An active knee orthosis for the physical therapy of neurological disorders

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Abstract. This paper presents the design of a new robotic orthotic solution aimed at improving the rehabilitation of a number of neurological disorders (Multiple Sclerosis, Post-Polio and Stroke). These neurological disorders are the most expensive for the European Health Systems, and the personalization of the therapy will contribute to a 47% cost reduction. Most orthotic devices have been evaluated as an aid to in-hospital training and rehabilitation in patients with motor disorders of various origins. The advancement of technology opens the possibility of new active orthoses able to improve function in the usual environment of the patient, providing added benefits to state-of-the-art devices in life quality. The active knee orthosis aims to serve as a basis to justify the prescription and adaptation of robotic orthoses in patients with impaired gait resulting from neurological processes.

Keywords: Rehabilitation robots, Exoskeletons, Knee orthoses, gait rehabilitation, neuro-rehabilitation

1 Introduction

Multiple Sclerosis (MS) is the most common neurological disease among young adults, it is usually diagnosed between 18 and 35 years. MS is a chronic, degenerative central nervous system disease. The symptoms of MS are very diverse and vary from person to person depending on the areas affected: fatigue, visual disturbances, balance problems, walking difficulty and coordination, etc. It is not possible to predict the disease course. It is more common among women and young adults. The disease leads to consequences that limit quality of life, so it has a great social impact. It is the second leading cause of disability in young people, behind traffic accidents [1].

Stroke is the leading cause of permanent disability in Europe and USA [2]. Neurological impairment after stroke frequently leads to hemiparesis or partial paralysis of one side of the body that affects the patient's ability to perform activities of daily living (ADL) such as walking and eating. One-third of surviving patients from stroke do not regain independent walking ability and those ambulatory, walk in a typical asymmetric manner. Neurological impairment after stroke can lead to reduced or no muscle activity around the ankle and knee causing the inability to lift the foot (drop foot).

Poliomyelitis (or simply polio) is an infectious disease transmitted by a virus (poliovirus). After World War II, the first polio vaccine was able to control the disease. Polio mainly affects children under three years. About 95% of cases are completely asymptomatic, but 0.5-1% are paralytic. The key of disability in patients with chronic sequelae of poliomyelitis is the emerging muscular weakness resulting from the combination of the initial effects in acute attack of polio and subsequent neuronal damage. This muscle deterioration often affects the ability for ambulation of patients with sequelae of poliomyelitis (PPS) and they need technical aids and orthotics for ADL.

Rehabilitation addresses these neurological diseases from a multidisciplinary approach. The goal of rehabilitation therapy is to achieve the highest level of physical, mental, emotional and social independence. If the rehabilitation treatment begins in the early stages of the disease, it can improve the general condition of the patient, quality of life, and prevent complications. The goal of rehabilitation exercises is to perform specific movements that provoke motor plasticity to the patient and therefore improve motor recovery and minimize functional deficits. Movement rehabilitation is limb dependent, thus the affected limb has to be exercised [3].

Traditional rehabilitation therapies are very labor intensive especially for gait rehabilitation, often requiring more than three therapists together to assist manually the legs and torso of the patient to perform training. This fact imposes an enormous economic burden to any country's health care system thus limiting its clinical acceptance. All these factors stimulate innovation in the domain of rehabilitation in such a way it becomes more affordable and available for more patients and for a longer period of time. The variability of symptoms, unpredictability of the illness course, and degenerative character of these three neurological disorders described above make it difficult to find a solution that can assist in the physical therapy by providing walking assistance. The requirement is for a general-purpose robotic orthosis, reconfigurable based on the illness progression, and provided with advanced perception-action capabilities that self-adapt to the disease variable symptoms. This is the main objective of our approach in the development of a robotic orthosis that provides gait assistance and rehabilitation to this group of patients. This paper presents the MB-ActiveKnee, its design and preliminary functinality tests.

