full exoskeletons (BLEEX, XOS and HAL-5) will be presented, a review of the development of the actuated lower limb exoskeletons will be shown subsequently.

A. Full exoskeletons

1) BLEEX: Unlike most of the exoskeletons designed for regaining or improving mobility of the disabled, the Berkley Lower Extremity Exoskeleton (BLEEX) is an exoskeleton project developed at the University of California which aims to increase the abilities of the wearer in both strength and endurance. In particular, it has been designed to allow the wearer to bear heavy loads on his back. BLEEX has projected uses with soldiers, wild land firefighters, disaster relief workers, and other emergency situations[2]. The device is composed from three parts, two actuated robotic legs, a power and computing unit, and a backpack frame. The power unit consist of a hybrid power source that supply the hydraulics of the robotic legs and an electric power that supply the exoskeleton computer [11]. Control algorithm based on measurements from the exoskeleton, has been designed by guaranteeing a minimal interaction between this latter and the wearer.

2) XOS: Sarcos Research Corporation (SRC) has developed a new exoskeleton (XOS). Its goal, like the BLEEX exoskeleton, is to increase the speed, strength and endurance with minimal effort exerted by the wearer when bearing heavy loads. The XOS robot includes 30 actuated degrees-of-freedom and is controlled using a number of multi-axis force-moment transducers that are located between the feet, hands, and torso of the operator and the machine [12], [13]. A force interaction between XOS and the wearer let this latter control smoothly the movements of the exoskeleton. At this stage, development of the device is undergoing and the goals planned by the company are as follow: walk at 5.6 km/hr with a 68 kg load, run at 8 km/hr, walk up a 25% grade carrying a 45 kg load, and use less than 6.5 kg of fuel to travel 100 km on level ground [12], [13]. Improvements concern mainly the control algorithm, performances of the servo-actuators, lightweight system of integrated skeletal structures and other comfort issues.

3) HAL-5: Unlike the abovementioned examples, the Hybrid Assistive Limb (HAL) developed by a Japanese company Cyberdyne[3] , uses electrical motors and relies on acquiring EMG signals from the wearer in order to identify its intention and to control subsequently the joint motors of the exoskeleton. To reduce its computational power during repetitive activities, the HAL-5 utilizes some stored functions such as standing up from a chair, walking, climbing up and down stairs as well as holding heavy objects. These stored functions are updated continuously to improve its autonomous actions. HAL-5 is expected to be applied in medical use such as rehabilitation and physical training support, but also for heavy labour support at factories, rescue support at disaster sites, etc. With a full body weight of approximately 23 Kg and lower body weight of approximately 15 Kg, and by using a hybrid control system, the HAL-5 is designed to act indoor and outdoor.
In the following we will be particularly interested in reviewing the actuated lower limbs exoskeletons used for mobility restoration of disabled patients.

B. Lower limb exoskeletons

Two conditions are necessary for the gait restoration that are: the stability of the joints and their control. An intuitive solution consists of using an orthosis. It is in the $1970-1980$ that the paraplegic orthosis has started to be developed. Rose describes a passive exoskeleton [14] where the patient is able to held upright due to the mechanical structure of the system. This kind of orthosis requires a considerable effort by the upper part of the body. Since, many tentatives have been carried out in order to improve the conditions of the patient such as the weight of the orthosis, the geometric and dynamic characteristics of the movement, etc. All these improvements did not prevent the abandonment of this equipment by the patients because of the enormous physical effort requested; their daily use has become very quickly tiresome. Looking back at the history of the lower limb exoskeletons evolution, Professor Miomir Vukobratovic at the Mihailo Pupin Institute in Belgrade has led an innovative work toward the development of active powered exoskeletons. He introduced in 1969 the first walking active exoskeleton, pneumatically

[2]http://bleex.me.berkeley.edu/bleex.htm

[3]http://www.cyberdyne.jp/english/

actuated and partly kinematically programmed, for producing near-anthropomorphic gait. This device has been evaluated with severely handicapped persons. Later in 1974, a new exoskeleton with electromechanical drives has been designed and tested. It was the first example known of active exoskeleton that used electric motors as actuators. This latter was considered later as the predecessor of contemporary high-performance humanoid robots [6].

