A Pediatric Robotic Thumb Exoskeleton for at-Home Rehabilitation

The Isolated Orthosis for Thumb Actuation (IOTA)

Patrick M. Aubin, Hani Sallum, Conor Walsh, and Leia Stirling
The Wyss Institute for Biologically Inspired Engineering
School of Engineering and Applied Science
Harvard University
Cambridge, MA 02138 USA
leia.stirling@wyss.harvard.edu

Annette Correia
Occupational Therapy Services
Boston Children's Hospital
Boston, MA 02115 USA
Annette.Correia@childrens.harvard.edu

Abstract — **In this paper, we present the design of a thumb exoskeleton for pediatric at-home rehabilitation. Pediatric disorders, such as cerebral palsy (CP) and stroke, can result in thumb in palm deformity greatly limiting hand function. This not only limits children's ability to perform activities of daily living but also limits important motor skill development. Specifically, the device, dubbed IOTA (Isolated Orthosis for Thumb Actuation) is a 2-DOF thumb exoskeleton that can actuate the carpometacarpal (CMC) and metacarpalphalangeal (MCP) joints through ranges of motion required for activities of daily living. The device consists of a lightweight hand-mounted mechanism that can be custom secured and aligned to the wearer. The mechanism is actuated via flexible cables that connect to a portable control box. Embedded encoders and bend sensors monitor the two degrees of freedom of the thumb and flexion/extension of the wrist. Using this platform, a number of control modes can be implemented that will enable the device to be intuitively controlled by a patient to assist with opposition grasp, fine motor control, and ultimately facilitate motor recovery. We envision this at-home device augmenting the current in-clinic therapy and enabling tele-rehabilitation where a clinician can remotely monitor a patient's usage and performance.**

Keywords— rehabilitation robotics, at home hand rehabilitation; thumb; metacarpophalangeal joint; carpometacarpal joint; exoskeleton.

I. INTRODUCTION

The human hand is a sophisticated instrument used to perform many activities of daily living. The opposable thumb is a remarkable anatomical feature of the hand which greatly increases the hand's versatility. Thumb opposition involves flexion, abduction, and medial rotation so that the pulp surface can contact the other digits [1]. A variety of pediatric diseases and brain injuries can affect hand function, including cerebral palsy (CP), pediatric stoke, and traumatic brain injury. CP is the most common motor disability in children, affecting approximately 3.6 per 1,000 school-age children [2]. Approximately 47% of patients with CP have a thumb in palm deformity in at least one of their hands, which negatively affects hand function [3]. According to the House classification, type 2 thumb in palm deformity is defined as fixed adduction of the CMC joint and flexion of the MCP joint[4].

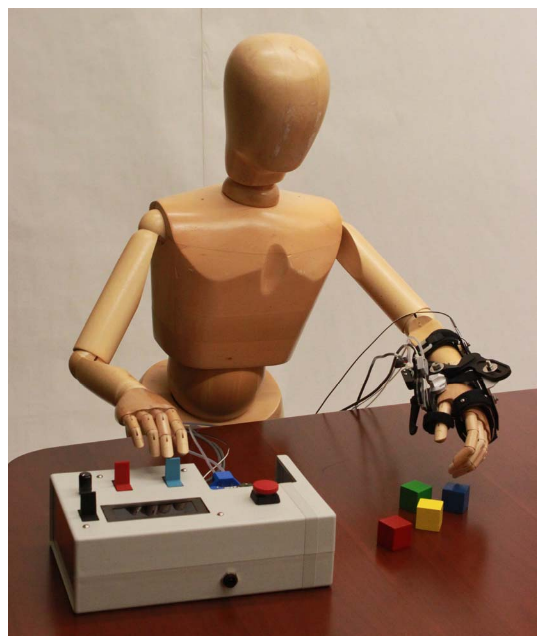

Figure 1. The Isolated Orthosis for Thumb Actuation (IOTA) is a 2 DOF exoskeleton for clinical and at home pediatric thumb rehabilitation.

