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REVIEW ARTICLE

SINGLE JOINT ROBOTIC ORTHOSES FOR GAIT REHABILITATION: AN EDUCATIONAL TECHNICAL REVIEW

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Robot-assisted physical gait therapy is gaining recognition among the rehabilitation engineering community. Several robotic orthoses for the treatment of gait impairments have been developed during the last 2 decades, many of which are designed to provide physical therapy to a single joint of the lower limb; these are reviewed here. The mechanism design and actuation concepts for these single joint robotic orthoses are discussed. The control algorithms developed for these robotic orthoses, which include trajectory tracking control and assist-as-needed control, are described. Finally, the mechanism design and control of single joint robotic orthoses are discussed. There is a strong need to develop assist-as-needed control algorithms and to perform clinical evaluation of these robotic orthoses in order to establish their therapeutic efficacy.

Key words: gait rehabilitation; robots; orthosis; stroke; control strategies; mechanism design.

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INTRODUCTION

Stroke and spinal cord injury (SCI) are the leading causes of lower limb disability and gait impairment (1). Patients with these neurological impairments may need to use a wheelchair and be unable to perform activities of daily living (ADL), leading to an increased burden on healthcare and social welfare systems. Thus, there is a need to rehabilitate these patients to be able to perform ADL (2–4).

The concept of body weight-supported (BWS) physical gait therapy has conventionally been used for the rehabilitation of neurologically impaired patients (5–7). In the process of BWS gait therapy, the weight of the patient is supported or compensated for and the lower limbs are moved in a repetitive manner by a team of physical therapists in order to restore the patient's gait functions. BWS physical gait therapy has shown promising results and is a widely used method (8–10). However, it has certain limitations, such as therapist fatigue, reduced number of physical therapy sessions, the non-repetitive nature of training sessions performed by different therapists, and a lack of any objective method to record and analyse the patient's progress and recovery (11).

These limitations have encouraged the rehabilitation community to devise automated methods of providing BWS physical gait therapy (12–15). Several robotic devices have been developed during the last 2 decades that can provide objective, customized, repetitive and prolonged gait training sessions compared with manual physical gait therapy (16–29). These robotic devices are powered by mechanical actuators, which can support and provide motion to the limbs of neurologically impaired subjects. Most of these robotic devices are wearable exoskeletons, commonly known as "robotic orthoses", which work in close proximity with the patient's joints.

Most of the above-mentioned robotic gait training orthoses, such as Lokomat® (Hocoma, Switzerland), are multi-joint devices, which can provide rehabilitation simultaneously to the ankle, knee and hip joints. Hussain et al. have reviewed the design and control of multi-joint robotic gait training orthoses (11, 30). There is an increasing trend of designing robotic orthoses that are intended for single joint rehabilitation, for example the Anklebot (Massachusetts Institute of Technology (MIT), Cambridge, MA, USA). These robotic orthoses have their own significance, e.g. the Anklebot is used for rehabilitation of hemiparetic patients with ankle joint injuries or drop foot. These single joint robotic orthoses have not been reviewed previously (11, 30).

A detailed review of mechanism design and control strategies developed for these single joint robotic orthoses is presented here. There are 2 categories of control strategy: trajectory tracking control and assist-as-needed (AAN) control. The following devices are not included in this review: platform-based robotic devices, e.g. Rutgers Ankle (31), which require the patient to be in a seated position (32, 33); robotic devices utilizing functional electrical stimulation (FES) (34, 35); and passive orthoses with no mechanical power or actuation (36). The preliminary design and evaluation of robotic orthoses published in the form of conference proceedings is also not included in this review.

SINGLE JOINT ROBOTIC ORTHOSES MECHANISMS

MIT's Anklebot

MIT's Anklebot was developed to assist with gait therapy for drop foot, which occurs as a result of stroke (37). The Anklebot is a 3-degree-of-freedom (DOF) robotic orthosis that provides complete range of motion to the foot in all 3 anatomical DOF relative to the shank. Two of these DOF (ankle plantar/dorsiflexion and inversion/eversion) are powered by mechanical actuators, whereas the third, internal/external motion of the ankle joint, is held passive (i.e. no mechanical power is provided). The Anklebot is powered by 2 brushless DC motors mounted in parallel. If both motors push or pull in the same direction a plantar/dorsiflexion motion is produced and if they push or pull in opposite directions an inversion/eversion motion is produced. The Anklebot is designed with low friction and inertia, so that it can provide maximum backdrivability. "Backdrivability" is an important aspect of the design of robotic rehabilitation orthoses and is defined as the extent of freedom provided by the robotic orthosis to the patients to be able to drive the robot voluntarily themselves. Knee and foot braces are used to secure the Anklebot to the patient's limbs (37).

