2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

WAKE-up: a Wearable Ankle Knee Exoskeleton

Stefano Rossi, Fabrizio Patanè, Fausto Del Sette and Paolo Cappa

Abstract— **In this paper we present the alpha-prototype of the WAKE-up, a wearable robotic device for the rehabilitation of locomotion of pediatric subjects with neurological diseases such as Cerebral Palsy. The WAKE-up is an active knee-ankle orthosis. It is composed of two robotic modules for the rehabilitation of knee and ankle, respectively. Each module can be utilized either alone or together with the other one. The working principle is based on series elastic actuators (SEA), i.e., dc motors equipped with a torsional spring mounted in series to avoid the direct connection of the actuator with the patient's limb. A SEA permits the control of the force and the emulation of different orthoses with given value of stiffness. The torque transmission is achieved by a timing belt and it is mediated by a torsional spring. The experimental tests conducted on each modules confirmed a good precision of the spring deflection control (position error < 2°) and good overall performances of the force control obtained with the spring stiffness chosen at the design phase.**

I. Introduction

Cerebral palsy (CP) is the most common motor disability in childhood. The prevalence of cerebral palsy (CP) ranges from 1.5 to 2.5 per 1000 live births [1]. Neonatal stroke is characterized by an incidence of up to 63 per 100,000 live births. Hemiparesis is the most common functional deficit after stroke. At present, the physical therapies that imply improvements for these impairments are labor intensive and expensive. Over the past 50 years several rehabilitation strategies have been used to increase functional recovery in children with neurological diseases, to improve their autonomy and quality of life. Nevertheless, if we analyze the motor outcome of these children in the last decades, we realize there has been no significant change [2]. Robotics technology can transform rehabilitation clinical practice from manual to a more technology-rich operation. The availability of a robotic therapy for the recovery of locomotion can improve the outcome, decrease the period of hospitalization, and transfer the rehabilitation in house. In the last decade, several wearable exoskeletons (WE) have been developed to assist subjects to recover their locomotion [3]–[8]. Hybrid Assistive Leg (HAL-5) was developed to accomplish both for performance augmenting and rehabilitative purposes [3]. The HAL-5 system is constituted by two active joints at the hip and knee powered by DC motors; the ankle joint remains passive. The interface with the wearer is allowed by special shoes with ground reaction force sensors, harnesses on the calf and thigh, and a wide waist belt. RoboKnee [4] was designed to add power at the knee and to provide balance and control, as well as most of the energy required to work against gravity while the user decides when and where to walk. RoboKnee allows not only to enhance strength and endurance during walking but also to increase the rehabilitation treatments as an exercise machine. Blaya et al. [5] developed an active AFO (AAFO) to assist drop foot gait, a deficit affecting many persons who have experienced a stroke. Specifically, the device permits to decrease both the slapping of the foot after heel strike and the dragging of the toe during swing. The device consists of a modified passive AFO with the addition of a series elastic actuator (SEA) to allow variations of joint stiffness for ankle rotations. Thanks to the SEA, the device varies the impedance of the ankle in plantar flexion during stance, and assists the dorsiflexion during the swing phase of walking. Ferris et al. [6] designed a pneumatically powered orthosis for the recovery of ankle mobility; the device consists of two artificial pneumatic muscles that provide plantar flexion and dorsiflexion torques. The air pressure in each artificial muscle is controlled by EMG. Also inspired with assisting post-stroke subjects with drop foot and also with a reported desire to develop a clinical measurement tool, Roy et al. [7] developed a robotic ankle orthosis named Anklebot. The Anklebot is a backdriveable device that allows rotations in all 3 DOF of the ankle, and controls the plantar-dorsiflexion and inversion-eversion directions by means of two linear screw actuators mounted in parallel. The only WE developed to be worn by children is the pediatric version of the Anklebot [8]. The working principle is the same of the adult version but it was reduced in terms of weight and maximum torque.

However, none of the mentioned systems is oriented to the simultaneous treatment of ankle and knee mobility of pediatric subjects. In this paper we report the preliminary results of the alpha-prototype of the WAKE-up (Wearable Knee Ankle Exoskeleton), a new active orthosis for the recovery of gait in children aged 5 to 8 years with CP.

II. Target Specification of the WAKE-up

The WAKE-up is a bi-articular assisted orthosis, composed of two modules. Each module can be utilized either alone or together with the other one. When the therapist intends to focus the treatment on a single joint, the patient can wear only the correspondent module, to reduce the weight and the complexity of the overall system. Conversely, when the motor disability compromises the control capability of knee and ankle, both the modules can be simultaneously used.