The goal of pediatric hand rehabilitation is to promote the independence of the patient by improving motor function. Depending on the severity, treatment can include stretching, serial casting, orthotic devices, chemical denervation, surgical release, and other techniques to help maintain range of motion and tone control in the upper extremity. All of these treatments require rehabilitation exercises and practice of motion tasks. The rehabilitation motions and tasks can be learned and retained because neuroplasticity, which is enhanced in children, allows the brain to reorganize neuronal networks and recover from brain damage [5]. Motor learning strategies that incorporate massed practice, cognitive engagement, and functional relevance are considered essential to successful therapy for pediatric movement disorders [4].

Rehabilitative therapies that can be performed at home have the potential to augment standard care and have the advantage of being more convenient, less expensive, and provide greater training frequency and intensity than conventional care delivered one-on-one by a therapist in a clinic. Robotic rehabilitation devices can be programmed to apply precise motions or torques to relevant joints in a repetitive manner during active participation while quantitatively monitoring progress over timescales that range from seconds to months. Through the use of video games or interactive feedback, these robotic rehabilitation therapies can also be entertaining and motivating which may help maintain use and encourage the completion of a rehabilitation program.

Robotic rehabilitative devices for the hand can either be end-effector [6–8] or exoskeleton [9–13] based systems. End-effector systems, such as the cable actuated handCare [6], only constrain the distal phalanges of the fingers while the proximal joints are unconstrained. Thus, if explicit control of each joint is desired then an exoskeletal system rather than an end-effector system is necessary. Exoskeleton systems can simultaneously constrain distal and proximal joints such as the proximal inter-phalangeal joint and the metacarpal phalangeal joint. For exoskeleton based systems, the robotic super structure can be mounted either in the palmar region of the hand as in [12], or on the dorsum of the hand [9–11, 14]. One limitation of devices with palmar structure is their inability for the user to perform palmar or pincer grasps, two functionally important motor control strategies, in real (not virtual reality) environments. Exoskeleton systems for the hand can have independent degrees of freedom (DOF) for each finger as in [12, 13] or they can lump the index through the small finger together into one functional unit with 1-DOF [7, 9, 10, 14, 15].

While the field of rehabilitation robotics has seen significant growth recently, very little work has been focused on pediatric applications [16]. In particular, no pediatric exoskeleton systems have been developed for hand rehabilitation. Such a device requires particularly careful design in terms of both its anthropometric size and weight; a system designed for an adult cannot simply be scaled down in size. Also, its user interface must be simple enough for a child to use. In addition, few studies have investigated the usability of at-home robotic rehabilitation devices or the feasibility of prescribing at-home rehabilitation programs with such devices. Given the incidence of pediatric stroke, traumatic brain injury, CP and other disorders, it follows that a pediatric robotic rehabilitation system for the clinic and home would be highly beneficial.

The long term goal of this research is to determine the effectiveness of robot assisted therapy to augment pediatric motor recovery using a wearable robotic orthosis. The opposable thumb is critical for grasping and manipulating objects and is responsible for 40% of hand function [17]. For this reason we focused first on developing a system that assists and rehabilitates the thumb, specifically the CMC and MCP joints, which are required for opposition grasp.

The aim of this paper is to present the design specifications, electrical and mechanical characteristics, and control methodologies an Isolated Orthosis for Thumb Actuation (IOTA). IOTA (Fig. 1) is a pediatric robotic thumb exoskeleton for at-home rehabilitation. Unlike many traditional exoskeletons, the IOTA device was designed specifically for children between the ages of 7 and 12 to facilitate actuation of the CMC and MCP joints of the thumb. The device was designed to be used within a home setting while performing natural tasks, making portability and ease of use paramount design considerations. In addition, IOTA does not obstruct the palmar region of the hand so it has the potential to be used during everyday activities rather than only within virtual reality environments.

