

Pediatric Anklebot

Hermano I. Krebs *Senior Member, IEEE*, Stefano Rossi, Seung-Jae Kim, Panagiotis K. Artemiadis, Dustin Williams, Enrico Castelli and Paolo Cappa

Abstract—In this paper we present the alpha-prototype of a novel pediatric ankle robot. This lower-extremity robotic therapy module was developed at MIT to aid recovery of ankle function in children with cerebral palsy ages 5 to 8 years old. This lower-extremity robotic module will commence pilot testing with children with cerebral palsy at Blythedale Childrens Hospital (Valhalla, NY), Bambino Gesu Children’s Hospital (Rome, Italy), Riley Children’s Hospital (Indianapolis, IN). Its design follows the same guidelines as our upper-extremity robots and adult anklebot designs, i.e. it is a low friction, backdriveable device with intrinsically low mechanical impedance. We show the ankle robot characteristics and stability range. We also present pilot data with healthy children to demonstrate the potential of this device.

I. INTRODUCTION

Cerebral palsy (CP) affects at least 2 in 1,000 children born in the United States. Studies have shown that in the US at least 5,000 infants and toddlers and 1,200 - 1,500 preschoolers are diagnosed with CP each year as developmental and motor delays become more apparent (<http://www.about-cerebral-palsy.org>). These numbers are expected to grow worldwide with the increased survival of pre-term babies. Spastic diplegia and hemiplegic CP are the most common syndromes in children born at term and preterm infants [1]. CP habilitation is a process that seeks to enable the child to fully participate in society, with physical and occupational therapy playing a major role. The motivation behind such therapy is best expressed by Hebbian ideas of nervous system plasticity, mainly

This work is supported by the Cerebral Palsy International Research Foundation (CPIRF) and the Niarchos Foundation. Prof Cappa acknowledges the financial support of the Italian Health Ministry (Grant 2009 “Pilot study on a novel typology of medical devices: exoskeleton for pediatric rehabilitation.” Dr. H. I. Krebs is a co-inventor in the MIT-held patent for the robotic device used in this work. He holds equity positions in Interactive Motion Technologies, the company that manufactures this type of technology under license to MIT.

H. I. Krebs is with the Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA, with the Department of Neurology and Neuroscience, Weill Medical College, Cornell University, Burke Medical Research Institute, White Plains, NY, USA, and with the Department of Neurology, University of Maryland, School of Medicine, Baltimore, MD, USA (email H. I. Krebs: hikrebs@mit.edu).

Stefano Rossi is with “Sapienza” University of Rome, Department of Mechanical and Aerospace Engineering, Rome, Italy.

Seung-Jae Kim and Panagiotis K. Artemiadis are Postdoctoral Research Associates in the Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.

Dustin Williams is the Vice-President of Interactive Motion Technologies, Watertown, MA, USA.

Enrico Castelli is with Bambino Gesu Children’s Hospital, Department of Neuroscience and Neurorehabilitation, Rome, Italy.

Paolo Cappa is with “Sapienza” University of Rome, Department of Mechanical and Aerospace Engineering, Rome, Italy.

that neurons that “fire” together, “wire” together. The human brain is capable of self-organization, or neuroplasticity [2, 3], so that learning offers an opportunity for motor recovery [4, 5]. Generally, therapy involves physical interaction with one or more therapists who assist and encourage the child through a number of repetitive exercises. The repetitive nature of therapy makes it amenable to being administered by properly designed robots. A robotic therapist can eliminate unnecessary exertion by the therapist, deliver a highly reproducible motor learning experience, quantitatively monitor and adapt to the child’s progress, and ensure consistency in planning a therapy program. Of course, one must take previous statement with the appropriate caveats as we do not know yet what constitutes optimal therapy for a particular individual needs.

A pioneer of its class, MIT-MANUS, a robotic upper-limb manipulandum for shoulder and elbow training, was completed in 1991 [6]. Clinical trials involving MIT-MANUS have shown that robot-aided neuro-rehabilitation has a positive impact in stroke rehabilitation, reducing impairment, improving function and quality of life in both stroke inpatients and outpatients without increasing total cost [5]-[16]. This has motivated the development of new modules designed for rehabilitation of anti-gravity movements of the wrist, of the hand, and of the ankle [15].