S. R. is with the Department of Economics and Management – Industrial Engineering (DEIM), University of Tuscia, 01100 Viterbo, Italy (phone: +390761357049; (e-mail: stefano.rossi@unitus.it).

F. P. is with the School of Mechanical Engineering, Niccolò Cusano University, Via Don Carlo Gnocchi 3, 00166 Roma, Italy (e-mail: fabrizio.patane@uniroma1.it)

F. D. S. and P. C. are with the Department of Mechanical and Aerospace Engineering, "Sapienza" University of Rome, 00184 Roma, Italy (e-mail: fausto.delsette@uniroma1.it, paolo.cappa@uniroma1.it).

978-1-4799-3127-9/6/14/$31.00 ©2014 IEEE

The target specifications of the developed device are:

- Suitable for patients aged 5-8 years;
- Easily wearable;
- To ensure an high level of safety of subjects;
- To assist the drop foot gait working as a Knee Ankle Foot Orthosis (KAFO) with an adjustable stiffness via software.

In order to achieve the first requirement and not to compromise the patient's mobility and locomotion, we decided to limit the maximum mass of the overall device to 2.5 kg [9]. As regards the second requirement we developed a quick release system between motors and anatomical joints. The last two requirements were accomplished by implementing SEAs in each joint module. The presence of SEAs, in addition, allows an active cooperation of the subject during rehabilitation exercises. The subject does not receive the therapy in a passive way but the device interacts with him/her, changing the stiffness as a function of his/her motor performance improvements. Specifically, the device can apply a corrective/perturbative action on the joint motion assisting or less the subject only when requested.

III. THE ALPHA PROTOTYPE OF WAKE-UP

A. *WAKE-up: Hardware*

Two pictures of the WAKE-up are reported in Figure 1. The modularity of WAKE-up permits a unified approach for the design of the ankle and knee modules, addressed as AM and KM respectively. This choice, on the one hand simplified the project, since the design is the same for both joints, but, on the other hand, complicated it because each module has to fit the same set of specifications in terms of weight, bulk, and power transmission.

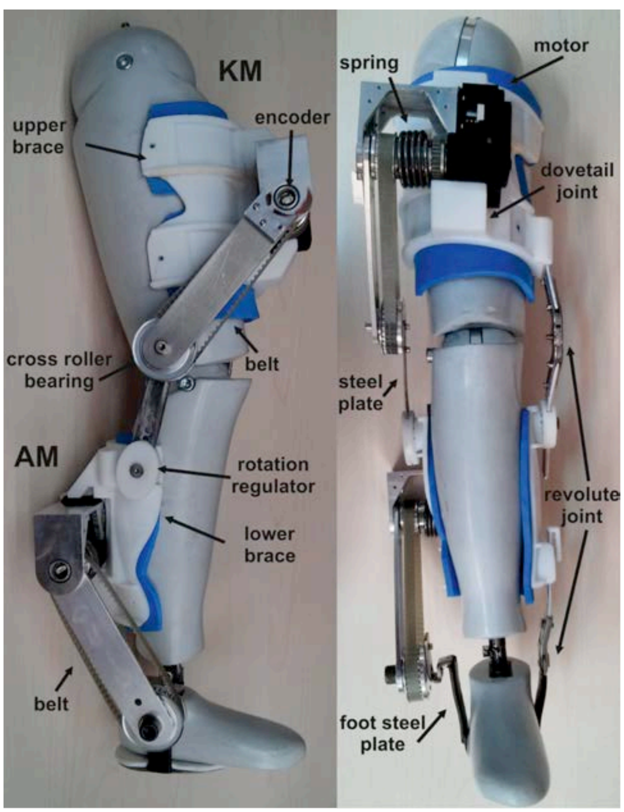

Figure 2. WAKE-up.

The crucial choice for the working principle of the device concerns the torque transmission implemented in the actuation system. The scheme, based on SEA, involves the use of a motor and a spring mounted in series to avoid a direct connection of the actuator with the patient's limbs. The torque, transmitted by the proximal body segment to the distal one, is controlled by setting the position of the motor shaft and, as a consequence, the torsional spring deflection. This methodology permits the implementation of a virtual spring with adjustable stiffness to generate precise assistive or resistive joint-torques.