II. Device Specifications

The mean adult flexion-extension range of motion of the CMC and MCP joints have been reported to be 52.9˚ [18] and 110˚ [19], respectively. The CMC has a mean adduction-abduction range of motion of 42.4˚ [18] while the MCP functions mostly as a flexion-extension hinge joint [19] (Fig. 2). From these data and from professional experience, 60° of rotation for the CMC and MCP joints was assumed to be a reasonable functional range of motion. Anthropometric sizing for the device was determined through pediatric databases [20]. Our key measures of interest from the pediatric population were the thumb length, the thumb diameter, the palm length, and the hand breadth (Fig. 2 and Table I). From these data, the IOTA was designed to allow the above stated 60° of CMC and MCP range of motion and fit children aged 7 to 12 with the anthropometric measures of Table I.

A recent study performed by the authors [21] examined the torque needed to passively abduct the thumb at the CMC joint in children with a diagnosis of hemiplegia or stroke. In this study, a passive modified wrist orthosis was fabricated with an adjustable thumb joint which could be placed over the CMC joint. The torque required to maximally abduct the thumb was recorded with a torque sensor. Preliminary results from this study indicated that the maximum and mean applied torques to reach maximum abduction in the affected side were 0.285 N·m and 0.168 ± 0.076 N·m [21]. These data were used to specify the torque requirements for the IOTA system (Table I).

The IOTA device was designed to be lightweight so that children could wear the device while performing standard daily activities without being cumbersome. The target weight to be worn on the hand was specified to be less than 0.450 kg (approximately 40% of the combined weight of a 7 year old child's hand, forearm and arm) (Table I). In order to facilitate use in a home setting, the device was specified to be compact, lightweight and portable so that it could be easily carried by a parent and be deployable on a home table or desk (Fig. 1). The initial design allowed for a control box on a table, with the intent to minimize the electronics in future versions so that the control box could be mounted to an arm or waist band.

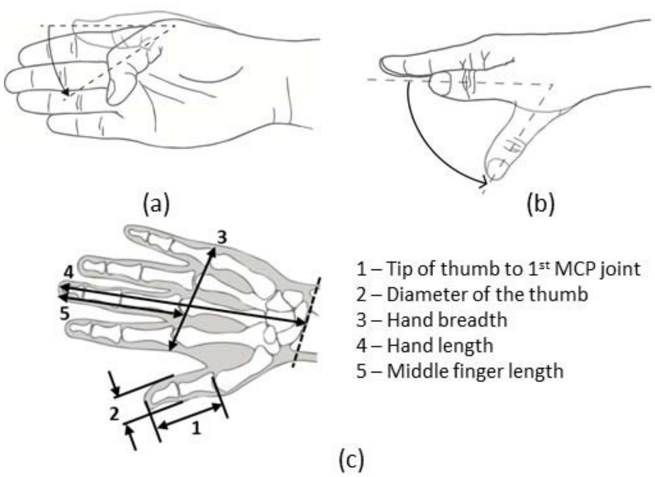

Figure 2. A diagram of (a) flexion of the metacarpalphalangeal (MCP) joint, adapted from [22], (b) abduction of the carpometacarpal (CMC) joint and (c) the anthropometric measures of the thumb.

TABLE I. IOTA DEVICE SPECIFICATIONS

Characteristic	Requirement	
	Target	*Actual*
CMC range of motion	60˚	65˚
MCP range of motion	60˚	65˚
Hand mounted weight	0.45 kg	0.23 kg
Control box size	Table top	25.0 x 15.8 x 7.5 cm
Portability	Carried by one hand	Fits into brief case
Battery life	45 min	>160 min
Fit thumb lengths	4.0 to 6.4 cm	4.0 to 6.4 cm
Fit thumb diameters	14 to 16 mm	10 to 16 mm
Fit hand breadths	5.7 to 8.1	4.4 to 8.1
Fit children aged	7 to 12	7 to 12
Torque requirement	0.285 N•m	3.25 N•m