In this paper, we report on development of a novel pediatric anklebot for children ages 5 to 8. We decided to focus on the ankle for two main reasons: first, in unimpaired subjects the ankle is the largest source of mechanical power during terminal stance [16], as the plantarflexors stabilize the forefoot rocker action [17]; second, the increase of plantarflexors muscular tone, with secondary equinus foot, is one of the main cause of gait impairment in CP [18]. The plantarflexors contribute as much as 50% of positive mechanical work in a single stride to enable forward propulsion [19]-[22]. In pre-swing, plantarflexors also act to advance the leg into swing phase while promoting knee flexion at toe-off [17]. Impairment at the ankle joint is of particular importance in CP. In some youngsters, it manifests as “equinus foot”, which is a simple name for a complex problem. The foot needs to clear the ground during the swing phase of gait and it needs to have a controlled landing during heel strike. It manifests itself as Equinus gait (True or Apparent) that, if allowed to mature as the child matures, can only be corrected through invasive orthopedic surgery. At present, equinus foot is typically addressed in the clinic via an ankle foot orthosis (AFO) that restricts the ankle’s range of motion.

Hence a pediatric anklebot for children with CP ages 5 to 8

y.o. is not only unique, but has the potential for revolutionizing the care of these youngsters. We expect that our endeavor will provide the tools to foster harnessing plasticity, guide neuro-development during this forming period, and prevent gruesome orthopedic problems.

The paper is organized as follows: Section II presents an overview of the target specifications of the pediatric anklebot robot; Section III presents the alpha-prototype and calculations of ankle kinematics and kinetics. Fitting of the device and pilot results with healthy children are discussed in Section IV, which is followed by the conclusions.

II. THE PEDIATRIC ANKLEBOT TARGET SPECIFICATION

We have been studying anthropometrics and collecting data of common gait patterns in CP at our collaborating institutions Blythedale (Valhalla, NY) and Bambino Gesu (Rome, Italy) (see Figure 1). From those, we developed the target anklebot requirement envelope shown below. Unfortunately the dimensional range for children 3 to 12 y.o. is too large to be covered by a single device. Thus we opted here to focus on the 5 to 8 y.o. population and to aim at the following requirements:

- Must be easy to put on and take off (< 2 minutes).
- Must be backdriveable.
- Must not cause pain or injury to the patient.
- Must actuate dorsi/plantarflexion and inversion/eversion.
- Must have accurate measurement and control of the actuated joint.
- Must include a passive mechanism in order to compensate for hypertonia.

We tested on two healthy children ages 5 and 6 to determine whether our target choice for unilateral weight was appropriate (H.I.Krebs' children). Average child mass was 21 kg and average height 1.2 m. We checked whether the children were able to play a soccer game with added mass of 0, 0.5, 1, 1.5, 2 and 2.5 kg mounted above the knee at their non-dominant leg. We also verified at laboratory setting at Bambino Gesu Hospital the impact of unilateral loading on walking speed, step time, stance phase, symmetry index (one leg loading) defined in (1) for both healthy and CP children with the same range of added masses.

Results suggested that our target specification shown in Figure 2 appears to be adequate, for both healthy and CP children age 5 to 8 y.o., with preferred walking speed decreasing from 1.34 to 1.05 m/s and step time increasing from 0.42 to 0.48 s. Stance phase did not change (56.2 to 58.7 %) and the symmetry index was close to 0. We observed no statistically significant difference between conditions (Figure 3).

$$\frac{(Stance_{left} - Stance_{right})}{\left(\frac{1}{2}\right) (Stance_{left} + Stance_{right})} 100 [\%] \quad (1)$$

III. THE ALPHA-PROTOTYPE OF PEDIATRIC ANKLEBOT

A. Hardware

The pediatric anklebot alpha-prototype is a low-friction, backdriveable device with intrinsically low mechanical



Fig. 1. Distinct Gait Patterns in CP. We investigated in a gait lab a multitude of gait patterns in CP including: true and apparent equinus, jump gait, crouch gait (Bambino Gesu Children's Hospital).