Currently, there are many groups around the world who are working on actuated lower limb exoskeletons for human assisting [15], [16], [17], [18], [19], [20], [21], [22]. We will be presenting in the following some achievements in this domain:

- Researchers from Ochanomizu University, Tokyo, Japan have developed a two-degree-of-freedom active lower limb orthosis based on the use of direct current (d.c.) motors for assisting the knee and the hip joint. This device was assessed with a T12 subject and with subjects for T5, T8, T11, and T12 injury level. Motions of the wearer were analyzed using the Vicon (Camera based motion analysis system). Evaluation of the device showed that all the subjects could walk without falling, both the knee and hip joint actuator increased the gait speed and the step length. The resulting knee joint flexion improved the overall dynamic of the walking [23].
- Another group of researchers from Tokyo Denkai University, has developed an ortosis where they applied a hydraulic bilateral servo system with bi-articular muscle function to the lower limbs. This device ensures a comfortable gait training and does not affect the natural human walking patterns [24].
- Researchers from the University of Delaware, department of Mechanical Engineering, have developed an Actively driven Leg EXoskeleton (ALEX). This device is motorized at the hip and the knee joints to assist the wearer during walking. For instance, it has been tested only on healthy subjects and it has demonstrated success in training them to walk differently from their natural gait through selective control [25].
- Researchers from Salford University have developed a ten-degree-of-freedom active lower limb device. Joints, powered by pneumatic muscle actuators, are carefully chosen for better flexibility and low weight use [26].

For more details about modular active orthosis, the reader is invited to refer to a recent review of A.M. Dollar and H. Herr [27] from MIT Division of Health Sciences and Technology and the MIT Media Lab.

In the next section we will be focusing on the active knee joint orthosis for movement assisting.

TABLE I

RANGE OF TIBIOFEMORAL KNEE JOINT MOTION IN THE SAGITTAL PLANE DURING COMMON ACTIVITIES [30]

Activity	Range of motion in degrees
Walking	0° - 67°
Climbing stairs	0° - 83°
Descending stairs	0° - 90°
Sitting down	0° - 93°
Tying a shoe	0° - 106°
Lifting an object	0° - 117°

III. KNEE JOINT ORTHOSIS

The knee joint is responsible of controlling the angle between femur and tibia for its flexion/extension during human walking, standing up, sitting down, etc. This joint is commonly modeled by one degree of freedom representing knee movements in the sagittal plane. It constitutes a key factor for human stability and for ensuring a smooth and natural movement. When designing an orthotic device around this joint, a special care should be taken (coincidence between centers of mass, shank and thigh should be carefully secured to the exoskeleton). Mechanical design and integration between exoskeleton and the wearer play an important role in maximizing the movement's margins. In fact, to ensure the biomechanics of the knee are not adversely affected, it is important that lockable orthotic knee braces accurately provide the angle of splintage or immobilisation that they are meant to [29]. Range of motion of at least 117 degree of flexion is required to carry out the activities of daily living as show in table I . Restriction of knee motion can be compensated for by increasing motion in other joints. In the following, we will present some advances in the design of active knee orthosis and the control of knee joint motion:

- Yobotics, Inc. which is a small company issued from the MIT Leg Laboratory, has developed an actuated lower limb orthotic device called RoboKnee. The RoboKnee[4] is designed to assist thigh muscles (quadriceps and hamstrings) for flexion and extension of the knee joint while standing, walking, climbing, etc. [31].
- At Ecole Polytechnique Fédérale de Lausanne (EPFL), a robotized knee orthosis prototype was developed for knee flexion/extension. The stimulation of the quadriceps muscles was realized in a closed loop control as a function of the kinematic and dynamic parameters. Knee torque and angular position where feedbacked in real-time to the controller. Experiments have been conducted on healthy subject and para/tetraplegic subjects. The movement of the knee was assisted/secured by an electrical motor [32].
- C. Fleischer and G. Hommel have developed a pow-