III. ELECTROMECHANICAL DESIGN AND IMPLEMENTATION

A. *Mechanical Design*

The actuated orthotic component of the IOTA is composed of two parts; a semi-disposable patient-specific glove and a robotic exoskeleton that mounts to the glove. The glove is fitted to an individual subject's hand, and the exoskeleton can be adjusted to fit the full range of hand sizes specified (Fig. 3). The glove is made of lycra fabric, delrin, and annealed aluminum alloy 1100 which is covered with soft neoprene rubber. The 1100 alloy aluminum is soft enough to be manually molded to the dorsum of an individual's hand by a therapist and has a flexible tab that extends around the first metacarpal towards the palm to secure the dorsal plate to the hand. A 0.75 mm delrin sheet extends from the aluminum dorsal plate proximally over the wrist and forearm and is secured with a Velcro strap proximal to the head of the ulna. The glove provides a stable base from which the exoskeleton can exert forces on the thumb, while allowing the subject to retain significant flexibility of the wrist and fingers (Fig. 3 & 4). The delrin forearm plate also houses a 0.22 mm thick by 5.08 cm

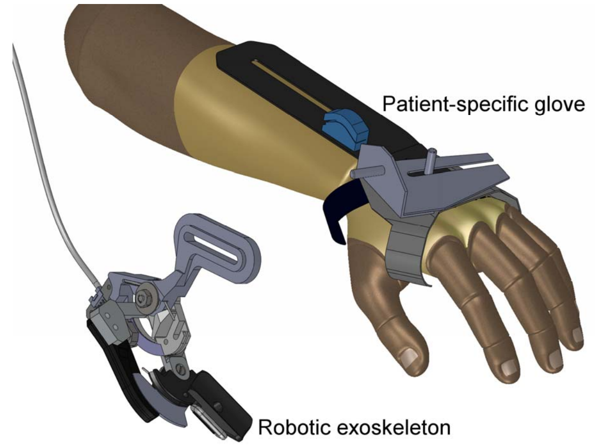

Figure 3. A CAD rendering of the hand mounted components of the IOTA system including the actuated robotic thumb exoskeleton and a patient-specific dorsal glove.

long bend sensor (Flexpoint Sensor Systems Inc. Draper, UT, USA) which extends across the wrist joint to measure flexion/extension (Fig. 4). Measurement of wrist flexion/extension allows the device to simulate the tenodesis effect whereby wrist extension adducts the CMC and flexes the MCP joint and wrist flexion abducts CMC and extends MCP.

In order to minimize the weight on the subject's hand, the actuators for the CMC and MCP joints are located off-board of the orthotic inside the control box. Actuation of the joints is achieved by two servos and two spring-return cable transmissions connected between the servos and the orthotic. To actuate the CMC and MCP joints the servos use internal encoders to determine servo angle and transmission cable position. Optical encoders integrated into the exoskeleton provide additional direct measurement of the CMC and MCP joint angles. The cable transmissions, sensor power supplies and sensor signals are connected to the orthotic from the control box via a wire bundle (Fig. 4).

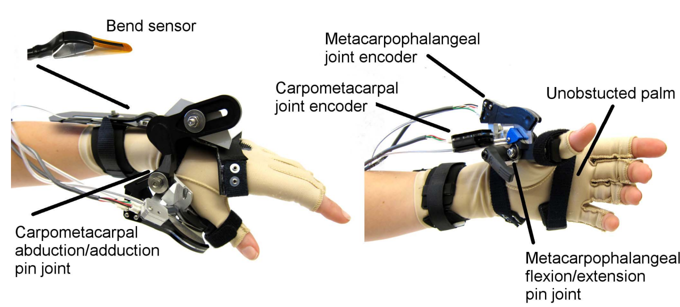

Figure 4. The aluminum and delrin on the dorsal glove provide a stable platform to which the exoskeleton device is mounted and houses a bend sensor used to measure wrist flexion/extension. The exoskeleton has pin joints for the carpometacarpal and metacarpophalangeal joints and two encoders to measure angular rotation about those two joints. The degree of CMC circumduction can be set by an Occupational Therapist by the molded configuration of the aluminum.

B. *Electromechanical Design*

An Arduino Mega 2560 (http://arduino.cc) was chosen as the microcontroller for the IOTA. A Cytron G15 shield (Cytron Technologies Sdn., Johor, Malaysia) was installed on top of the

Arduino board and controls the servo motors via half duplex serial communication. Dynamixel AX-12A servo motors (Robotis Inc., Seoul, Korea) were selected as they met the torque, speed, size and weight requirements for the given application. The Dynamixel servos were connected in a daisy chain fashion and controlled by the serial packets sent from the Cytron shield via the communication bus. Each AX-12A servo has an internal potentiometer position sensor with a resolution of 0.29˚ (300˚/1024 levels) (Fig. 5).