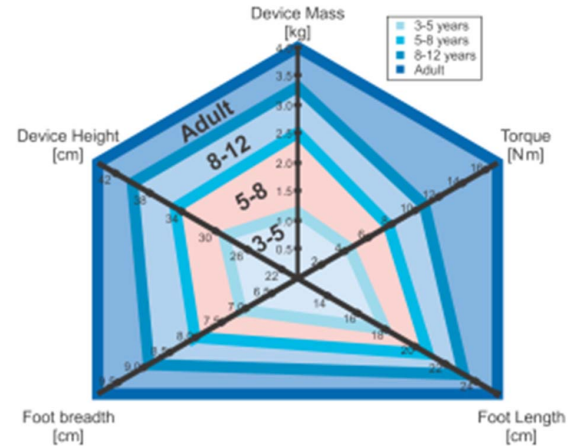


Fig. 2. Anklebot Target Envelope.

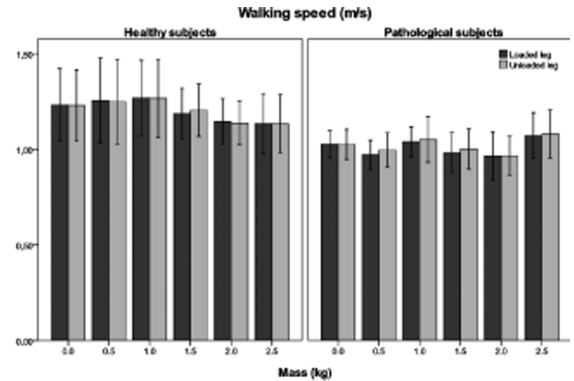


Fig. 3. Healthy and CP Children Walking with Added Weight on their Non-Dominant Knee. Data suggests that both healthy and CP children ages 5 to 8 y.o. can play and walk with asymmetrical loading of up to 2.5 kg.

impedance that allows normal range of motion (ROM) in all three degrees-of-freedom of the foot relative to the shank during walking overground or on a treadmill. Specifically, it allows 25° dorsiflexion, 45° plantar flexion, 25° inversion, 15° eversion, and 15° internal or external rotation. These limits are near the maximum range of comfortable motion for normal subjects and beyond what is required for typical gait [23]. The robot provides independent, active assistance in two of these three degrees-of-freedom, namely, dorsi-plantar flexion and inversion-eversion, and a passive degree-of-freedom for internal-external rotation. The kinematic design consists of two linear actuators mounted in parallel such that if both push or pull in the same direction, a dorsi-plantarflexion torque is produced at the ankle. Similarly, if the two links push or pull in opposite directions, inversion-eversion torque results (see Figure 4). The device can deliver a maximum stall torque $\sim 7.21Nm$ in dorsi-plantarflexion and $\sim 4.38Nm$ in inversion-eversion. Of course, this torque capability does not afford lifting the weight of the child (approx 25%). At best, we can cue him/her to use their voluntary plantarflexor function by providing supplemental support to the paretic ankle plantarflexors during this phase. The device also possesses minimal friction and inertia to maximize the backdriveability.

The Anklebot is actuated by two brushless DC motors (Maxon EC-powermax 22-327739) which are cogless and produce maximum continuous torque $\sim 51.2mNm$ that is augmented by a Rohlix linear traction drive. Motion and torque information is provided by two sensors: the first is a mini-rail linear encoder (MNS9-135 length, Schneeberger) mounted in parallel with the motors and possessing a resolution of $1\mu m$. The linear dimensions measured by the encoders are used to estimate ankle angle in plantar-dorsiflexion and inversion-eversion. The second is a Gurley rotary encoder with 40960 lines. Load cells were added at each actuator output (LSB200:00105, 25 lb, 2mV/V Futek).