2 The Enabling Technology

2.1 Current State of the Technology

Although research on joint-specific orthoses is in progress, at present two types of braces are widely used in the clinical domain for gait rehabilitation of neurological disorders (see Fig.1):

– AFO (Ankle Foot Orthosis), which controls the foot and ankle, and indirectly the knee.
– KAFO (Knee Ankle Foot Orthosis) for the control of foot, knee and ankle.

The control of the knee joint is critical in the rehabilitation of neurological diseases. Conventional KAFOs use some type of knee joint close (sealing ring, Swiss close), which may or may not lock the knee in extension while walking, and unlock for sitting. The locking of the knee during walking is indicated for: Instability of the knee in the sagittal plane, quadriceps weakness, weakness of hip extensors, inability to balance the trunk over the extremities.

These conventional passive orthoses, although less complex and cheaper, cannot supply energy to the affected limbs, hence are limited compared to active devices. Proprioception and skills are required to maintain a stable walk, controlling the body position with the center of mass always ahead of the knee.

To approach the active orthosis field, robotics is an emerging field which is expected to grow as a solution to automate rehabilitation and training. Robotic orthoses can (i) replace the physical training effort of a therapist, allowing more intensive repetitive motions and delivering therapy at a reasonable cost, (ii) assess quantitatively the level of motor recovery by measuring force and movement patterns, (iii) potentially assist in daily life activities providing power to walk up slopes or stairs. Many robotic systems have been developed to enforce or restore ankle and knee motion specifically. These systems can be grouped into stationary or active orthoses.

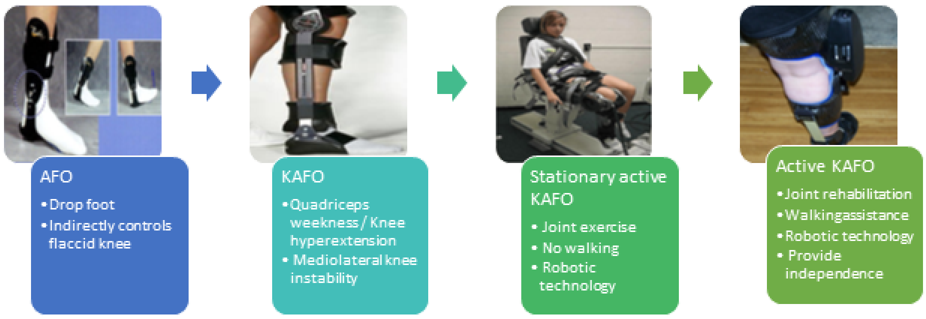

Fig. 1. State of the art orthoses

Stationary System: Stationary systems are those robotic mechanism designed to exercise the human ankle and knee motions without walking. The patient is positioned always in the same place, and only the target limb is exercised. Devices like the Rutgers Ankle[4], the High Performance Ankle Rehabilitation Robot[5] by the IIT, based on a Stewart Platform. A more recent system, the Active Knee

Rehabilitation Orthotic Devices (AKROD)[6], provides variable damping at the knee joint, controlled in ways that can facilitate motor recovery in post stroke and other neurological disease patients.

Active Orthoses: On the contrary to stationary systems, active foot orthoses are actuated exoskeletons that the user wears while walking overground or in a treadmill. They are intended to control position and motion of the ankle, compensate for weakness, or correct deformities. They are an evolution of traditional passive lower limb orthoses, with additional capabilities to promote appropriate gait dynamics for rehabilitation. They have the potential of providing tools to facilitate functional recovery, reducing cost of treatment and providing patients with adequate level of independence.

