Towards Applying Pneumatic Gel Muscles to Augment Plantar Flexor Muscle Stretching for Children with Cerebral Palsy

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Figure 1: Our PGM system being used to help a boy with cerebral palsy stretch his left plantar flexor muscle.

ABSTRACT

Many children in the world suffer from cerebral palsy (CP), which is the leading cause of children's disabilities, affecting their body movement and muscle coordination [18]. At present, the rehabilitation training of children with cerebral palsy has long relied on the physical therapist (PT) workforce. Our research wants to empower parents of children suffering from cerebral palsy to engage in simple

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training exercises themselves, supporting the rehabilitation process. We collaborate with physical therapists of a children's hospital to design a system that uses pneumatic artificial muscles (PAMs) to help children with cerebral palsy train their plantar flexor muscles (Figure 1). We present an initial experimental prototype validated with physical therapists and doctors. We also show a feasibility test with patients with informed consent from parents and monitored by the physical therapists.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

Home rehabilitation, children with cerebral palsy, soft exoskeleton, artificial muscles

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1 MOTIVATION

Seventy-three percent of children with cerebral palsy have difficulty walking, and the situation gets worse with age [11, 16, 18, 23]. Early rehabilitation training is the only way to recover and is vital to their future development, preventing walking problems as adults [2, 24].The most crucial rehabilitation session for children with cerebral palsy is physical therapy. The one-to-one physical therapist training, including muscle stretching and other sessions, is very effective yet also time-consuming [10, 13, 15]. Rehabilitation practitioners generally formulate 4-6 family rehabilitation training movements for each child with cerebral palsy [3, 20]. These contents are usually expressed in medical professional terms. Then, the rehabilitation therapists demonstrate each action for the parents of the cerebral palsy child, and the parents usually record these rehabilitation actions by taking photos or videos. So in the next three months, parents would act as rehabilitation therapists and do rehabilitation training for their children with cerebral palsy. When their children with cerebral palsy can achieve the goals set by the therapist before, they return to the hospital for review. Then, the physical therapist will develop a new rehabilitation plan. There are also some effective parents community and support efforts [5, 27, 34]. However, the muscle stretching exercises and rehab plans are quite traditional and the basic processes have not been changed in many years.

There are a couple of efforts using novel therapy approaches, exoskeletons, and other mechanical designs to help the rehabilitation process, yet most of them are rather large, expensive and require a large amount of power/air pressure etc. [7, 27, 28, 30, 31]. There are also a lot of works using lower-limb exoskeletons and artificial muscles for rehabilitation purposes [1, 4, 9, 12, 17, 19, 22, 25, 26, 32].

In our research, we work towards novel rehabilitation solutions for cerebral palsy and want to support the process on several scales in the hospital and at home. Especially, we investigate wearable actuators and soft materials (like the pneumatic gel muscles) as a new, unobtrusive, affordable opportunity for children with cerebral palsy to help them perform rehabilitation training exercises [8, 29]. We hope that our research will allow more children with cerebral palsy to get opportunities for rehabilitation exercises, liberate parents' hands in family rehabilitation scenarios, improve family rehabilitation efficiency, shorten rehabilitation time, and reduce rehabilitation costs. This work is an initial step towards a novel rehabilitation solution, a soft exoskeleton system for children with cerebral palsy applicable in a home setting.

The contributions of this work on cerebral palsy rehabilitation are: (1) we present a novel soft exoskeleton rehabilitation prototype based on a low-pressure type PAM called Pneumatic Gel Muscle (PGM) for children with cerebral palsy, (2) we present an experimental protocol applying the prototype to plantar flexor muscle stretching comparing it to a physical therapist stretch. (3) We present an initial feasibility test with 3 patients (under supervision of 2 doctors and a physical therapist), as well as discussing future improvements and potential issues.

2 APPROACH AND ETHICAL CONSIDERATIONS

Since we are interested in the complexity of cerebral palsy rehabilitation exercises, we conducted ethnography research, including observations of cognitive assessment, cerebral palsy screening, rehabilitation course observation, expert interviews, cerebral palsy rehabilitation-related documents, and review of rehabilitation aids. Before starting the research to inform the design, we went to our partner children's hospitals and observed daily rehabilitation training for three months to insight research opportunities. We observed different rehabilitation courses to understand clinical rehabilitation, focusing on the interaction between cerebral palsy children and rehabilitation experts during rehabilitation training, including the use of equipment, the time of each rehabilitation action, and how to attract the child to complete a certain action.