[4]http://yobotics.com/

ered orthosis to support the thigh muscles during flexion/extension of the knee while performing common motions (standing, walking, climbing, etc.). Intended motions of the subject which are evaluated through EMG signals, guide the orthotic device. [33], [34]

- Researchers from the Northeastern University - Robotics and Mechatronics Laboratory, have developed a knee orthotic device [35]. This latter has been designed through a standard brace coupled with two Electro-Rheological Fluid (ERF) actuators. The knee torque was controlled in real time. The knee orthotic device could resist up to 25.4% of an average human knee's torque.
- In order to decrease the thigh muscle functions, some researchers from University of Michigan have developed an elastic knee brace that adds a stiff spring in parallel to the knee. The overall goal is to develop a passive compliant lower-body exoskeleton to assist in human running [36].

IV. Rehabilitation and assisting dependant persons

In this section, we will present two different techniques for rehabilitation; the first one concerns the use of special treadmill-based motorized platform and the second one concerns the use of functional electrical stimulation (FES) for movement restoration.

A. Treadmill-based device

Among the solutions adapted for the rehabilitation of the paraplegic patients suffering from a Spinal Corde Injury (SCI), we notice the use of special rehabilitation therapeutic robotic platform (Treadmill-based device). The main role of this machine is to support partially the patient weight on one side and to generate symmetrical and periodic gait patterns on the other side. The goal is to improve the patient walking abilities. It has been shown that the use of such kind of rehabilitation robotic platforms is potentially beneficial for the patient, particularly in terms of reducing the muscular activities, minimizing energy expenditure, etc. [37]. At the beginning, the training manipulation was done by the intermediary of two physiotherapists responsible of the mobilization of the lower limbs [38]. This operation requires a considerable effort and is difficult to be realized. Recently a robotized version of the therapeutic platform was commercialized (lokomat- Hocoma [39]). The movement carried out is more precise and requires only one person to supervise the operation.

B. Functional Electrical Stimulation and Control

Functional Electrical Stimulation is used to excite paralyzed muscles that are under lesions and consequently, no more controlled by paraplegic patients with upper motor neurone injuries. One of the main facing challenges when applying FES to paralyzed lower limbs is to defer the muscular fatigue as much as possible by avoiding hyperstimulation. Choosing appropriate stimulation patterns would extend the overall performance while standing up, standing, walking, etc. The control paradigms using FES has been described as open-loop and closed-loop. Although, open-loop control strategies do not account for any changes in the muscles performance such as fatigue or load changes, they are widely used in clinics due to their relative simple implementations [40]. However, open loop controllers and in order to fulfill fair tracking performances, should be based on realistic and accurate models, that are often difficult to estimate carefully [41]. On the other hand, closed-loop control strategies are rarely adopted in clinical use because of the relative high number of parameters to be identified, the lack of understanding the muscle contraction phenomena, etc. These controllers, as reported in many studies [42], [43], [44], use sensor feedback to update the stimulation levels (intensity and pulse width) as a response to any external disturbances. Some authors use a simple PID controller [45], a Knee Extension Controller KEC [46], a combination of feedback and feedforward controller or an adaptative approach, a high order sliding mode based approach [47]. Others use a first or a second order switching curve in the state space to control the patient movements: the On/Off controller [43] and the ONZOFF controller [48], in the so-called "controller-centered" strategies. The so-called "subject centered" strategies, (PDMR: Patient-Driven Motion Reinforcement [42] and CHRELMS: Control by Handle REactions of Leg Muscle Stimulation [44]), introduce the voluntary contribution of the upper body of the patient as a part of the control diagram. There are many other movements of the upper body that have been achieved using feedback control such as grasp and release control of the forearm, wrist, elbow, and shoulder [49]. As open loop stimulation system we can notice the European project SUAW (Stand Up And Walk) led by professor Rabishong [50] which aimed to restore the standing position and the deambulation of paraplegic patients by stimulating 14 under-lesion muscles. The implant is connected to the muscles by implanted wires until the electrodes and receives by RF connection, the energy and the necessary data to generate the stimuli sequences. Two patients have been implanted in 1999 and 2000. One patient is able to stand up and to ambulate in open loop.