At present, the controller is a simple impedance controller implemented as a proportional-derivative (PD) controller with programmable reference or neutral position, a programmable proportional gain (approximating a controllable torsional stiffness), and a programmable derivative gain (approximating a controllable torsional damping in parallel with the stiffness).

B. Estimation of ankle kinematics and kinetics

The ankle robot provides information about ankle kinematics and ankle torques based on the geometry of the device, sensor outputs, anthropometric data, and a simple linearized mathematical model of the shank-ankle-foot system. In this paper we are only concerned with the ankle angles and torques in dorsi-plantarflexion (DP) since the goal is to estimate the stiffness of the human ankle in that dimension. Towards that end, ankle angles in DP are estimated using the following expressions:

$$\begin{aligned}\theta_{dp} &= \sin^{-1}(x) + \theta_{dp,offset}, \\ \tau_{dp} &= (F_{right} + F_{left})x_{length},\end{aligned}\quad (2)$$

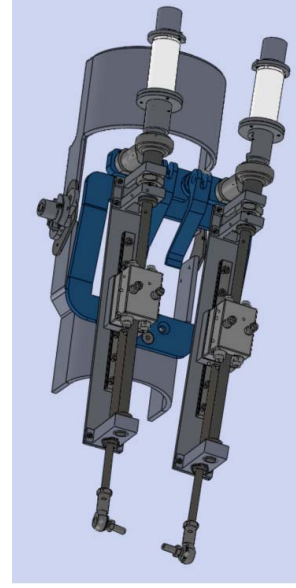


Fig. 4. Pediatric Alpha-Prototype Anklebot for Children with CP ages 5 to 8.

$$x = \left(\frac{x_{tr,len}^2 + L_{shank}^2 - x_{link,disp}^2}{2x_{length}L_{shank}} \right), \quad (3)$$

$$x_{link,disp} = \left(\frac{x_{av-act,len} - x_{right}}{2} \right) + \left(\frac{x_{av-act,len} - x_{left}}{2} \right) \quad (4)$$

where θ_{dp} is the ankle angle as measured from neutral in the sagittal plane, $\theta_{dp,offset}$ is the offset in ankle angle, τ_{dp} is the net torque at the ankle joint, F_{right} and F_{left} are the forces generated by the right and left actuators, respectively, x_{length} is the distance between the line of action of actuator force and the point of attachment between the ankle and the robot in the sagittal plane, L_{shank} is the shank length, $x_{link,disp}$ is the linear displacement of linkage, x_{right} and x_{left} are the lengths of the right and left actuators, respectively, and $x_{av-act,len}$ is the average actuator length. Ankle angle and torque in the frontal plane, i.e., eversion-inversion (IE), are similarly calculated using link displacement, device geometry, and sensor information:

$$\begin{aligned}\theta_{ie} &= \tan^{-1} \left(\frac{x_{right} - x_{left}}{x_{tr,width}} \right) + \theta_{ie,offset}, \\ \tau_{ie} &= (F_{right} - F_{left})x_{width},\end{aligned}\quad (5)$$

where θ_{ie} is the angular displacement from neutral in the frontal plane, $\theta_{ie,offset}$ is the IE offset angle, $x_{tr,width}$ is the transverse “ball-to-ball” width, τ_{ie} is the net torque at the ankle joint, and x_{width} is half the distance between the points of attachment in the frontal plane.

C. Achievable Impedance

The achievable impedance range of the device is characterized by the uncoupled stability curve shown in Figure 5. The stability data points were obtained by manually perturbing the pediatric anklebot at the ball joints of the two linear actuators with no user attached to it. This was performed for several

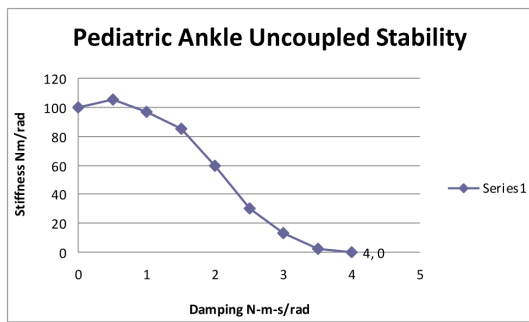


Fig. 5. Impedance ranges of the ankle robot as shown by the uncoupled stability curve. The graph shows the torsional stiffness-damping (K-B) stability profile. The machine is stable for (K, B) values under the curve.