Our hospital rehabilitation observation found that plantar flexor muscle stretching is essential for most children with cerebral palsy [11, 14]. So we decided first to focus on applying pneumatic gel muscles (PGMs) to rehabilitate the ankle movement. Another difficulty is that when parents recover their children at home, they cannot achieve accurate rehabilitation actions like a therapist. Therefore, the accuracy of rehabilitation training is what we are exploring and solving with PGM equipment. As a background, we described the rehabilitation process from the perspective of multiple rehabilitation experts who make rehabilitation plans for children with cerebral palsy. We have observed the rehabilitation treatment of children with cerebral palsy and analyzed which muscle training is essential to better provide information for designing our artificial muscles' system. A major concern for conducting experiments is not to interfere with the rehabilitation process of the children and to ensure the safety of the children when using our research prototypes. To this end we discussed potential experimental setups with doctors and ethical board members at all institutions involved. Our Ethics proposal containing the experimental design and the PGM system description have been approved by the ethics committees

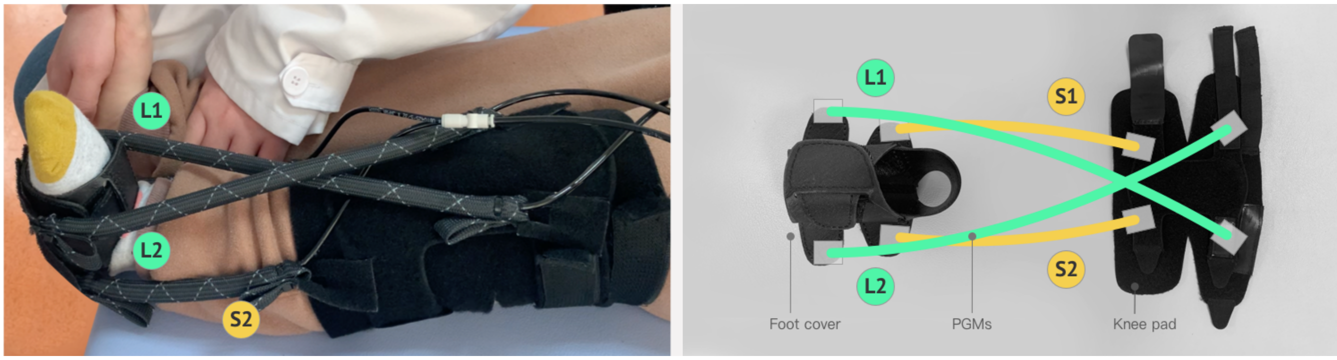

Figure 2: PGM foot cover and Knee pad. "L1" and "L2" are the longer PGMs, "S1" and "S2" are the shorter ones.

from both the partner hospital and university as well as external engineering and medical advisors.

3 PNEUMATIC ARTIFICIAL MUSCLE PROTOTYPE DESIGN

Together with physical therapists, we designed and refined our functional PGM prototype. Before applying it to children, we did several pre-tests on multiple adults, including a physical therapist, as well as demonstrations to the parents. Our system uses four pneumatic gel muscles (PGM) as soft actuators worn by the user on their leg. Total weight of the system excluding the air pressure source is around 400g (including four PGMs of weight 86g).

The PGMs we use can be activated with low air pressure and have been used in related work for soft exoskeletons in training and other rehabilitation research by Ogawa et al., Takashi et al. and others [6, 21, 29, 33]. Each PGM is either actuated or deflated through a dedicated 3/2 solenoid valve, operated in normally-closed configuration. The solenoid valve used in our device is the SYJ312M-SLZD-M3 (SMC) with an operating pressure range of 0-0.7MPa. Our device does not required to use a stationary air compressor, instead we can opt for a NTG mini CO_2 gas cylinder (with a gas volume of 74 grams). The cylinder is attached to a regulator used to maintain an input air pressure of 0.2MPa to the solenoid valves. One charge can work for up to 500 muscle contractions. Our device is controlled via a ESP32 microcontroller. The air pressure to the PGMs can be controlled individually, although in the current setup we activate them together (only stretch an relax state). Therefore, the microcontroller can receive instructions over wifi/bluetooth or USB connection and actuates the corresponding channels to energize or de-energize the solenoid valves. The system also offers a stand-alone mode, in which the stretching programs can be loaded directly into the micro-controller (used in the experimental setup). The program can be started and stopped over a simple button-press.

We tested the prototype under the supervision of the physical therapist together with 3 children (aged 3, 6 and 9). The prototype is functional and can be adjusted to stretch the plantar felxor muscle in a similar fashion as the physcial therapist does.

Four PGMs with two different lengths were used in our experiment. We also designed a special foot cover and a knee pad for fixing the PGMs by Velcro. The function of the two longer PGMs which are crossed with each other is responsible for the stretching, and the two shorter ones are used for safety consideration (2). One side of the longer PGMs is fixed on the knee pad's upper part, and another side is fixed on the upper part of the foot cover. One side of the shorter ones is fixed on the lower part of the knee pad, and another side is fixed on the lower part of the foot cover. We used the CO_2 gas cylinders to actuate the PGMs and maintained the air pressure at max 0.2MPa to ensure the safety of the experiment using over-pressure valves.