The power transmission is achieved by timing belt and pulleys and it is mediated by a torsion spring characterized by a stiffness of 3.0 Nm/rad, selected following the results of the simulation reported in the next paragraph. The spring allows the actuator to act indirectly on the limbs to increase patient's safety. The modules are equipped with crossed roller bearings (CRBH208A, IKO) to reduce weight, and to resist to bending moments occurring in clinical use. The chosen motors are high-torque digital servos (EX 106+, DYNAMIXEL), which have an embedded positional controller. A 1.5 pulley reduction was chosen to increase the transmitted torque. The deflection of torsion spring is measured by a miniature absolute encoder (MA3, US Digital, accuracy of 0.5°) embedded inside the transmission shaft. The frame is composed by two braces rigidly attached to thigh and shank by adjustable velcro belts. The frame length is adjustable to permit the use of the WAKE-up with children with different leg length. The braces were designed from a 3D scanner (CAM2, FARO) acquisition of a mock leg and they were realized with a rapid prototyping machine (S250, INSPIRE). Custom braces will be designed specifically for each subject that will undergo robotic-rehabilitation treatments. In order to make easier the wearability for children, an ad-hoc connection system between the braces and the motors was designed. It is composed of two sliding dovetail joints, one for each module, where the motors can be easily inserted after that subject has worn the braces. The socket is embedded in the braces, while the tails are mounted on the motor block. The material of dovetail joints is ABS in order to decrease the overall weight. The lateral knee joint connection is composed of a harmonic steel plate and a regulator of the distance and rotation between AM and KM. The lateral ankle joint connection is composed by a handmade steel plate for the foot that can be insert in the shoe of the subject. Two revolute joints connect the two braces together and the lower brace with the foot steel plate. The phases of gait are estimated by foot switches placed under the inner sole.

B. *WAKE-up: Estimation of spring stiffness*

The estimation of the spring stiffness that characterizes the SEA scheme was performed by means of a kinematic analysis consisted in a simulation of a 3-segment/2-DOF mechanism (femur, tibia, and foot). Since it is not possible the prediction of the patient's response to the dynamic action of the device, a simplified scenario was tested. The scenario consisted in assuming the angle/torque patterns of knee and ankle equal to the ones that occurred during the unperturbed gait of a healthy pediatric subject. The gait of a healthy child (7 years old, mass of 24.5 kg) was acquired by means of an optoelectronic system (VICON MX, UK) and two force platforms (OR 6-5, AMTI, MA, USA) camouflaged into the floor. The angles and moments of knee and ankle are reported in Figure 2.

In the simulations we selected: (1) the motor EX 106+ characterized by maximum rotation of 260° and maximum speed of 100 rpm (the values are reported in the datasheet of the motor); (2) transmission ratio equal to 1.5; (3) range of motion of knee and ankle equal to 70° and 40°, respectively (Figure 2); (4) a maximum motor torque of 6 Nm, that was chosen as the 20% of the moment peak of knee and ankle measured from the healthy subject trials. It is worthy to note that the WAKE-up has not to sustain the child during the locomotion, but only it has to interact with him to require an active cooperation of the subject. The simulation was performed varying the stiffness of the spring between 1.0 to 4.0 Nm/rad. The optimal spring was identified as the one that does not require an excessive motor rotation. In TABLE I the results of the simulation are reported. The table permits the identification of the optimal solution for the spring stiffness