values of robot damping, with the highest stiffness attainable determined at each damping value before instability occurred. In this context, instability was characterized by the occurrence of constant non-decaying oscillations. It is important to note that even very “small” oscillations were accounted for in this test. A shape-preserving interpolant was then used to obtain the stability boundary. For proper operation, the controller gains should be chosen below the stability curve.

IV. FEASIBILITY AND FITTING

We tested on the two healthy children ages 6 and 7.5 (H.I.Krebs’ children a year later, male and female) whether our alpha-prototype was comfortable and allowed them to play two full sets of games with the first game requiring 320 movements of dorsi-plantarflexion placing a target between moving gates and the second game 320 movements of inversion-eversion. We mounted the device on their non-dominant leg and the average child mass was 24.2 kg and height 1.23 m. Children were capable of playing the games without any complaints. Figure 6 shows one of the children during test and typical unassisted movement towards the targets demonstrating the high backdriveability of the device.

V. CONCLUSIONS

This paper has presented an overview of the pediatric ankle robot prototype. Only a small sample of healthy children used the device so far, but indications are that the device can be used simply and efficiently with children with cerebral palsy. We are currently initiating feasibility tests with the device in three different hospitals (Blythedale Children’s Hospital (Valhalla, NY), Bambino Gesù Children’s Hospital (Rome, Italy), and Riley Childrens Hospital (Indianapolis, IN)). We expect feasibility studies will be completed over the spring and pilot clinical testing will commence then. We will first test the device in open-chain (i.e. children will be seated playing video-games without touching the floor) and ultimately we will move to more task-oriented training walking over a treadmill and overground, while at the same time employing the device to characterize biomechanical aspects such as ankle stiffness.

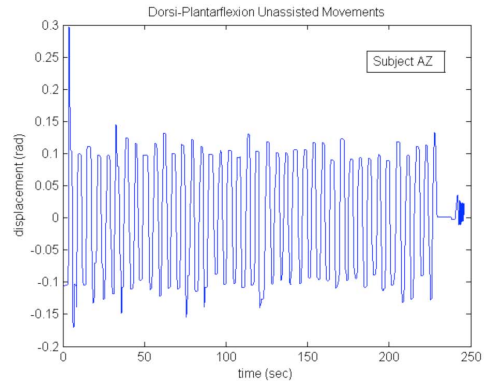


Fig. 6. Healthy Child (age 6) Playing Video-Games with the Pediatric Anklebot.