The integrated wrist bend sensor changes resistance with sensor curvature. The bend sensor was placed into a voltage divider circuit with a potentiometer tuned to the base resistance of the bend sensor. A two stage operational amplifier (Op-amp) with an adjustable gain ranging between 1.0 and 10.0 was used to amplify the output of the voltage divider circuit. The bend sensor produces a change in resistance of approximately 125 Ω/º. The output of the Op-amp circuit was connected to the 10-bit A/D converter on the Arduino Mega and converted to wrist flexion/extension angle.

Three momentary toggle switches and a rotary knob on the control box are used to navigate through a menu system for setting the appropriate control modes and therapy routines and for manual control of the exoskeleton. The function of the buttons changes depending on the mode of operation. A 4x20 LCD presents the navigable menu system to the user and displays messages and instructions when necessary. An emergency stop button immediately halts servo motion if pressed (Fig. 1 and 5).

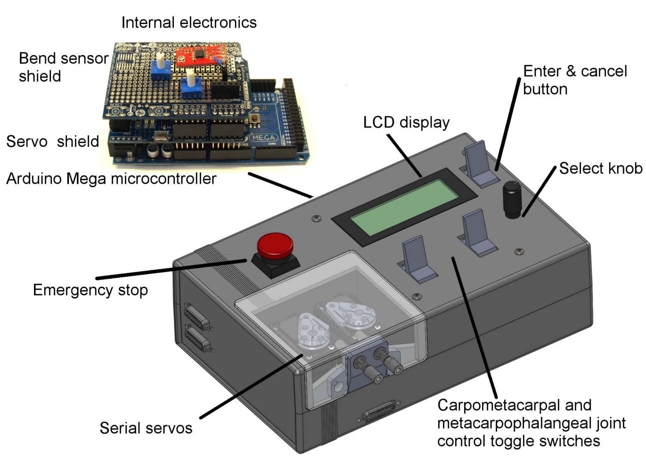

Figure 5. The portable control box measuring 25.0 cm x 15.8 cm x 7.5 cm houses the Arduino Mega microcontroller board and servos. Momentary toggle switches, a knob and a 4x20 LCD display allow the user to control the exoskeleton joints and navigate through the different IOTA modes of operation. The Arduino Mega 2560 microcontroller based board connects to a Cytron G15 serov shield which communicates with the Dyamixel AX12-A servo motors via a half-duplex single line serial protocol. The servos have internal potentiometer position sensors.

IV. Exoskeleton Joint Control

Immediately after turning on the device a calibration protocol is performed to set user-dependent safety limits for the CMC and MCP range of motion and to obtain the wrist range of motion. To set the CMC and MCP range of motion limits, the user is asked to use the toggle switches to manually actuate the CMC and MCP joints to the maximally adducted and flexed position, respectively, and then into a maximally abducted and extended position. The CMC and MCP angles achieved during this procedure are stored in the device as the range of motion limits. The wrist range of motion is then recorded by asking the participant to perform a maximally flexed and then maximally extended wrist motion. After the calibration procedure is completed the user can enter into one of the control modes.

Five different methods to control the IOTA's actuation were developed in order to investigate which method is most intuitive for the patient and most effective in assisting with grasping tasks and motor recovery. The following subsections describe the five control modes.

1) Manual Control Mode

In manual control mode, the toggle switches located below the LCD screen on the control box are used to flex/extend and adduct/abduct the MCP and CMC joints. The joints can be actuated individually or simultaneously. The speed of actuation (˚/s) is set by the user to be slow, medium, or fast.

If the user tries to manually actuate the CMC or MCP joint to a position beyond the specified range of motion limit the software will stop the servo motors to prevent injury to the user.

