Wearable Exoskeletons for the Physical Treatment of Children with Quadriparesis

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Abstract—Quadriparesis, caused by a number of congenital and acquired neuropathologies, affects children with the symptoms of weakness and motor impairment in all four limbs. The physical treatment of this disease could be hypothetically improved by the use of wearable exoskeletons which would contribute to avoiding the side effects of the permanent sitting position: scoliosis, osteoporosis, spasticity, respiratory disorders, blood circulation problems, among others. Overall, the use of a wearable exoskeleton would contribute substantially to the improvement of these children’s quality of life. This paper presents the first pediatric wearable exoskeleton for the physical treatment of this disease. The paper shows the main components of the device and the laboratory proof of concept in two voluntary subjects.

I. INTRODUCTION

Quadriparesis, also known as tetraparesis, is weakness of all four limbs, both arms and both legs. Main possible causes are: traumatic (cervical spinal cord injury), genetic (neuromuscular diseases like muscular dystrophy), congenital (cerebral palsy), allergic, auto-immune disorders (encephalitis) \cite{1}. In all cases, the signals sent along the spine are interrupted in any form, at least partially, meaning that the nerves below the area of the interruption do not have full functionality. In quadriplegia, the connection between the patient’s central nervous system and the muscle receptors is interrupted, and they experience a lack of motor and sensory input. Patients with quadriparesis can experience varying levels of function in their limbs, depending on the specifics of the illness. In some patients, the limbs may be weak and the patient may lack motor control (i.e. spinal muscular atrophy type II). Other patients may have substantial areas of paralysis, while others may have relatively good motor skills.

Treatments are multicentric, and depending on the diagnosis can include drugs (i.e. neuroprotectors, muscle strength stimulants), nutrition, along with physical therapy to keep the muscles from atrophying and to prevent contractures. Surgery can be indicated in some cases to reduce complications. Patients may also benefit from the use of a mobility-assist device, like a cane, wheelchair, or scooter. Different complications usually emerge during the course of the disease, most of them caused primarily by the lack of walking ability, including joint deformities, scoliosis, respiratory disorders, hip dislocation, osteoporosis and fractures \cite{2}.

Walking can contribute to the prevention of contractures, delaying osteoporosis and scoliosis \cite{3}, facilitating transfers, and overall greater patient satisfaction. Unfortunately at present there is no available procedure to facilitate walking to these patients, since they have a significant deficit of major force in the upper limbs and trunk, so the use of conventional orthoses produce them an excessive fatigue. Therefore it is a current need to have a device that allows these patients to walk effortlessly and so to delay related complications.

For this reason, medical experts consider it is very important to investigate a method that maintains the walking exercise of children with quadriparesis, in order to improve motor level, reduce or delay complications and increase their quality of life, achieving a reduction of disability and increased functional independence.

An hypothesis that should be clinically confirmed is that maintaining walking in these children would have an impact on their rehabilitation and on their quality of life. This paper describes the work conducted under the ATLAS project to develop a robotic gait training orthosis indicated for children with quadriparesis. The device has been configured as a rehabilitation tool. This paper presents the main research results of this project, making emphasis on the joint actuation.
ation system, which provides adaptable joint stiffness and yields an economic gait control, showing a reduction in power consumption when compared with conventional joint actuation. A proof of concept has been performed on two voluntary subjects affected by tetraplegia and Duchenne muscular dystrophy.

II. THE ENABLING TECHNOLOGY: WEARABLE EXOSKELETONS FOR GAIT TRAINING AND ASSISTANCE

A. State of the Technology

Recent advances in assistive and rehabilitation robotics research have led to new wearable active orthoses that allow paralyzed people ambulate. These orthotic devices for human lower limbs are defined as active mechanical devices worn by a patient that operate in parallel with the human legs (see Fig. 1). Joint motion is generated making use of actuators that are controlled by an on-board computer that follows programmed joint trajectories. However the current state of the art in wearable lower-limb active orthoses constrains their application to below-cervical spinal cord injury (paraplegia), adults, and up to now children with quadriparesis cannot be assisted by such devices.