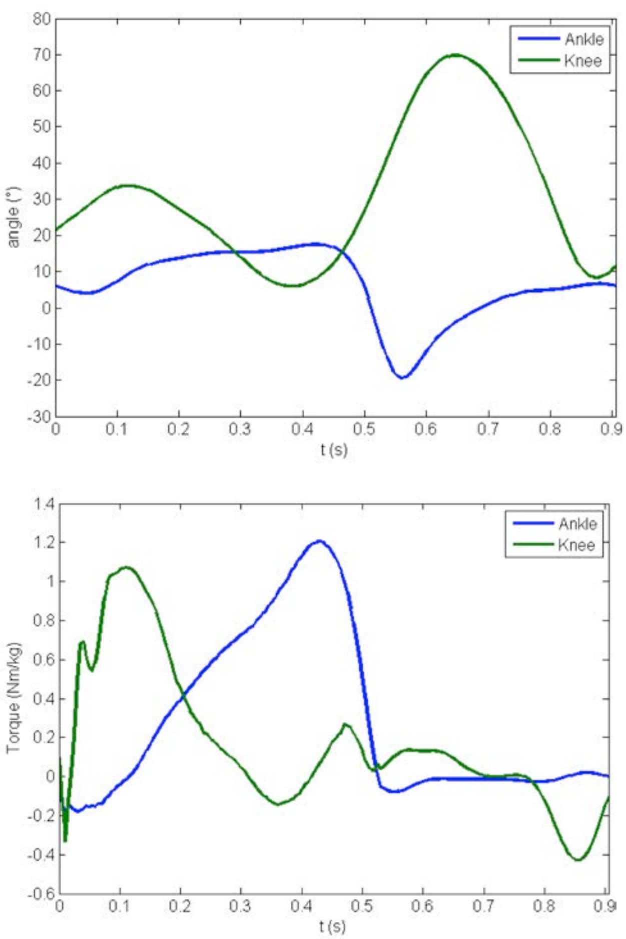

Figure 2. Angle and moment of ankle and knee used as simulation inputs.

as a function of the motor electrical characteristics. The value of 3Nm/rad was selected for each joint of the device because it ensure up to 20% of torque at the joint level and lower dimensions.

TABLE I. RESULTS OF THE SIMULATION. THE CHOSEN SPRING STIFFNESS WAS 3.0 NM/RAD

Trial	Ks (Nm/rad)	Results
1	1.0	NO - Motor angle exceed 260°
2	2.0	NO - Motor angle exceed 260°
3	**3.0**	**YES - Motor angle lower than 260°**
4	4.0	YES - Motor angle lower than 260°

C. *WAKE-up: Mechanical characterization*

In order to evaluate the characteristics of AM and KM, a test bench (TB) was designed and realized (Figure 3). TB consisted of a linear positioner, a uniaxial load cell and a frame for the attachment of AM or KM module. The module is fixed to the positioner forming a crank-slider mechanism. The theoretical scheme of the motor module and the linear positioner is reported in Figure 4.

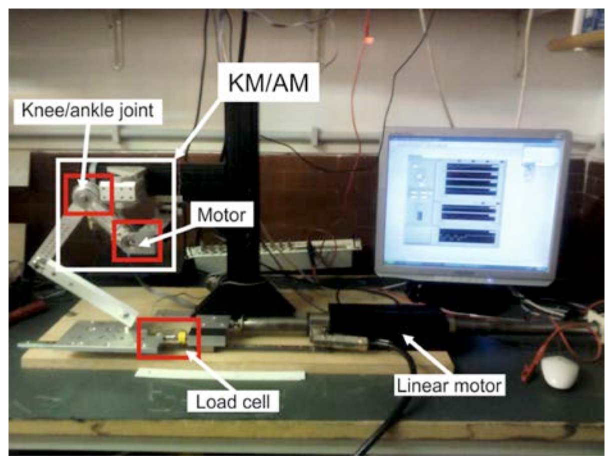

Figure 3. Experimental test bench.

The direct kinematics of TB is:

$$y(\vartheta_1) = \sqrt{l_2^2 - (x - l_1 c_1)^2} + l_1 s_1 \tag{1}$$

The inverse kinematics of TB is:

$$\begin{aligned} \vartheta_1(y) &= \operatorname{acos}\sqrt{\frac{x^2 - l_2 s_2}{(l_1 + l_2 c_2)^2 - l_2 s_2}}, \\ \vartheta_2(y) &= \operatorname{acos}\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}\right) \end{aligned} \tag{2}$$

where y is the slider position and ϑ_1 is the ankle/knee rotation.

The dynamics of TB can be evaluated by means of the Jacobian J_A where M_z is the ankle/knee torque and F_y is the load cell force:

$$M_z = J_A F_y$$
$$J_A = -\frac{l_1 s_1 (x - l_1 c_1)}{\sqrt{l_2^2 - (x - l_1 c_1)^2}} + l_1 c_1 \tag{3}$$

The experimental tests consisted in controlling the spring deflection ϑ_s with a sinusoidal signal in order to transmit a sinusoidal torque at the joint level:

$$\vartheta_s = A_s \sin\left(\frac{2\pi}{T_s} t\right) + O_s \tag{4}$$

Several testing conditions were tested: spring period T_s (1s-2s), offset spring O_s (10°-30°), spring amplitude A_s 30° and joint angle ϑ_1 (0°-20°-40°-60°).