University of Michigan's ankle-foot orthosis

A simple, lightweight ankle-foot orthosis (AFO) has been developed at the University of Michigan, Ann Arbor, MI, USA, to provide plantar flexion to the ankle joint during treadmill or over-ground training of neurologically impaired subjects (38–40). The AFO is made of lightweight carbon polymeric composites and has a single DOF hinge joint (i.e. revolute joint) to provide ankle plantar flexion motion. The AFO is powered by a lightweight and inherently backdrivable actuator, known as pneumatic muscle actuator (PMA). The PMA has behaviour similar to skeletal muscles and can provide only unidirectional force. The PMA uses compressed air to generate forces. It is attached to the rear of the AFO in order to provide plantar flexion to the ankle joint.

MIT's ankle-foot orthosis

An AFO for stroke patients has also been developed at MIT in order to control the movement of ankle plantar/dorsiflexion in the rehabilitation of drop foot (41). The active AFO consists of a standard polypropylene AFO with a metallic hinge joint to provide ankle plantar/dorsiflexion and is rigid for inversion/eversion movements. A series elastic actuator (SEA) is added to the AFO to control ankle plantar/dorsiflexion movements. The SEA consists of a brushless direct current (DC) motor in series with a spring (42). The SEA provides force control by controlling the compression of series spring. The AFO prevents foot slap during the stance phase of the gait cycle and foot drag during the swing phase.

Arizona State University's ankle joint orthoses

A robotic gait trainer (RGT) has been developed at Arizona State University, Tempe, AZ, USA for rehabilitation of the ankle joint in stroke patients (43). The RGT provides ankle plantar/dorsiflexion and inversion/eversion movements. PMA and springs, also termed a spring over muscle actuator, are used to actuate the RGT. The concept of a spring over muscle actuator reduces the number of actuators required to produce the same DOF compared with use of PMAs alone (43).

A powered ankle orthosis has also been developed at Arizona State University to provide ankle plantar/dorsiflexion movements (44). The powered ankle orthosis uses an actuation concept based on a robotic tendon. A robotic tendon is a spring-based linear actuator. A lightweight, low-energy motor is used in series with a spring to control the spring stiffness.

Bio-inspired ankle-foot orthosis

A bio-inspired AFO has been reported for treatment of gait pathologies (45). The AFO provides power for the ankle plantar/dorsiflexion and inversion/eversion motions. The bio-inspired AFO has been designed after studying the muscle anatomy of the lower limb and has no rigid frame structure, unlike the above-mentioned devices. This implies that there is no constraint on natural joint motions. It has a foot section and has ankle and knee braces to secure the orthosis to the human limb. Actuation of the bio-inspired AFO is effected by PMAs, tendons and ligaments. Four PMA are placed on the lower leg, with the artificial tendons anchored at the knee brace and the foot brace.

Miscellaneous ankle orthoses

A portable powered AFO has also been proposed for providing assistance to plantar/dorsiflexion movements (46). The portable orthosis utilizes a bidirectional pneumatic rotary actuator for providing plantar and dorsi-flexion movements. A portable pneumatic cylinder filled with compressed carbon dioxide is used to power the AFO (46).

A robotic ankle exoskeleton for assisting plantar flexion motion has also been designed at Ghent University, Gent, Belgium (30). The robotic exoskeleton is used to study the metabolic cost of human walking and has a similar mechanism design and the same actuation as the University of Michigan's AFO.

Northeastern university's knee orthosis

A robotic orthosis for knee joint rehabilitation has been developed at the Department of Mechanical Engineering of Northeastern University, Boston, MA, USA (47). The knee orthosis has been powered by a new type of actuator, known as an electro-rheological fluid (ERF)-based actuator (47). ERF experience changes in the viscosity and yield stress in the presence of an electric field. The mechanism design of knee orthosis consists of a standard brace with a hinge and gear. Two ERF-based actuators are coupled to this mechanism. The motivation behind using ERF has been to design a smaller, simpler and more economical robotic orthosis (47).

