Journal of Mechatronics, Automation and Identification Technology

Vol. 1, No.1. pp. 25 – 28

Gait rehabilitation robotics: State-of-the-art and future trends

Danijela RISTIĆ-DURRANT

Institute of Automation, University of Bremen, Otto-Hahn-Allee NW1, 28359 Bremen, Germany
ristic@iat.uni-bremen.de

***Abstract*—Rehabilitation robotics is a growing field of research dedicated to investigation of the application of robotics in motor therapy procedures for recovering motor control and motor capabilities in persons with impairment following such diseases as stroke, as well as to development of robotic and mechatronic technical aids for independent living for disabled and elderly people. In this paper, the focus is on lower-limb robotic rehabilitation. An overview of the state-of-the-art in gait rehabilitation robotics is given. In particular, the novel gait rehabilitation system developed within the EU FP7 project CORBYS is presented. The CORBYS system represents state-of-the-art system with respect to both mechanical Degrees of Freedom (DoF) enabling training of natural-like walking and robot control enabling integration of high-level robot cognitive capabilities. A gap between the state-of-the-art research platforms such as CORBYS and gait rehabilitation systems with commercialization capabilities which influences the future trends in research and development of the gait rehabilitation systems is also discussed in the paper.**

***Keywords*— Rehabilitation robotics, gait rehabilitation, mechanical Degrees of Freedom**

I. INTRODUCTION

The development of robotic devices for training of walking has been gaining intensity in recent years. This development has been driven by the expectation that robot-assisted gait rehabilitation may reduce the physical load to the therapist during the training, may increase the training intensity, may allow a quantitative assessment of the patient's performance and may improve a patient's walking ability. This increased research and development has led to new challenges in the design and control of robotic systems for walking rehabilitation. These robotic systems are no longer simply devices to support basic movements, but rather advanced robotic systems that enable, for example training of natural walking through the appropriate degrees of freedom and adaptation to the abilities and physical and psychological state of the patient.

Since the introduction of the treadmill-based orthosis Lokomat in the late 90s [1], numerous commercially available gait rehabilitation systems and research prototypes have been developed [2-9]. Two of these systems, which are mentioned in this paper, are shown in Fig. 1.

(a) (b)

Fig. 1 (a) Lokomat (picture courtesy of Hocoma Company) (b) ReWalk (picture courtesy of Argo Medical Technologies)

In the commercially available rehabilitation systems such as Lokomat [1] and AutoAmbulator [2], the patient's movement is limited to the sagittal plane. The next generation Lokomat, LokomatPro [3] has additional lateral and rotational movements of the pelvis and so enables enhanced locomotion therapy. Systems which are not commercially available as they are rather research prototypes such as LOPES [4] and ALEX [5] enable additional movements. In its first prototype, LOPES had a total of 8 actuated DoFs: 2 for horizontal pelvis translation, and 3 rotational joints per leg. In the ALEX system, the hip joint in the sagittal plane and the knee joint are actuated. Besides this, the human trunk is secured to the trunk of the orthosis which has 3 DoFs, vertical and lateral translations and rotation about the vertical axis. All above mention systems are stationary as they are lower-limb exoskeletons linked to a treadmill and a body weight support (BWS) system.

Additional DoF is provided by the robotic systems that provide patients mobility such as the Rewalk [6] and eLEGS [7]. In those systems, the robotic legs help the user's joint motions while the body balance is maintained by the forearm crutches. As they require upper limb functions to keep the body balance, these systems are not suitable for people with severe physical disabilities. Because of this, the robotic exoskeletons are rarely used for gait rehabilitation but for human strength enhancement.

However, none of the above mentioned systems, as well as of other existing robotic systems [8], have the necessary combination of all the DoFs needed for natural-like walking. As the number of mechanical degrees of freedom of rehabilitation robots directly influences the scope of movements that a patient can do when training walking, current gait rehabilitation robots limit the possible movements. The novel gait rehabilitation system developed within the EU FP7 project CORBYS [9] is the first system which combines all the necessary mechanical DoFs, with a particularly novel and specifically designed 3 DoFs hip joint, needed to enable natural-like walking. Beside the mechanical design of the CORBYS robotic system, the cognitive capabilities integrated within the CORBYS robot control architecture also support natural-like walking. Among others [10], these capabilities enable learning of gait by therapist demonstration. The learned "therapist-assisted gait" is used as the reference gait trajectory in robotic gait therapy [11]. Consequently, the therapists' way of providing corrective actions in standard gait rehabilitation, where the therapist provides manual corrective actions that change the gait pattern of the patient in a way that conforms to the general goal of the gait rehabilitation program, but within the patient's limitations and capabilities, is incorporated into the robotic system.