There are currently four commercially available wearable lower-limb orthotic devices designed for adult paraplegics [4], [5], [6], [7] and some ongoing research initiatives on the subject [8], [9], [10], but they have the following common shortcomings for their use in quadriparetic children:

1) They generate motion by actively controlling only two joints per leg: hip flexion-extension and knee flexion-extension. This underactuation results in a non-physiological gait which is not indicated for quadriparetic neuromuscular rehabilitation.
2) Because of featuring a limited number of controlled degrees of freedom, the device cannot provide balance so the user needs to make use of crutches or walkers to maintain balance during standing and walking. The use of such devices requires physical strength in arms and hands, as the crutches must support the extra weight of the robotic device (ranging from 20 to 36 kg) during some phases of the gait. Quadriparetic children present acute weakness in arms and hands so they are unable to make use of these stabilizing aids.
3) Also, thoracic control and weight-bearing capacity are required for the use of the exoskeleton. Quadriparetic children do not have these capabilities.
4) These devices are not adaptable to children, as the minimum accepted height of the user is 1.54 m.

B. The ATLAS Exoskeleton

There is currently one wearable lower-limb exoskeleton that has been designed for children. The ATLAS pediatric exoskeleton [11], shown in Fig. 1, is a research result of the ATLAS project [12] carried out at the Centre for Automation and Robotics (CSIC), and which technology has been licensed to Marsi Bionics [13], an SME specialized on robotics for healthcare.

ATLAS is an active trunk-hip-knee-ankle-foot orthosis (THKAFO) especially designed for children, having the following features:

1) It reproduces human-walking patterns in the sagittal plane,
2) It provides over-ground walking,
3) It is adjustable in size for children from 95 cm up to 140 cm height,
4) It provides postural balance, making use of a supporting frame directly attached to the exoskeleton. Therefore there is no need for using the upper limbs and trunk to control balance during walking,
5) It provides gait training to children with no motion capability,
6) In the cases of partial limb paralysis or weakness, the exoskeleton detects the child’s intention of motion and provides the required movement.

Figure 1 shows a user wearing the exoskeleton attached to the supporting frame. ATLAS is able to support a 40-kg child and help her/him out with walking at a moderate speed (< 0.8 m/s). In the case of quadriplegia it is assumed that the user cannot move her/his extremities, and she/he cannot control the trunk to keep balance. The ATLAS exoskeleton is a lightweight, easy to handle and to don and doff robotic system composed of the following main components, sketched in Figure 2.

- Mechanical structure: As a lower limb orthosis, it is simple, lightweight compared to similar commercial devices (9 kg), strong and durable. It is a 6 DOF
mechanism, having 3 DOF per leg: hip, knee and ankle flexion and extension in the sagittal plane. The structure is attached to the user body through comfortable belts.

- Actuation system: The motion of the joints is driven by electrical motors at hip, knee and ankle, and adjustable-stiffness actuators (ARES) [14] at the knee joint. These actuators allow a compliant, safe and comfortable motion to the user, added to a reduced energy requirement for locomotion. The ARES actuator is a patented device [15], owned by CSIC and licensed to Marsi Bionics company.

- Sensorial system: A variety of sensors are used to acquire the state of the user and robotic system. Angular position at the hip, knee and ankle; Limb and body inertia based on IMUs, and Centre of Pressure (CoP) trajectory during the stance phase based on an in-shoe plantar pressure measurement system.

- Gait controller: The controller runs on a real-time platform onboard. An impedance controller [11] is programmed to follow natural joint trajectories while reacting compliantly to small perturbations in the sagittal plane. The controller, related electronics, sensor amplifiers and batteries are located along the mechanical structure, not supported by the user, but by the device.

The ATLAS exoskeleton is a device that will be used to demonstrate the benefits of exoskeletons for the physical treatment of quadriplegia in a forthcoming clinical evaluation, demonstrating following hypothesis:

1) It is adequate for the use of children.
2) It does provide self-balance (controlled by the device in the sagittal plane, and by a supporting frame in the lateral plane).
3) It does not require patient’s thoracic motion for the use of the device.

Prior to entering the clinical trial, a proof of concept of the device and its components is required, to show usability and overall safety.