KNEXO

A robotic orthosis (KNEXO) for knee joint rehabilitation has been designed at Vrije University Brussel, Brussels, Belgium

(44, 48). A new type of PMA, called a pleated PMA (PPMA), is used in an opposing pair configuration to provide actuation to the knee joint. The PPMA is an improved version of the PMA and results in a reduction in energy loss and can develop higher forces and contraction compared with a conventional PMA.

Adaptive knee joint exoskeleton

An adaptive knee joint exoskeleton, based on anatomical knee geometry, has been proposed (49). Five different design configurations of exoskeleton are considered to analyse the effects of internal joint forces/torques in the knee joint due to the human-machine interaction. These design configurations include: pin and fixed end, pin and slider, cam and slider, pin and pinned slider, and cam and pinned slider. An adaptive knee joint exoskeleton, comprising a pin slider/cam mechanism is designed based on knowledge of knee joint kinematics, which helps in eliminating the negative effects associated with the closed leg-exoskeleton kinematic chain on a human knee (49).

Quasi-passive knee exoskeleton

A quasi-passive knee exoskeleton for human locomotion augmentation has been proposed recently (50). The quasi-passive exoskeleton comprises a stiffness control module on the thigh segment and a pulley on the shank segment. The shank segment is connected to the thigh segment by a steel tendon. The stiffness control module consists of a friction-based latching mechanism that has been designed to provide 2 levels of stiffness for knee flexion. The latching mechanism comprises a friction lever, shaft, bearing block, DC motor, worm-gear, cam, spring-loaded push-button and retreat push-button. This latching mechanism is used to engage/disengage an assistance spring.

Powered hip exoskeleton

The developers of the Active Leg Exoskeleton (18) (ALEX II) have modified it to interface and provide assistance at the hip joint only (51). The knee and ankle joints of ALEX II are removed to study the muscle activation patterns. The unilateral powered hip exoskeleton comprises a single link interfaced with the user's left leg. A back support with several passive DOF is attached to the user to provide physiological movement to the pelvis and gravity compensation for the device (18, 51). The powered hip exoskeleton provides power for hip flexion/extension motion by utilizing geared DC motors. The hip abduction/adduction motion is held passive.

Robotic hip exoskeleton

A robotic hip exoskeleton has been designed at the University of Michigan (52) in order to enhance the understanding of biomechanics of human gait as well as providing rehabilitation to neurologically impaired subjects. The robotic exoskeleton can provide hip flexion/extension motions and is powered by pneumatic cylinders.

CONTROL OF SINGLE JOINT ROBOTIC ORTHOSES

The control of the above-mentioned single joint robotic orthoses is important. Different control algorithms can be developed to provide customized gait rehabilitation according to the disability level and stage of rehabilitation of neurologically impaired subjects (11, 53–55). Control of robotic gait training orthoses is a rapidly evolving research field and different control algorithms have been designed and evaluated for the above-mentioned robotic orthoses. Control of such orthoses can be divided into 2 general categories: trajectory tracking or path control and AAN control.

Trajectory tracking control

Robotic gait training orthoses have traditionally been controlled by simple position control algorithms, commonly known as trajectory tracking or path control. The legs of the neurologically impaired patients are guided on pre-recorded physiological gait trajectories during the trajectory tracking control. The trajectory tracking control is useful for the initial phases of rehabilitation when the patients are in bed or using a wheelchair and cannot contribute any effort towards the gait training process.

A trajectory tracking control scheme based on proportional derivative (PD) control law has been developed for the initial prototypes of MIT's Anklebot (37). The trajectory tracking control scheme has been evaluated with 10 neurologically intact subjects in a seated position. A trajectory tracking control scheme has also been implemented for the RGT (43). A simple proportional controller has been used to guide the ankle joint on the desired physiological trajectories.

A trajectory tracking controller has also been developed and implemented for the bio-inspired AFO (45). A model of the human-robotic system has been developed and, based on that model, a path control scheme has been developed (45), which been evaluated for seated positions and has provided the intended results (45). Trajectory tracking control has been developed and implemented for KNEXO. The trajectory tracking control works on the basis of a proportional-integral (PI) control law (44, 48).