- Active Foot Orthoses: Currently, the only commercialized system for rehabilitation of the ankle joint is the Anklebot (Interactive Motion Technologies, Inc.), developed at the Massachusetts Institute of Technology (MIT) to rehabilitate the ankle after stroke[7]. It allows normal range of motion in all 3 DOF of the foot relative to the shank while walking overground or on a treadmill. Pilot controlled trials with such device showed a general improvement in the walking distance covered and time. The MIT also developed an Active Ankle-Foot Orthosis (AAFO) where the impedance of the orthotic joint is modulated throughout the walking cycle to treat drop-foot gait[8].
- Active Knee Orthoses are mostly dissipative by combining an electro-rheological fluid-based variable damper with a modified commercial knee brace[6]. This device is intended to provide resistive torques to the user for rehabilitation purposes.
- Active Knee-Ankle-Foot-Orthosis (AKAFO): Commercial devices like C-Brace by Ottobock are a combination of AFO and KO, having a dissipative variable damper at the knee. Quasi-passive devices are being tested in clinical setting for stroke, MS, PPS, and other neurological affections[9]. Active KAFOs having a powered knee joint are mainly at a research stage powered by artificial pneumatic muscles [10] or by electrical motors [11].

For many patients, a programmable actuated orthosis could guide and facilitate the recovery of a more efficient and clinically desirable gait pattern via retraining sessions. Current clinical practice is generally restricted to brief periods of less than 1 hour of gait training provided a few times per week. In between these sessions, patients continue to walk using their typical gait pattern, and likely reinforce compensatory gait patterns. A wearable training orthosis could be used by patients to guide them through a targeted gait pattern while undertaking daily activities. This strategy of reinforced therapy in a real-world environment has the potential to provide more effective gait retraining, improving one's ability to ambulate.

Finally, clinical studies conducted still show little evidence for a superior effectiveness of the robotic therapy, although a clear benefit is shown in reduced therapist effort, time, and costs [12]. It has been shown that robotic rehabilitation can be as effective as manually assisted training for recovery of locomotor capacity, but a higher benefit should be desirable to spread its use in clinics worldwide.

This paper presents the design and preliminary tests of an orthotic device configured as an active KAFO(see Fig. 2). Joint actuation is based on the ARES technology [13] developed at the Centre for Automation and Robotics and currently being commercialized by Marsi Bionics. The ARES technology provides power and controllable compliance to each joint.

Fig. 2. Active knee orthosis using ARES technology

3 Biomechanics analysis of the human knee motion

Let us distinguish six phases of the knee motion along the gait cycle for regular walking on level ground. Figure 3 shows the knee angle vs. torque and power consumed at the knee during regular walking on level ground, and distinguishes these six phases:

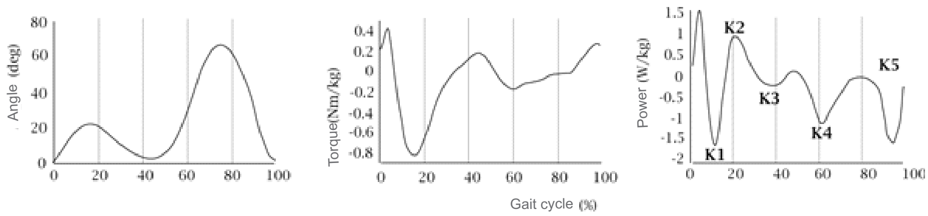

Fig. 3. Joint angle trajectory, torque and power consumption at the knee when walking on level ground

Phase 1 Load response at stance (0% to 15% of the gait cycle): Immediately after heel strike the supporting leg slightly flexes. This slight bending allows accommodating the body weight on the supporting foot. Drawing the knee angle versus torque (see Figure 4) it can be observed that in this phase the knee acts as a spring which elastic constant is the slope of the curve mentioned.

Phase 2 Knee extension at stance (15% to 42% of the gait cycle): After a maximum knee flexion of near 20 degrees at stance, the knee is then extended, reaching the maximum extension at 42% of the walking cycle, although the knee is not completely stretched (not reaching 0 degrees).