III. ATLAS ADJUSTABLE-COMPLIANCE JOINTS

An Actuator with Adjustable-Rigidity and Embedded Sensor (ARES) has been conceived as an adaptive joint to cover the requirements of the ATLAS exoskeleton [14]. Because the ATLAS orthosis is intended to be worn by children, rotary actuators were chosen instead of linear actuators to consider the wide range of sizes of potential users. Linear actuators impose limits on the link length adjustment. Based on this configuration for being compact and powerful, ARES incorporates variable compliance and provides an accurate torque measurement. The stiffness adjustment is based on the pivot displacement principle in which joint positioning and stiffness adjustment are decoupled in an energy efficient fashion [16]. The torque provided by the gear-motor is transmitted to an elastic device that moves the joint compliantly. This compliance is modified by a second motor which modifies the distance between the position of the elastic element and the joint axis, thus modifying the torsional stiffness of the joint. The longer the distance to the joint axis, the larger the joint rigidity. A linear encoder measures the spring compression, thus providing a measure of the torque applied by the relationship:

\[ \tau = \frac{2\Delta x K_{eq} L}{\cos(\phi)} \]  

where, \( \Delta x \) corresponds to the deflection of the elastic element sensed by the encoder, \( K_{eq} \) is the equivalent rigidity of the elastic element, \( \phi \) is the deflection angle between the actuator and the joint, and \( L \) is the arm length of the elastic element position. Figure 3 shows the main components in the design of ARES, and Fig. 4 shows a photograph of the developed prototype.
Thus, ARES allows the modification of joint stiffness while providing information about the torque applied, allowing compliant force control. The reduced weight and size are an advantage when compared with other compliant joints that employ different elements in parallel to present similar characteristics. The distribution of the components along the structure, that reduce the actuator dimension in the lateral direction, in combination with the way the coupling between the stiff set and the compliant mechanism is achieved, are some of the differences with other novel actuators based on the same working principle and is one of the keys that allows ARES to embed the force sensor in its structure without extra bulky elements. Table I presents the main specifications of the variable impedance actuator with embedded sensor (ARES).

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<thead>
<tr>
<th>TABLE I</th>
<th>GENERAL SPECIFICATIONS OF ARES</th>
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<tr>
<td>Peak Torque</td>
<td>Up to 76 Nm</td>
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<tr>
<td>Max Deflection</td>
<td>8</td>
</tr>
<tr>
<td>Stiffness Adjusting Time</td>
<td>0.6 sec</td>
</tr>
<tr>
<td>Weight</td>
<td>900 g</td>
</tr>
<tr>
<td>Length</td>
<td>235 mm</td>
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<tr>
<td>Width</td>
<td>50 mm</td>
</tr>
<tr>
<td>Power</td>
<td>90 W</td>
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IV. ENERGY-EFFICIENT GAIT CONTROL

The variable-compliance property conferred by ARES to the joints of the ATLAS exoskeleton is also key to the design of an energy-efficient gait control scheme. Taking advantage of the inherent compliance of the joint, the gait control system is able to:

1) Store and release energy in the elastic elements of ARES.
2) Exploit passive dynamics during the leg swing phase.
3) Reduce energy costs at heel strike by exploiting the intrinsic impedance adjustment.

The ATLAS gait controller takes advantage of these properties to achieve a reduction in energy consumption with two parallel strategies:

1) Impedance control of a gait pattern based on a commanded stiffness.
2) State machine selecting the required stiffness at each gait phase (to command the above impedance controller).

The motion control of active orthoses has traditionally been based on stiff tracking of joint trajectories obtained from clinical gait analysis (CGA), typically resulting in high power consumption. Instead of following accurately the CGA pattern, the ATLAS gait controller exploits the inherent compliance of the ARES joint to follow compliantly the reference joint pattern, allowing the joint to adapt to the different gait phases and to the varying ground stiffness while walking.

Figure 6 compares a typical command of knee trajectory based on CGA data and the command used in ATLAS.
exoskeleton. The ATLAS reference trajectory does not command joint motion during the first 50% of the gait cycle (stance phase), thus motor is off during half of the gait cycle, being the compliance of the ARES the one that provides the resultant knee behavior, which as it is shown in Fig. 6, resembles the one observed in humans during walking.

During locomotion, a state machine switches between stiffness values for the knee joint. This state machine is based on a previously published study on the biomechanics of locomotion [17]. Four discrete knee stiffness states are defined, as shown in Fig. 7:

State 1. Immediately after toe-off, at the beginning of swing phase, a large stiffness is needed to let the motor lift up the shank.

State 2. During swing, zero stiffness and the potential energy stored when the motor changes its direction allows exploiting the inherent dynamics of the limb for swinging it forward.