2) Teach & Learn Mode

The purpose of the teach & learn mode is to record therapist-assisted thumb motion for later playback. Here the occupational therapist physically moves a patient's thumb through a range of motion while the patient is wearing the exoskeleton. For the therapist to manipulate the thumb freely, the device must be as mechanically transparent to the wearer as possible. This means the servo motors must respond to motions generated by the therapist to permit an appropriate cable tension. Not enough slack prevents motion and too much can cause misalignment of the transmission cables. This scheme can be thought of as a cable slack regulator, whereby a proportional controller is used to maintain a specified length of cable slack in the cable driven joints. If the patient's thumb is moved by the therapist so as to tighten the cable, then the servo will rotate to loosen the cable. Similarly, if the patient's thumb is moved so as to loosen the cable then the servo will rotate to tension the cable system. The system follows the joint motion imposed by the therapist by maintaining a fixed amount of slack within each joint. A proportional controller regulates the cable slack by monitoring the difference (δ) between the MCP and CMC servo angular positions ($\varphi_{MCP}{}^{o}$ and $\varphi_{CMC}{}^{o}$), as measured by the servo encoders, and the MCP and CMC joint positions (θ_{MCP} and θ_{CMC}), as measured by the joint encoders (eq. 2 and 3).

$$\delta_{MCP} = \varphi_{MCP} - \theta_{MCP}, \tag{2}$$

$$\delta_{CMC} = \varphi_{CMC} - \theta_{CMC}, \tag{3}$$

If δ_{MCP} (or δ_{CMC}) is greater than a small positive threshold (d_1˚) then the therapist has applied a force on the patient's thumb in a manner so as to decreased θ_{MCP} (or θ_{CMC}) and the servo should rotate to decrease φ_{MCP} (or φ_{CMC}). If δ_{MCP} (or δ_{CMC}) is less than a small negative threshold ($-d_1^{\circ}$) then the therapist is applying a force on the patient's thumb in a manner so as to increase θ_{MCP} (or θ_{CMC}) and the servo should rotate to increase φ_{MCP} (or φ_{CMC}) (Fig. 6). After manipulation, the MCP and CMC joint angle trajectories are recorded and saved for later playback within the cyclic control mode.

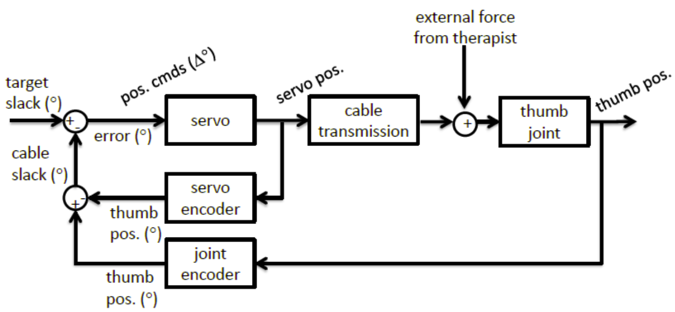

Figure 6. A cable slack regulator with proportional feedback control is used to make the exoskeleton sytem mechanically transparent during the teach & learn mode. A constant amount of slack is maintained on the transmission cable by comparing the servo position to the thumb joint positions. The error signal between the target slack and the actual slack is sent as a delta position command to the servo motors.

3) Cyclic Control Mode

Cyclic control mode allows a pre-set trajectory for the CMC and MCP joints to be repeated a set number of times. The nominal trajectory moves the CMC and MCP joints through their full range of motion. The joints are actuated simultaneously at a speed of slow, medium, or fast as specified by the user until they reach their range of motion limit and then they are actuated in the opposite direction until the other end range of motion is reached. This cycle is then repeated the input number of times based on the user selection. Additional trajectories can be created using teach & learn mode and implemented in cyclic control mode.

4) Wrist Control Mode

Wrist control mode utilizes the bend sensor mounted across the wrist to provide a signal that can modulate the CMC and MCP thumb joint angles. In healthy individuals, as the wrist is moved from flexion to extension, there is a natural synergy called the tenodesis effect that causes finger flexion [23]. Patients with poor grasp control often exploit the tenodesis effect by extending their wrist when they need assistance with finger flexion; thus we believe such a control strategy will be intuitive for them. As the wrist is flexed the servo motors actuate so as to extend the MCP and abduct the CMC. Similarly, if the user extends her or his wrist then the IOTA will actuate to flex the MCP and adduct the CMC. In all cases the CMC and MCP joint are actuated at a constant speed specified by the user until a range of motion limit is reached.