Assist-as-needed control

A limitation of robot-assisted physical therapy with trajectory tracking control is that it guides the patient's limbs on pre-recorded trajectories. Thus, there is a need to estimate the physical capabilities of individual patients and provide gait training according to their disability level and stage of rehabilitation.

AAN control schemes have been proposed for single joint robotic orthoses, which estimate the physical capabilities of the patients and modulate the robotic assistance accordingly. The terms *adaptive, impedance and interactive* control schemes have also been used for this purpose.

An AAN control scheme has been designed for the powered hip exoskeleton (51). The AAN controller has 3 stages during which it estimates the current phase of gait cycle online, estimates the required assistive torque and transfers the assistive torque to the human subject's limb (51). The AAN controller was evaluated with 10 healthy subjects walking on the treadmill with the powered hip exoskeleton.

An adaptive control scheme has been developed for MIT's Anklebot. An adaptive internal model (IM) feedback control has been utilized (56). This IM controller monitors the position of the foot continuously throughout the gait cycle and applies the forces necessary for adequate forward motion. Furthermore, the research group is developing an adaptive predictor to determine the appropriate levels of correction during rehabilitation therapy (56).

An adaptive control scheme has also been developed for MIT's AFO in order to assist drop foot gait (41). A finite-state machine with 3 states was designed in order to address each complication of drop foot gait. The adaptive control has been performed by modulating the impedance of the AFO for the different phases of the gait cycle. For the controlled plantar flexion, a torsional spring control is applied in order to adjust the stiffness of the AFO joint so that forefoot collisions with the ground are minimized. Joint impedance is minimized for the late stance phase so that the powered plantar flexion movements are not impeded. During the swing phase, a torsional spring-damper control provides toe clearance. A control scheme based on finite-state machine has also been designed for the quasi-passive knee exoskeleton in order to engage the assistance spring (50). The controller identifies the states of the gait cycle using in-sole sensors that indicate the heel and toe contacts with the ground (50).

A control scheme based on biological principles has been developed for the control of the University of Michigan's AFO (40). Electromyographic (EMG) activity of the medial gastrocnemius muscle has been used to proportionally control the plantar flexor PMA attached to the AFO (40). The pneumatic cylinders of the robotic hip exoskeleton are controlled via foot switches (52). A force sensor is used in series with the pneumatic cylinders to regulate the forces applied by the robotic exoskeleton to the hip joint (52).

DISCUSSION

Robot-assisted gait rehabilitation is an emerging therapeutic practice. Several robotic orthoses have been proposed during the last 2 decades for gait training of neurologically impaired patients. These robotic orthoses can be divided into full lower limb or multi-joint robotic orthoses (11) and single joint robotic orthoses (37). Single joint robotic orthoses have increasingly been developed to address gait problems, such as drop foot. A review of the mechanism design and control strategies utilized by these single joint robotic orthoses is presented in this paper.

Robotic orthoses designed for the ankle joint primarily serve the function of assisting drop foot gait. The ankle has a complex anatomical joint structure with 3 major DOFs. Only MIT's Anklebot is designed to provide motion in all 3 DOFs, but only 2 DOF are powered by DC motors (37). The remaining ankle robotic orthoses are either 2 DOF or single DOF devices. This presents a limitation in the design of ankle robotic orthoses, as the patients may feel discomfort and the rehabilitation may not yield significant improvements. Due to this limitation of ankle joint robotic orthoses, physical therapists provide manual training sessions for the DOF that are not provided by the robotic orthoses.

Extensive work on the mechanism design of knee joint robotic orthoses has also been reported. Similarly, the kinematics of the knee joint have been studied in detail and incorporated while designing the new generation of knee joint orthoses (49). A hip joint exoskeleton has also been used recently to study gait kinematics and muscle activation patterns. The robotic hip exoskeleton (52) is powered by compliant (i.e. low stiffness or backdrivable) pneumatic cylinders, but it can provide only limited assistance in the sagittal plane. The hip joint of ALEX II provides 2 DOFs for gait training of neurologically impaired patients. Internal/external rotation of the hip joint has not been included in the mechanism design, which is a design limitation. The compliant actuation concepts have not been utilized significantly for the hip joint orthoses, as ALEX II is powered by electromagnetic actuators.