State 3. At the end of swing, the stiffness is increased to prepare for the collision at heel strike but kept low enough to allow the actuator springs to absorb the impact energy, enabling an adequate load response to begin the stance phase.

State 4. During stance the joint motor is kept blocked and a high stiffness is enforced to support the user weight but still providing some compliance.

It is important to remark that due to the characteristics of the variable compliance joint design, the force required to change the stiffness of the joint increases with torque. Therefore, to reduce the energy consumed by the motor which changes the stiffness, every modification in stiffness is performed when a reduced torque is being done.

V. PROOF OF CONCEPT

The ATLAS device has been successfully tested on two voluntary subjects: a 9 year old quadriplegic (spinal cord injury C4-C7) child and a 12-year old child with Duchenne muscular dystrophy (the most frequent neuromuscular disease in childhood). Both subjects had sufficient cephalic control but no enough thoracic control so the exoskeleton was supporting the patient torso during walking. Both patients were unable to use their arms and hands to control postural balance making use of crutches, so the attached frame was used for this purpose. It took 5 minutes to don the exoskeleton with the aid of skilled personnel. Both children were able to stand up and walk with the use of the exoskeleton. During the trials the children were able to perform a 10-meter walk in 1.5 minutes without experiencing fatigue. Figure 8 shows snapshots of one complete gait cycle during real trials.

The performance of the gait controller has been assessed during these tests. Figure 9(a) presents the commanded position to the actuator and the real joint position achieved due to the compliance, controlled with the state machine. A comparison with a CGA knee trajectory is shown. Notice that the knee follows the natural pattern due to the impedance implemented that allows the knee to adapt to the ground during the support phase. The controlled knee stiffness reproduces the natural knee behavior, without commanding a stiff CGA-based pattern.

The energy consumption at the knee during the trials is shown in Figure 9(b) and compared with the consumption when following a CGA pattern with a rigid actuator. During the support phase, no energy is required to block the knee due to the large stiffness, the high reduction ratio in the motor-gear set and the position command proposed.

Notice also the smaller current peaks when using the compliant actuator, which are most likely due to the presence of elastic elements such that when a change of direction in the rotation occurs, the compressed springs contribute to movement reducing the energy required from that of traditional stiff actuators.

Implementing an energy-economic gait and exploiting the compliant actuators characteristics at the knee joint achieve a 39% reduction of energy expenditure compared with traditional stiff actuation.

For a single user and constant walking speed, a good optimization of the joint compliance can be made. Nevertheless, the cadence and the characteristics of the terrain can vary along the locomotion cycle; this is one of the reasons why variable stiffness actuators are needed. Achieving a dynamic variation of the stiffness along the phases of the gait, should result in even bigger energy savings, and the implementation of these adjustments together should be the aim of future work.

At the end of the proof of concept the two patients were asked about how they experienced during the test. None of them experienced pain, nor skin irritation. However, the evaluation of the effect of the exoskeleton on these children should be evaluated in a clinical trial where physiological parameters such as heart rate, respiratory rate and saturation of oxygen will be measured before and after a 10 minutes walk with the aid of the exoskeleton.

VI. CONCLUSIONS

Exoskeletons and gait training robotic systems can contribute to the physical treatment of quadriplegia in children. Providing gait assistance to these children could help delay or even avoid the onset of side effects of the prolonged wheelchair-bound state. However, there is a lack of devices for pediatric use. The ATLAS project is the first approach to the problem, having designed an exoskeleton for the use of paralyzed children. This paper presents the main research results of this project, making emphasis on the joint actuation.
system, which provides adaptable joint stiffness and yields an economic gait control, showing a reduction in power consumption of 39% when compared with conventional joint actuation. A laboratory proof of concept of the device has been performed, on two subjects: One 9 year old girl affected by quadriplegia (spinal cord C4-C7) and a 12 year old boy affected by muscular dystrophy. Both subjects had no motor capacity and the ATLAS exoskeleton successfully tested usability on these subjects allowing them to walk effortlessly along a 10 meter distance. Making use of the ATLAS active orthosis the child is able to ambulate in a controlled and safe fashion over ground. However this device still provides motion only in the sagittal plane, which currently is sufficient for gait training. Nevertheless, the development of a 3D-mobility exoskeleton is in progress under the KINDER project. The results of the laboratory proof of concept have to be demonstrated in a clinical evaluation.

REFERENCES