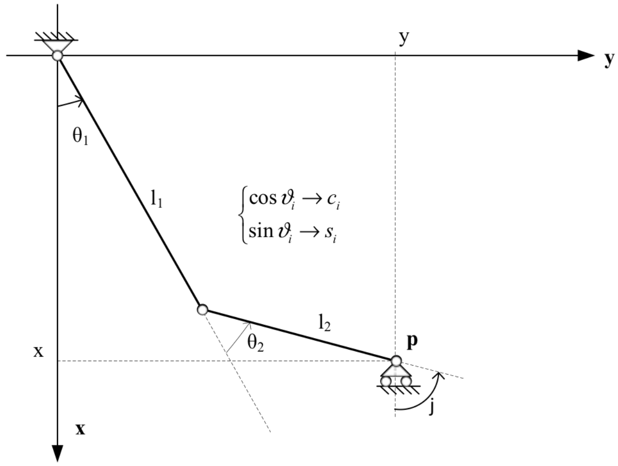

Figure 4. Scheme of the motor module and the linear positioner.

The results showed a good precision of the position tracking for the spring deflection (position error <2°) (TABLE II). A distortion of the torque signal was measured, due to the combined effect of the spring non-linearity and the servo-motor performance. However, the experiments resulted in good agreement with the performances obtainable with the spring stiffness chosen in the design phase. Therefore, the accuracy of the torque transmission was considered sufficient, taking also into account that the torque applied by the module to the joint is further mediated by a foam interface when the WE is worn by the subject.

TABLE II. RMSE MEASURED WITH THE BENCH TEST

Parameters	**RMSE measured at joint level**
Joint angle ϑ_1 (°)	1.3
Spring offset O_s (°)	0.8
Spring stiffness K_s (Nm/rad)	0.7
Spring amplitude A_s (°)	0.9
Torque offset (Nm)	0.34
Torque amplitude (Nm)	0.14

IV. CONCLUSION

This paper has presented an overview of the alpha-prototype of the WAKE-up. We are currently initiating feasibility tests at the Neurorehabilitation Department Children's Hospital of Bambino Gesù in Rome. An evaluation of the robotic therapy efficacy with WAKE-up orthosis will be the goal of future researches.

ACKNOWLEDGMENT

This project was sponsored by a grant from the Italian Institute of Technology (IIT) — Project Seed ('ITINERE—interactive technology: an instrumented novel exoskeleton for rehabilitation' 2009) and by a grant from Italian Health Ministry (grant 'Pilot study on a novel typology of medical devices: robotic exoskeletons for knee rehabilitation' 2009) to P. C.

REFERENCES

[1] N. Paneth, T. Hong, and S. Korzeniewski, "The descriptive epidemiology of cerebral palsy.," *Clin. Perinatol.*, vol. 33, no. 2, pp. 251–67, Jun. 2006.

[2] H. Anttila, I. Autti-Rämö, J. Suoranta, M. Mäkelä, and A. Malmivaara, "Effectiveness of physical therapy interventions for children with cerebral palsy: a systematic review.," *BMC Pediatr.*, vol. 8, p. 14, Jan. 2008.

[3] H. Kawamoto, S. Kanbe, and Y. Sankai, "Power assist method for HAL-3 using EMG-based feedback controller," in *SMC'03 Conference Proceedings. 2003 IEEE International Conference on Systems, Man and Cybernetics. Conference Theme - System Security and Assurance (Cat. No.03CH37483)*, vol. 2, pp. 1648–1653.

[4] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, "The RoboKnee: an exoskeleton for enhancing strength and endurance during walking," in *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, 2004, vol. 3, pp. 2430–2435 Vol.3.

[5] J. A. Blaya and H. Herr, "Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait.," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 12, no. 1, pp. 24–31, Mar. 2004.

[6] D. P. Ferris, J. M. Czerniecki, and B. Hannaford, "An ankle-foot orthosis powered by artificial pneumatic muscles.," *J. Appl. Biomech.*, vol. 21, no. 2, pp. 189–97, May 2005.

[7] A. Roy, H. I. Krebs, D. J. Williams, C. T. Bever, L. W. Forrester, R. M. Macko, and N. Hogan, "Robot-Aided Neurorehabilitation: A Novel Robot for Ankle Rehabilitation," *IEEE Trans. Robot.*, vol. 25, no. 3, pp. 569–582, Jun. 2009.

[8] H. I. Krebs, S. Rossi, S.-J. Kim, P. K. Artemiadis, D. Williams, E. Castelli, and P. Cappa, "Pediatric anklebot.," *IEEE Int. Conf. Rehabil. Robot.*, vol. 2011, p. 5975410, Jan. 2011.

[9] S. Rossi, A. Colazza, M. Petrarca, E. Castelli, P. Cappa, and H. I. Krebs, "Feasibility study of a wearable exoskeleton for children: is the gait altered by adding masses on lower limbs?," *PLoS One*, vol. 8, no. 9, p. e73139, Jan. 2013.