Although compliant actuation of rehabilitation robots is a challenging engineering task (11, 57), significant work has been performed in this area. Compliant actuation concepts have been developed in the form of intrinsically compliant PMA, PPMA (44, 48) and ERF (47) for robotic ankle and knee orthoses. The compliant actuation of robotic rehabilitation orthoses is important in order to provide safe human-robot interaction. The compliant actuators, such as PMA and PPMA, have been used for the University of Michigan AFO, bio-inspired AFO and KNEXO for providing passive compliance. The compliance of these robotic orthoses has not been controlled actively (i.e. use of computer programs) in order to achieve variable compliance. Advance control schemes, such as impedance control, can be utilized to control the compliance of these robotic orthoses actively so that AAN gait training can be provided to neurologically impaired subjects. Such control schemes have already been proposed for the multi-joint robotic gait training orthoses powered by PMA (19, 20) and can be adapted to the single joint orthoses.

Various control schemes have also been utilized for these single joint robotic orthoses. Most of the control schemes have been designed to guide the patient's limbs on pre-recorded trajectories. This presents a limitation of single joint robotic orthoses. An AAN control scheme has been proposed for MIT's Anklebot, but no experimental results have yet been reported (56). An AAN control scheme has also been developed for MIT's AFO and powered hip exoskeleton. An AAN control scheme based on EMG activity has also been proposed for the University of Michigan's AFO.

The use of EMG activity as a feedback signal in order to control the AFO presents some limitations. The EMG signal has noise and cross-muscle talk, which may provide an unreliable control signal. The signal from bi-articular muscles, such as the medial gastrocnemius, also has reliability issues. Also, the placement of EMG electrodes for different training sessions presents a problem, as it is difficult to locate them at the same position for every different session.

The evaluations of mechanisms and control strategies of the single joint robotic orthoses with human subjects present a limitation. Few experimental evaluations of these robotic orthoses have been performed compared with multi-joint robotic orthoses. The trajectory tracking control schemes of MIT's Anklebot (37) and KNEXO (44, 48) has only been evaluated with 10 healthy subjects. Similarly, the AAN control scheme of Powered Hip Exoskeleton (51), Quasi-passive Knee Exoskeleton (50) and University of Michigan's AFO (40) has also been evaluated with 5, 3 and 10 healthy subjects, respectively. The trajectory tracking control of RGT (43) and bio-inspired AFO (45) has been evaluated with only one able-bodied subject.

The Northwestern University Knee Orthosis (47) and Adaptive Knee Joint Exoskeleton (49) have not been evaluated with human subjects and only initial prototype experiments have been performed. Similarly, the proposed adaptive control scheme of MIT's Anklebot has not been evaluated with human subjects (56). Relatively significant clinical trials with neurologically impaired patients have been performed for MIT's AFO. The adaptive control scheme has been evaluated with 2 patients with drop foot and yielded satisfactory results (41). The portable powered AFO has been evaluated with one neurologically impaired patient (46). The robotic hip exoskeleton has been evaluated with 8 neurologically intact subjects to study muscle moments (52).

In conclusion, significant work has been performed regarding the design and control of single joint robotic gait rehabilitation orthoses. Various mechanism and compliant actuation concepts have been proposed for these orthoses; however, their bio-mechanical design needs to be improved so that they can provide effective and safe gait training. The alignment of these robotic orthoses, especially, hip and ankle joint orthoses with anatomical joints, present a major design challenge because the hip and ankle are complex anatomical joints. An attempt has been made to design a knee robotic orthoses based on the anatomical joint features, but no such attempt has been reported for ankle and hip joints (49). Various mechanisms have been proposed for upper limb orthoses that can provide better alignment with anatomical joints (58, 59). These mechanisms can be modified and adapted to the lower limb robotic orthoses in order to provide better joint alignment.

The majority of control schemes designed for single joint robotic orthoses work on the basis of trajectory tracking control. There is a strong need to design AAN control schemes for these orthoses in order to provide customized gait training. Trajectory tracking and AAN control schemes have not been evaluated extensively with human subjects. These control schemes must be clinically evaluated with neurologically impaired patients in order to determine their therapeutic efficacy.

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