II. CORBYS – GAIT REHABILITATION SYSTEM

The novel robotic gait rehabilitation system CORBYS consists of an omnidirectional mobile platform, a powered robotic orthosis attached to the platform via a pelvis link, and a linear unit. During the CORBYS project life time two operating modes were made functional, the *Learning* and *Corrective* modes respectively. In both operating modes, the patient is walking on a treadmill while wearing the powered orthosis. This is illustrated in Fig. 2 where a healthy subject is walking with the CORBYS system during the initial evaluation phase. The treadmill was integrated into the CORBYS demonstrator while the mobile platform is static in order to introduce a controlled environment for the Learning mode, and to introduce a controlled environment for development and initial evaluations of the cognitive control in the Corrective operating mode.

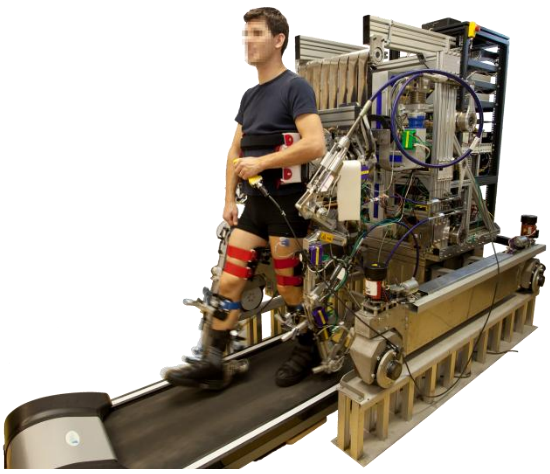

Fig. 2 Person walking on a treadmill with the CORBYS gait rehabilitation system

A. Operating modes

The Learning operating mode has two phases, the "native gait phase" and the "therapist-assisted gait phase". The powered orthosis is attached to the mobile platform which is stationary and the treadmill is setup between the platform's wings. The patient walks freely, unconstrained from the system, as the orthosis controller is implemented in the so called "zero-force mode" so that the powered orthosis follows the patient's movement without imposing any movement restrictions. Sensors placed on the orthosis measure the native gait parameters (joint angles) as well as the actuation forces. In the second phase, the "therapist assisted gait phase", the therapist provides manual corrective actions that change the gait pattern of the patient as they are walking in cooperation with the CORBYS orthosis. The therapist manipulates the patient's lower extremities whilst the patient is strapped into orthosis and walking on the treadmill, with the mobile platform stationary. Using the gathered sensor data values of the patient's joint angles while walking with the assistance of the therapist, the SOIAA module, one of the CORBYS cognitive modules [11], extracts the so-called "therapist-assisted" gait pattern. This gait pattern is the reference gait trajectory for the low-level (real-time) control system to be followed by the orthosis joints in the Corrective mode.

In *the Corrective operating mode,* the patient walks on the treadmill while wearing the orthosis. The powered orthosis is attached to the mobile platform which is stationary and the treadmill is setup between the platform's wings. In this mode the patient walks constrained by the robotic system as the orthosis controller is implemented in "impedance mode" which enables the changing (correction) of the actuation (assistance) level.

B. CORBYS Control architecture

The CORBYS control architecture is a generic robot control architecture that allows the integration of high-level cognitive modules to support human-robot co-working. The details of the architecture can be found in [10]. Here, only a brief overview of the architecture with its specifics regarding control of the gait rehabilitation system is given.

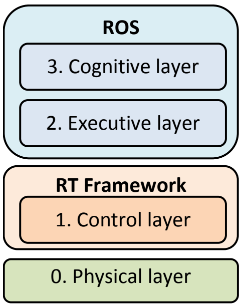

Fig. 3 Layout of the CORBYS control architecture

As illustrated in Fig. 3, the CORBYS control architecture is divided into layers. Strictly speaking, the robotic system itself does not belong to the control architecture as it is rather a control plant and can be considered as layer 0, the physical layer. The physical layer contains actuators and sensors of the system. The 1st, "real-time (RT)" control layer is in direct connection with the physical layer where it reads sensor data and provides direct commands to the actuators. The 2nd, layer is an executive layer which is responsible for enabling the communication between the control and the cognitive layers, as well as for coordinating and supervising the overall system functionality. The 3rd, highest, layer is the cognitive layer that contains the high-level cognitive modules that enable the robot to understand the current state of the system and the patient in order to generate adequate high-level commands. One of the cognitive modules is SOIAA, a module which generates the reference gait trajectory through the learning from the therapist demonstration. The other one is SAWBB, situation awareness module, which enables adaptation of robotic support according to patient's performance and patient's state.