C. Hybrid solution

Because the stability of the patient during walking could not be completely assured by the passive orthosis alone, a hybrid solution would be to use in addition to this latter the Functional Electrical Stimulation. While the orthosis is responsible of the stability and the kinematics of walk, FES ensures the compensation of gravity and the minimization of effort exerted by the upper body parts. The ambulation is thus safer and could be maintained longer. By using

FES, the walking speed could be doubled, it passes from *1 km/h* to *2 km/h*, The walking speed of a valid subject being from *4 km/h* to *5 km/h* and the traversed distance passes from *150 m - 400 m* without FES to *200 m - 1400 m* with FES [51]. Despite the significant contribution of this technique it remains unsatisfactory for the patient, the stimulation sequences are open loop applied based on the only appreciations of the therapist/doctor. On the other hand, we should notice that despite these disadvantages, this technique remains the most used in the rehabilitation centers. Popovic [52] was between the first to talk about Hybrid Assistive System which consists on the use of an actuated articular system where actuators control the hip and knee joints. The FES in open loop comes as an extra to improve the comfort of the patient and to decrease the percentage of the body mass supported by the arms. Theses performances remain, however, far from the optimal ones obtained for a valid subject.

V. Discussion

Wearable robots/actuated exoskeletons are no more from science fiction; this field is attracting more researchers and we are expecting commercial robotic exoskeleton products in a few years [53], [54]. When designing a given exoskeleton, we try to improve human abilities of disabled/elderly persons in their daily activities. Consequently, advances in exoskeleton are closely related to a better understanding of physiological phenomena. This latter could particularly help for two major challenges facing the developing of the active orthosis that are the reduction in the metabolic energy expenditure of the wearer, and the minimization of the energy requirements for actuating the exoskeleton [55]. Solving these issues will have significant impact on the advances of the active orthosis, particularly, in terms of low weight and high efficiency. A close view of the human/animal physiological phenomena that occurred during walking, climbing, standing, etc. such as muscle dynamics, central pattern generators, could play a major role in the advancement of future prototypes [55]. In fact, development of power source is the common serious problem facing all the actuated devices mentioned in this study. This factor influences both the portability and the design of the device. This problem has pushed many researchers to seek for an innovative solution based on dynamics, sophisticated feedback control scheme, etc. Although the big step forward that has been made in the development of intelligent actuated lower limb orthosis, a number of challenges still need to be solved and future studies will be addressing issues like:

- safety; as most of the experiments could not be performed without the presence of an operator person and applications are mainly indoor.
- acceptability; as many trainings have to be performed firstly before the patient feels the difference, this is mainly due to every case person and its adaptability to the device
- interaction between the wearer and the device is of great importance, a wearer feeling safe and confortable would perform better.
- social constraints/high costs

Rehabilitation therapy for neurological movement disorders using treadmill-based devices has shown satisfactory results in terms of improving/regaining mobility of the lower limbs, oxygen consumption and muscular activities. For people suffering from a serious spinal cord injuries, Functional Electrical Stimulation could give a solution for movement restoration, however stimulating muscles at maximal rate in open loop control will induce rapid muscular fatigue. Closed loop solution are still facing problems like, parameter identification, muscle modeling, etc. Synthesis of optimal stimulation patterns in open loop is of great importance taking into account physiological muscular properties and interaction with the environment.

This study gives some of the latest advances researches in the actuated lower limb wearable robots and particularly the knee joint active orthosis. A background on the evolution of the exoskeletons and their increasing need to the society has been presented. Authors have also reviewed rehabilitation using special treadmill-based platforms and movement restoration using Functional Electrical Stimulation.

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