Phase 3 Fast knee bending (42% to 62% of the gait cycle): At toe off, between the end of leg stance and the beginning of leg swing, a fast knee flexion occurs preparing for leg swing. Here again the leg acts as a spring but featuring a lower stiffness than in the load response phase.

Phase 4 Knee flexion at swing (from 62% to 73% of the gait cycle): While the hip transfers the foot forwards, the knee remains flexed (near 60 degrees) to avoid tripping over the floor. At this phase the knee does negative work against gravity by braking to avoid the fall of the calf.

Phase 5 Knee extension at swing (from 73% to 95% of the walking cycle): The knee extends to prepare for support again.

Phase 6 Knee flexion for heel strike (95% to 100% of the walking cycle): Just before leg stance begins again, the knee flexes minimally to minimize the foot speed relative to the ground, this substantially reduces the impact with the ground, and thus improves stability and energy consumption is reduced.

Based on these biomechanics characteristics of the human knee, the MB-ActiveKnee, an active knee brace has been designed. Particularly relevant, the human knee load response properties will be mimicked by a spring with the adequate stiffness, while an actuator provides the necessary energy demanded in those knee phases of high consumption.

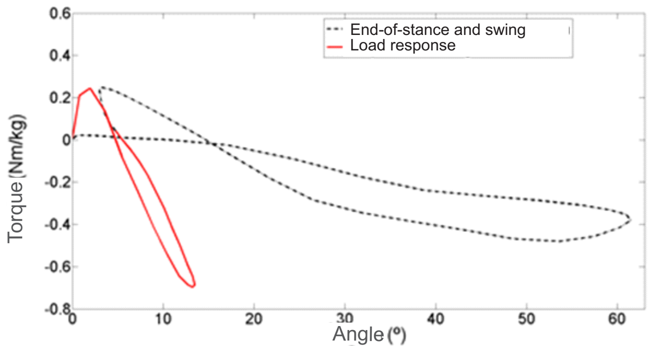

Fig. 4. Torque versus knee angle. An almost linear behavior is observed in the load response phase

4 Design of the MB-Active Knee

The MB-ActiveKnee is a joint work between the Centre for Automation and Robotics and Marsi Bionics. It has been conceived to provide active knee control in the leg stance providing the necessary rigidity, and active power during swing. Therefore this active brace compensates for the lack of knee mobility or quadriceps weakness, present in MS, Stroke and PPS.

Figure 5 presents the CAD design of the MB-ActiveKnee. It is an AKAFO (Active Knee Ankle Foot Orthosis), where the ankle joint responds passively. The brace extends down to the foot to provide better grip and stability on the subject. The shank link is adjustable in extension from 20 cm to 70 cm.

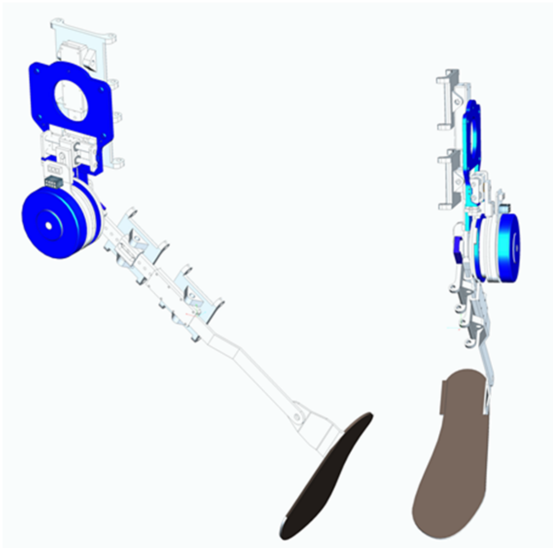

Fig. 5. CAD detail design of the Active Knee

The knee actuator is based on the ARES [14] patented technology. It can be conceptually divided into two parts, a rigid actuation set and a transmission based on elastic elements. A gear motor combination is used to provides speed and torque ratings above 2.5 rad/s and 30 Nm respectively, sufficient for the requirements of this application.