REFERENCES

- [1] Hagberg B, Hagberg G, Olow I, von Wendt L. The changing panorama of cerebral palsy in Sweden. VII. Prevalence and origin in the birth year period 1987-90. *Acta Paediatr.* 1996; 85(8): 954-60.
- [2] M. Hallett, “Plasticity in the human motor system,” *Neuroscientist*, vol. 5, pp. 324-332, Sept 1999.
- [3] W. M. Jenkins and M. M. Merzenich, “Reorganization of neurocortical representations after brain injury: a neurophysiological model of the bases of recovery from stroke,” *Progress Brain Res.*, vol. 71, pp. 249-266, 1987.
- [4] M. L. Aisen, H. I. Krebs, F. McDowell, N. Hogan, and B. Volpe, “The effect of robot assisted therapy & rehabilitative training on motor recovery following a stroke,” *Arch. Neurology*, 54: 443-446, 1997.
- [5] Krebs, H.I., N. Hogan, M.L. Aisen, and B.T. Volpe, “Robot Aided Neuro-rehabilitation,” *IEEE Transactions on Rehabilitation Engineering*, 6:75-87, 1998.
- [6] H. I. Krebs, B. T. Volpe, M. L. Aisen, and N. Hogan, “Increasing productivity and quality of care: robot-aided neurorehabilitation,” *VA J. Rehab. Research and Development*, 37: 639-652, 2000.
- [7] B. T. Volpe, H. I. Krebs, N. Hogan, L. Edelstein, C. M. Diels, M. L. Aisen, “A novel approach to stroke rehabilitation: robot aided sensorimotor stimulation,” *Neurology*, 54: 1938-1944, 2000.
- [8] B. T. Volpe, H. I. Krebs, and N. Hogan, “Is robot-aided sensorimotor training in stroke rehabilitation a realistic option?” *Current Opinion in Neurology*, Lippincott Williams & Wilkins, 14: 745-752, 2001.
- [9] M. Ferraro, J. J. Palazzolo, J. Krol, H. I. Krebs, N. Hogan, and B. T. Volpe, “Robot aided sensorimotor arm training improves outcome in patients with chronic stroke,” *Neurology*, 61: 1604-1607, 2003.
- [10] S. Fasoli, H. I. Krebs, J. Stein, W. R. Frontera, and N. Hogan, “Effects of robotic therapy on motor impairment and recovery in chronic stroke,” *Arch of Phys Med and Rehab*, 84: 477-482, 2003.
- [11] S. Fasoli, H. I. Krebs, J. Stein, W. R. Frontera, R. Hughes, and N. Hogan, “Robotic therapy for chronic motor impairments after stroke: follow-up results,” *Arch. Phys. Med. Rehab.*, 85: 1106-1111, 2004.
- [12] AC Lo, PD Guarino, LG Richards, JK Haselkorn, GF Wittenberg, DG Federman, RJ Ringer, TH Wagner, HI Krebs, BT Volpe, CT Bever, DM Bravata, PW Duncan, BH Corn, AD Maffucci, SE Nadeau, SS Conroy, JM Powell, GD Huang, P Peduzzi. Robot-assisted therapy for long-term upper-limb impairment after stroke. *N Engl J Med.* 362:1772-1783; 2010.

- [13] Forrester, L.W., Roy, A., Krebs, H.I., Macko, R. F., "Ankle Training With a Robotic Device Improves Hemiparetic Gait After a Stroke," *Neurorehabilitation and Neural Repair*, (EPUB ahead of publication).
- [14] HI Krebs, B Landenheim, C Hippolyte, L Monterroso, J. Mast, "Robot-Assisted Task Specific Training," *Journal of Developmental Medicine & Child Neurology*, 51:S4:140-145 (2009).
- [15] H. I. Krebs and N. Hogan, "Therapeutic Robotics: A Technology Push," *Proc. IEEE*, 94: 1727-1738, 2006.
- [16] DGE Robertson, DA Winter. Mechanical energy generation, absorption, and transfer amongst segments during walking. *J Biomech.*; 13:845-854, 1980.
- [17] J. Perry. *Gait Analysis: Normal and Pathological Function*. Thorofare, NJ, Slack, Inc., 1992.
- [18] JR Davis. The foot and ankle in Cerebral Palsy. *Orthop Clin N Am* 41:579-593, (2010).
- [19] GS Sawicki, DP Ferris. A pneumatically powered knee-ankle-foot orthosis (KAFO) with myoelectric activation and inhibition, *Journal NeuroEng and Rehabilitation*, 6:23, 2009.
- [20] JJ Eng, DA Winter. "Kinetic analysis of the lower limbs during walking: what information can be gained from a three-dimensional model?" *Journal of Biomechanics*, 28:753-758, 1995.
- [21] LF Teixeira-Salmela, S Nadeau, MH Milot, D Gravel, LF Requiao, "Effects of cadence on energy generation and absorption at lower extremity joints during gait." *Clinical Biomechanics*, 23:769-778, 2008.
- [22] BR Umberger, PE Martin. "Mechanical power and efficiency of level walking with different stride rates." *Journal of Experimental Biology*, 210:3255-3265, 2007.
- [23] P. Weiss, R. Kearney, and I. W. Hunter, "Position dependence of ankle joint dynamics Part I and II" passive mechanics," *J. Biomech.*, 19: 727-735 and 737-751, 1986.