5) Functional Assistance Mode

The functional assistance mode seeks to anticipate the desired motion of the user and then assists with that motion. The target patient population for this system typically has some volitional control of their thumb but lacks the necessary strength or persistent coordination to perform functionally useful tasks. In this scenario, the functional assistance mode will be helpful as it amplifies the volitional motion. Thus, a small initial motion by the user generates a larger response motion. In the functional assistance mode the system continuously monitors the orientation of the patient's thumb. If the patient performs a small weak MCP extension ($\Delta\theta_{MCP}^{\circ}$), greater than a minimum threshold value (d_2°), the servos will actuate the MCP and CMC joints by an amount ($\Delta\theta assist$) proportional to $\Delta\theta_{MCP}$ by a gain factor k (eq 1).

$$\Delta\theta assist = k \cdot \Delta\theta_{MCP},\ \Delta\theta_{MCP} > d_2 \qquad (1)$$

Once the MCP and CMC joints are rotated by an amount $\Delta\theta assist$ they are held there momentarily and then released back into their flexed and adducted poses.

V. Conclusion and Future Work

In the long term, we aim to investigate the efficacy of an at-home hand rehabilitation program based on a portable pediatric robotic system. Towards this end we have developed IOTA, a 2-DOF robotic thumb exoskelton and a compact table top controller box. The specifications for IOTA were based on pediactric anthropometric data so that children aged 7 to 12 could use the device. The control modes for IOTA were designed to span simple specified movements to those that provide intuitive assistance during grasping and object manipulation.

A clinical pilot study is currently being carried out which aims to (i) demonstrate that the IOTA can effectively facilitate a patient's ability to perform a box and block task and a peg task, and (ii) demonstrate the ability to extend standard occupational therapy rehabilitation through a daily home use program.

The IOTA has the potential to provide increased freedom and independence for children with thumb in palm deformity. The device also has the potential to not only assist functionality, but with continued usage may lead to motor memory that will train the child to use the thumb without the device.

Acknowledgment

This work was funded by the Wyss Institute for Biologically Inspired Engineering at Harvard University and the Deborah Munroe Noonan Memorial Research Fund. The authors would like to thank Alessandro Puiatti for his helpful comments during the preparation of the manuscript.

References

[1] L. Jones, "Human hand function." Oxford University Press,, Oxford□;;New York□:, 2006.

[2] M. Yeargin-Allsopp, K. Van Naarden Braun, N. S. Doernberg, R. E. Benedict, R. S. Kirby, and M. S. Durkin, "Prevalence of cerebral palsy in 8-year-old children in three areas of the United States in 2002: a multisite collaboration.," *Pediatrics*, vol. 121, no. 3, pp. 547–54, Mar. 2008.

[3] E. S. Park, E. G. Sim, and D.-W. Rha, “Effect of upper limb deformities on gross motor and upper limb functions in children with spastic cerebral palsy.,” *Research in developmental disabilities*, vol. 32, no. 6, pp. 2389–97, 2011.

[4] D. Damiano, “Activity, activity, activity: rethinking our physical therapy approach to cerebral palsy,” *Physical therapy*, vol. 86, no. 1, 2006.

[5] M. V Johnston, “Plasticity in the developing brain: implications for rehabilitation.,” *Developmental disabilities research reviews*, vol. 15, no. 2, pp. 94–101, Jan. 2009.

[6] L. Dovat, O. Lambercy, R. Gassert, T. Maeder, T. Milner, T. C. Leong, and E. Burdet, “HandCARE: a cable-actuated rehabilitation system to train hand function after stroke.,” *IEEE Transactions on Neural and Rehabilitation Systems Engineering*, vol. 16, no. 6, pp. 582–591, 2008.

