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Review

Robot assisted treadmill training: Mechanisms and training strategies

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ABSTRACT

The rehabilitation engineering community is working towards the development of robotic devices that can assist during gait training of patients suffering from neurologic injuries such as stroke and spinal cord injuries (SCI). The field of robot assisted treadmill training has rapidly evolved during the last decade. The robotic devices can provide repetitive, systematic and prolonged gait training sessions. This paper presents a review of the treadmill based robotic gait training devices. An overview of design configurations and actuation methods used for these devices is provided. Training strategies designed to actively involve the patient in robot assisted treadmill training are studied. These training strategies assist the patient according to the level of disability and type of neurologic injury. Although the efficacy of these training strategies is not clinically proven, adaptive strategies may result in substantial improvements. We end our review with a discussion covering major advancements made at device design and training strategies level and potential challenges to the field.

Contents

1. Introduction

Neurologic injuries such as stroke and SCI cause damage to neural systems and motor function, which results in lower limb impairment and gait disorders. Patients with gait disorders require specific training to regain functional mobility. Traditionally, manual physical therapy is used for gait training of neurologically impaired patients. Body weight supported (BWS) manually assisted treadmill training is in practice for more than 20 years [1,2]. BWS treadmill training has proven significant improvements in step length, endurance and walking speed of neurologically impaired patients [3–10]. BWS treadmill training requires a team of three or more physical therapists to guide patient's legs on predefined paths and to stabilize patient's pelvis.

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Table 1
Overview of treadmill based active gait training orthoses.

Device	Actuation	Actuated degrees of freedom	Training strategy	Citations
LOKOMAT	DC motor drive	2	Impedance based assistance, adaptive assistance	[46,55]
Autoambulator	DC motor drive	2	–	[22]
LOPES	Series elastic actuation (SEA)	4	Impedance based assistance	[26,74]
ALEX	Servo drive	2	Force field based impedance controller	[23,39,53]
ARTHUR	Servo drive	2	Impedance based adaptation	[27,42]
PAM and POGO	Pneumatic cylinders	7	Admittance based assistance	[28,29]

The quality of manually assisted BWS treadmill training is dependent on therapist's experience and judgment which varies widely amongst therapists. Also the training sessions are short due to physical therapist's fatigue and do not have any proper method of recording patient's progress and recovery. Automated rehabilitation solutions are researched lately to overcome above mentioned shortcomings of manual physical therapy [11]. Robot assisted gait training has several advantages over manual physical therapy. It relieves the physical therapist from the strenuous task of manual assistance and facilitates in delivering well controlled repetitive and prolonged training sessions. The physical therapist's role is limited to supervision. The subjectivity of manually assisted training is eliminated by providing measurement of interaction forces and limb movements to assess the quantitative level of motor function recovery. In US each year 0.78 million stroke survivors and 200 000 SCI patients may benefit from these robotic devices [12].

The history of robot assisted training started with the adaptation of industrial robotic manipulators to the field of rehabilitation [13–15]. Following that trend various devices are designed for restoration of upper limb and gait functions. The industrial robotic manipulators are mainly designed for tasks such as pick and place and are inherently stiff and massive. Robotic training devices on the other hand need compliant and safe human–machine interface. Subsequently, robots for applying suitable forces and capable of providing a safe interaction with the patient are developed [11]. Most of these robots are wearable and work in proximity with the patient's limbs. *Active orthosis* is a more common term for these wearable robotic devices. From the studies of gait biomechanics and manual physical therapy practice, different training strategies are incorporated in the robot control schemes to enhance motor function recovery.

The field of robot assisted treadmill training has evolved significantly during the last decade. Rehabilitation engineering community is now evaluating different training strategies in combination with new actuation concepts for standardization of robot assisted treadmill training process (Table 1). Our focus in this paper is the active orthoses for treadmill training of neurologically impaired patients. Mechanism design and actuation methods of these active orthoses are discussed. Gait training strategies deployed by the active orthoses for treadmill training are investigated with an overall emphasis on strategies which encourage patient's active participation in the training process. Active orthoses using functional electrical stimulation [16] and those designed for a single joint like Ankle robot [17] are not a part of this review. The paper is organized as below.

Section 2 deals with the design configuration and actuation mechanisms of the prevailing active orthoses. Gait training strategies are discussed in Section 3. Finally a discussion is provided in Section 4.

2. Active orthoses for treadmill training

Active orthoses are training devices that work in parallel with the human body and have mechanical actuation to apply forces to the human limbs. The history of active orthoses started in late 1970s. Early active orthoses were standard braces with added actuation mechanisms [18]. Amongst the first full lower limb active orthosis is the University of Wisconsin prototype [19]. The orthosis has universal joints at hip and ankle and provides sagittal plane flexion/extension motions by means of hydraulic cylinders. The remaining degrees of freedom (DOF) are passively held by springs.

2.1. Commercial active orthoses

The first modern automated BWS treadmill training system LOKOMAT was developed in late 90s and is commercially available. The system has a wearable driven gait orthosis (DGO) having mechanical actuation to power hip and knee sagittal plane rotations [11]. DC motors with a ball screw mechanism are used to power these joints. Dorsiflexion to the ankle joint is provided by passive elastic bands and the hip abduction/adduction is kept free. DGO works on the assumption that the orthosis joints are in perfect alignment with patient's joints and the joint positions are measured with encoders built into DC motors. The physical contact between DGO and patient is through two force-torque sensors placed in series with DC motors that move orthosis links. DGO is connected to the treadmill by a rotatable parallelogram linkage in order to stabilize patient's trunk. In this manner the DGO moves only in vertical direction, avoiding any sideways tilt of trunk. BWS up to 40% of total body weight can be selected. Later on an automated and adaptable BWS system is designed by the developers of LOKOMAT which compensates the weight of patient according to his weight bearing capabilities during the training process [20]. Also a control method for automated treadmill speed adaptation is designed which can adjust treadmill speed according to the patient disability level and intention in real time [21]. Hence if patient feels comfortable with the current treadmill speed then he can switch to a higher treadmill speed automatically which may in turn improve gait parameters like stance duration, stride length and speed. The automated treadmill speed adaptation feature is not available with commercial LOKOMAT.

Autoambulator is a similar treadmill training device developed by Health South for patients with gait disorders, coordination, balance and postural problems [22]. This device also has DC motor drives at hip and knee joints for sagittal plane rotations. Detailed description of working of Autoambulator is not available.

2.2. Research prototype active orthoses

2.2.1. Active leg exoskeleton

Recently a robotic orthosis, active leg exoskeleton (ALEX) is developed at the University of Delaware for gait training of stroke survivors [23]. ALEX uses gravity balancing orthosis (GBO) [24] as its foundation. GBO is a passive device without any mechanical actuation and utilizes the conventional method of geometrically locating the center of mass by using a parallelogram mechanism. Zero free-length springs are then placed at appropriate positions to balance the effect of gravity [25]. Linear servo drives are used on the GBO for providing actuation at hip and knee joints for flexion/extension rotations in sagittal plane. Hip abduction/adduction and four trunk rotations are held passive by means of springs. ALEX