C. *CORBYS powered orthosis*

The CORBYS powered orthosis assists the patient's lower limb joint motions. The configuration of the DOFs of the CORBYS orthosis was implemented to follow natural human limb kinematics. There are 6 DoFs at each leg: 3 DOFs in the hip, 1 DoF in the knee, and 2 DoFs in the ankle joints. The hip and knee joint motions on the sagittal plane (flexion and extension), as well as ankle joint motions in the sagittal plane (plantarflexion and dorsiflexion), are selected as the active DOFs based on the biomechanics properties of human walking, while the hip DoFs in the frontal and the transverse plane (adduction/abduction and internal/external rotation) as well as the ankle DoF in the frontal plane (eversion and inversion) are passive. The orthosis of the CORBYS system is attached to a mobile platform via a 4 DoFs pelvis interface mechanism (consisting of the pelvis link and the linear unit), which enables pelvis rotation in the frontal and transverse planes as well as the pelvis vertical and side to side movement. Together with the 4 DoFs of the pelvis interface mechanism, the CORBYS orthosis provides a total of 16 DoFs for the body movement, which makes it the first orthotic device with such a number of DoFs. Additionally, the orthosis was designed in order to satisfy the requirement of adaptability to the patient's height and weight, as well as the requirement of the range of motion of the biomechanical joints.

The particular novelty of the CORBYS orthosis is that the hip joint provides all 3 DoFs of the human hip joint where only the rotation in sagittal plane is actuated which, however, does not influence the rotations in the transverse and frontal planes. This is achieved via a common center of rotation of three hinge-joints which is aligned with the biomechanical hip joint of the human as described in [11]

The movements of the orthosis joints in the sagittal plane are controlled by a push-pull control (PPC) cable actuation system [12][14]. There are three actuators (PRL+ modules, SCHUNK) per orthosis leg that actuate the hip, knee and ankle joints in the sagittal plane. The actuators are placed on the mobile platform while the PPC cables are flexible links to the joints used to transfer the rotational movement of the motors to specifically designed orthotic joints. This has the advantage of keeping the powered orthosis weight low while the necessary torques are applied through the PPC cables to the patient's joints.

D. *Preliminary testing of the CORBYS system*

In [13], the results of preliminary testing of the fully integrated cognitively controlled CORBYS rehabilitation system are presented. The powered orthosis was tested in a single healthy person and several gait cycles were compared with free treadmill walking. Authors demonstrated that the CORBYS robotic gait rehabilitation system does not hinder the natural movement of the person as it enables similar movement at lower speed as free treadmill walking that is used in conventional rehabilitation programs. The results of the initial evaluation of the robotic system obtained in tests with a selected patient are given in [11]. The patient that was tested in the test presented in [11] was cooperative and positive towards using the system. Walking in the Learning mode felt quite natural, while walking in Corrective mode presented a substantial challenge to the patient. One issue was related to the inability of the patient to get adequately synchronized with the reference trajectories rendered by the CORBYS cognitive module SOIAA as was the case in tests performed with the healthy subject [13]. One possible explanation is that the presented testing sessions with the patients were in the initial phase, it is likely that with more experience from future sessions the performance will result in a better tracking compliance. Further testing of the CORBYS system will certainly lead to more insights on effectiveness of the robot-assisted gait rehabilitation as well as it will provide feedback for the optimization of the system.

III. Future Trends

Beside the studies [11] and [13], several other studies have examined whether robotic devices can exceed conventional gait training in terms of long term rehabilitation outcomes. Most of the research reported on promising results and pointed out the advantages of rehabilitation robots over strenuous manual physiotherapy [15]. However, despite of achieved results there is still not enough evidence on effectiveness of gait rehabilitation robots which makes those robots still far from the commercial robotic systems. Beside this, a cause of the gap between the state-of-the-art research platforms such as CORBYS and gait rehabilitation systems with commercialization capabilities is that current solutions are still bulky, heavy and expensive. Because of this future trends are in developing novel concepts such as the concept of exosuits. These soft, robotic devices are primarily made of textiles and can be worn like clothes. They assist the user during specific motions by transmitting forces around the human joints making use of the bone structure. Exosuits are expected to be more suitable for many daily life situations and long term use than their rigid counterparts. However, exosuits are mostly designed to augment walking of healthy individuals and as such they can not be used for large range of rehabilitation needs. Because of this, future trends in rehabilitation robotics concern also optimization of rigid exoskeletons in sense of using lightweight materials and rather crucial degrees of freedom to enable natural-like walking. In that sense, possible future use of CORBYS system is its use as benchmarking system for evaluation of other gait rehabilitation robotic systems with less degrees of freedom.

Acknowledgment

This research was supported by the European Commission as part of the CORBYS (Cognitive Control Framework for Robotic Systems) project under contract FP7 ICT-270219. The views expressed in this paper are those of the author, and not necessarily those of the consortium).

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