As shown in Figure 6, the passive elastic elements in series to the transmission allows for a safe user-robot interaction, intrinsically absorbing undesired perturbations. Furthermore, this design allows also to absorb jerky movements usual in some patients. A position sensor measures the spring deflection, thus providing a measure of the torque being applied by the following relationship:

$$\tau = \frac{2 \Delta x K_{eq} L_{arm}}{\cos(\theta)} \tag{1}$$

Where Δx is the measured deflection of the elastic elements, K_{eq} is the equivalent elastic constant of the springs and L_{arm} is the radial distance to the joint axis.

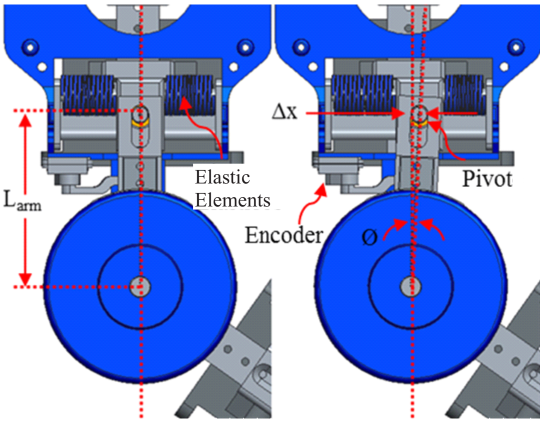

Fig. 6. ARES spring deflection at torque transmission

5 Hardware

Power to weight and power to volume ratios have been optimized during the selection of hardware components. Lithium-ion batteries provide more than three hours of continuous operation.The orthosis includes a magnetic position sensor for measuring the joint angle. As mentioned, the joint torque is computed from the measured spring deflection, by which good parallel force-position control can be performed.

Foot plantar pressure sensors are used for real-time detection of the gait phase. An insole with two pressure sensors, one at the heel and one in the toe is integrated in the orthosis. Figure 7 shows how the sensors are very effective in differentiating the stance and swing phases. It can be observed how the beginning of the stance is detected by the heel sensor (in red line) while the end of the stance is detected by the toe sensor (in green line).

6 Control approach

The control approach has been designed to exploit the advantages of the mechanical design to mimic the biomechanics of the human knee. The innovative mechanical design and underlying technology confer great versatility to the MB-ActiveKnee brace, facilitating adaptation to the symptomatology of the patient. To offer such versatility the following control schemes have been implemented:

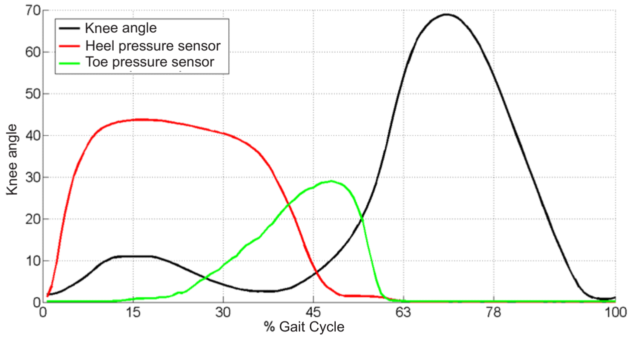

Fig. 7. Relationship between knee angle and plantar pressure

Zero force control: Based on a purely force control scheme, the knee brace "gets out of the away" when the user initiates the motion. This allows the user and the therapist to manipulate the brace effortlessly or to programm rehabilitation exercises through demonstration of the therapeutical movements. The brace is made transparent to the user, who does not perceive resistance to his/her own motion.

Position control: The knee is able to repeat a number of joint trajectory patterns that the user or the therapist programmed.

The combination of these control schemes yields the following operation modes:

Gait training by learn and repeat: The patient having the brace adequately adjusted, the therapist performs a series of movements which the MB-ActiveKnee learns and then repeats cyclically.