[7] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo, and T. Milner, “A haptic knob for rehabilitation of hand function.,” *IEEE transactions on neural systems and rehabilitation engineering□: a publication of the IEEE Engineering in Medicine and Biology Society*, vol. 15, no. 3, pp. 356–66, Sep. 2007.

[8] H. Kawasaki and T. Mouri, “Design and Control of Five-Fingered Haptic Interface Opposite to Human Hand,” *IEEE Transactions on Robotics*, vol. 23, no. 5, pp. 909–918, Oct. 2007.

[9] C. N. Schabowsky, S. B. Godfrey, R. J. Holley, and P. S. Lum, “Development and pilot testing of HEXORR: hand EXOskeleton rehabilitation robot.,” *Journal of neuroengineering and rehabilitation*, vol. 7, p. 36, Jan. 2010.

[10] R. C. V. Loureiro and W. S. Harwin, “Reach & Grasp Therapy: Design and Control of a 9-DOF Robotic Neuro-rehabilitation System,” in *2007 IEEE 10th International Conference on Rehabilitation Robotics*, 2007, pp. 757–763.

[11] M. Turner and D. Gomez, “Preliminary tests of an arm-grounded haptic feedback device in telemanipulation,” *Proc. of the ASME …*, 1998.

[12] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, “The Rutgers Master II-new design force-feedback glove,” *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 2, pp. 256–263, Jun. 2002.

[13] L. Connelly, M. E. Stoykov, Y. Jia, M. L. Toro, R. V Kenyon, and D. G. Kamper, “Use of a pneumatic glove for hand rehabilitation following stroke.,” *Conference proceedings□: ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, vol. 2009, pp. 2434–7, Jan. 2009.

[14] S. B. Godfrey, C. N. Schabowsky, R. J. Holley, and P. S. Lum, “Hand function recovery in chronic stroke with HEXORR robotic training: A case series.,” *Conference proceedings□: ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, vol. 2010, pp. 4485–8, Jan. 2010.

[15] J. Ochoa, Y. J. Dev Narasimhan, and D. G. Kamper, “Development of a portable actuated orthotic glove to facilitate gross extension of the digits for therapeutic training after stroke.,” *Conference Proceedings of the International Conference of IEEE Engineering in Medicine and Biology Society*, vol. 2009, pp. 6918–6921, 2009.

[16] S. E. Fasoli, B. Ladenheim, J. Mast, and H. I. Krebs, “New horizons for robot-assisted therapy in pediatrics.,” *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*, vol. 91, no. 11 Suppl 3, pp. S280–9, Nov. 2012.

[17] M. G. Carlson, G. S. Athwal, and R. A. Bueno, “Treatment of the Wirst and Hand in Cerebral Palsy,” *The Journal of Hand Surgery*, pp. 483–490, 2006.

[18] W. Cooney, M. Lucca, E. Chao, and R. Linscheid, “The kinesiology of the thumb trapeziometacarpal joint,” *J Bone Joint Surg Am*, vol. 63, no. 9, 1981.

[19] R. Yoshida, H. House, and R. Patterson, “Motion and morphology of the thumb metacarpophalangeal joint,” *The Journal of hand …*, vol. 5023, no. 03, pp. 753–757, 2003.

[20] R. Snyder, S. LW, O. CL, R. HM, G. DH, and S. MA, “Anthropometry of Infants, Children, and Youths to Age 18 for Product Safety Design. Report No. UM-HSRI-77-17,” Bethesda, MD, 1977.

[21] L. Stirling, M. Qureshi, D. Bae, B. Snyder, and A. Correia, “Examination of the Torque Required to Passively Palmar Abduct the Thumb CMC Joint in Patients with Hemiplegia and Stroke,” *manuscript in preparation*, 2013.

[22] S. Hoppenfeld and R. Hutton, *Physical examination of the spine and extremities, Volume 798*. Appleton-Century-Crofts, 1976, p. 276.

[23] F.-C. Su, Y. L. Chou, C. S. Yang, G. T. Lin, and K. N. An, “Movement of finger joints induced by synergistic wrist motion.,” *Clinical biomechanics (Bristol, Avon)*, vol. 20, no. 5, pp. 491–7, Jun. 2005.