Gait assistance: MB-ActiveKnee assist in gait performance to patients having weak quadriceps. MB-ActiveKnee detects gait phase and provides the additional power required to complete the phase.

As discussed in Section 3, where the biomechanics behavior of the knee is studied, in the load response phase the human knee behaves like a spring. The elastic elements of the MB-ActiveKnee knee show a elastic constant similar to that obtained in the human knee load response phase (see Figure 4). During operation the MB-ActiveKnee reaches a 40% reduction of energy consumption and provides a more natural movement of the knee[14] by taking advantage of this intrinsic impedance during the load response, while power is only supplied during swing to flex and extend the knee.

7 Results

Figure 8 shows in black line the motor trajectory, in blue line the resulting knee joint trajectory provided by the MB-ActiveKnee brace, while it is compared to

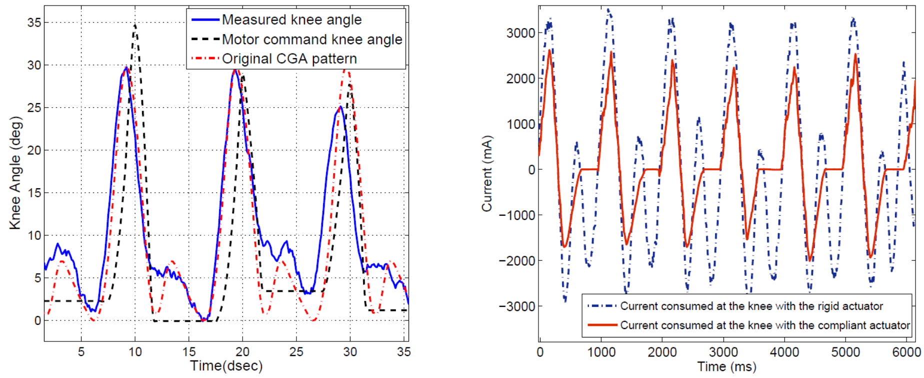

Fig. 8. Knee joint trajectory along three gait cycles using ARES elastic actuation vs. CGA pattern. Notice that the power during stance is provided by the elastic elements while the actuator is not commanded

the Clinical Gait Analysis (CGA) pattern for the human knee. During the load response the motor is not commanded, not providing power to the brace, which is simply powered by the elastic elements, able to provide sufficient adaptation to body weight during stance. Therefore a reduction in energy consumption is resulting in longer battery life.

Functional tests were performed in healthy subjects. Gait speed and maximum knee flexion/extension angles are configurable for each patient via a user interface. During the tests the MB-ActiveKnee adapts naturally to the user detecting gait phases and providing the required power. A video of this performance is shown in `https://www.youtube.com/watch?v=oDd7dI3lZc0`.

8 Conclusions and future work

This paper describes the design and functionality of the MB-ActiveKnee brace developed by Marsi Bionics SL (www.marsibionics.com) in collaboration with the Center for Automation and Robotics (CSIC-UPM). It is an AKAFO for use in the therapy of multiple sclerosis, stroke, post-polio syndrome or spinal cord injury.

MB-ActiveKnee results in a light device (1 Kg), allowing portability with a range of more than three hours in continuous operation. It incorporates the ARES technology, a geared motor assembly which allows to provide the necessary power in swing phases but also provides energy-efficient weight bearing during stance based on the inherent elastic behaviour of the ARES joint. As a result the user interaction is safe throughout time as these springs absorb shocks.

The functionality of this AKAFO brace has been tested in a healthy user with significant results. Work is in progress to test the device on a number of voluntary patients suffering from quadriceps weakness, in different types of ground profiles, uphill, downhill and flat, also up and down stairs. The clinical evaluation will provide understanding of the potential, limitations and challenges of the robotic technology applied to the orthotics field.

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