4 CONCLUSION AND FUTURE WORK

We designed a lower-limb rehabilitation system for children with cerebral palsy to train their plantar flexor muscles by applying pneumatic artificial muscles. After the initial tests, we will now move forward to conduct a control experiment on children with cerebral palsy, using PGM to imitate the same movement performed by physical therapists and comparing the rehabilitation effect between the physical therapists and PGM. We hope to show that PGM stretching can be an effective alternative for cerebral palsy rehabilitation.

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REFERENCES

[1] Wang Biyuan, Takahashi Nobuhiro, and Koike Hideki. 2020. Sensor Glove Implemented with Artificial Muscle Set for Hand Rehabilitation | Proceedings of the Augmented Humans International Conference. *AHs '20: Proceedings of the Augmented Humans International Conference* (Mar 2020), 1–4. https://doi.org/10.1145/3384657.3384791

[2] Bruno Bonnechère, Bart Jansen, Lubos Omelina, Serge Van Sint Jan, et al. 2016. The use of commercial video games in rehabilitation: a systematic review. *International journal of rehabilitation research* 39, 4 (2016), 277–290.

[3] Hilde Capjon and Ida Torunn Bjørk. 2010. Rehabilitation after multilevel surgery in ambulant spastic children with cerebral palsy: children and parent experiences. *Developmental neurorehabilitation* 13, 3 (2010), 182–191.

[4] Chia-Yu Chen, Yen-Yu Chen, Yi-Ju Chung, and Neng-Hao Yu. 2016. Motion guidance sleeve: Guiding the forearm rotation through external artificial muscles. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 3272–3276.

[5] Johanna Darrah, Mary C Law, Nancy Pollock, Brenda Wilson, Dianne J Russell, Stephen D Walter, Peter Rosenbaum, and Barb Galuppi. 2011. Context therapy: a new intervention approach for children with cerebral palsy. *Developmental Medicine & Child Neurology* 53, 7 (2011), 615–620.

[6] Swagata Das, Yusuke Kishishita, Toshio Tsuji, Cassie Lowell, Kazunori Ogawa, and Yuichi Kurita. 2018. ForceHand glove: a wearable force-feedback glove with pneumatic artificial muscles (PAMs). *IEEE Robotics and Automation Letters* 3, 3 (2018), 2416–2423.

[7] Mariya I Gonkova, Elena M Ilieva, Giorgio Ferriero, and Ivan Chavdarov. 2013. Effect of radial shock wave therapy on muscle spasticity in children with cerebral palsy. *International Journal of Rehabilitation Research* 36, 3 (2013), 284–290.

[8] Takashi Goto, Swagata Das, Yuichi Kurita, and Kai Kunze. 2018. Artificial Motion Guidance: an Intuitive Device based on Pneumatic Gel Muscle (PGM). In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. ACM, 182–184.

[9] Taryn A Harvey, Benjamin C Conner, and Zachary F Lerner. 2021. Does Ankle Exoskeleton Assistance Impair Stability During Walking in Individuals with Cerebral Palsy? *Annals of Biomedical Engineering* 49, 9 (2021), 2522–2532.

[10] Steven J Korzeniewski, Jaime Slaughter, Madeleine Lenski, Peterson Haak, and Nigel Paneth. 2018. The complex aetiology of cerebral palsy. *Nature Reviews Neurology* 14, 9 (2018), 528–543.

[11] Karen W Krigger. 2006. Cerebral palsy: an overview. *American family physician* 73, 1 (2006), 91–100.

[12] Zachary F Lerner, Diane L Damiano, and Thomas C Bulea. 2017. The effects of exoskeleton assisted knee extension on lower-extremity gait kinematics, kinetics, and muscle activity in children with cerebral palsy. *Scientific reports* 7, 1 (2017), 1–12.

[13] Sophie Levitt and Anne Addison. 2018. *Treatment of cerebral palsy and motor delay*. John Wiley & Sons.

[14] Laura Muñoz-Bermejo, Jorge Pérez-Gómez, Fernando Manzano, Daniel Collado-Mateo, Santos Villafaina, and José C Adsuar. 2019. Reliability of isokinetic knee strength measurements in children: A systematic review and meta-analysis. *PLoS One* 14, 12 (2019), e0226274.

[15] Karin B Nelson and Jonas H Ellenberg. 1982. Children who 'outgrew'cerebral palsy. *Pediatrics* 69, 5 (1982), 529–536.

[16] Karin B Nelson and Judith K Grether. 1999. Causes of cerebral palsy. *Current opinion in pediatrics* 11, 6 (1999), 487–491.

[17] Huu Tho Nguyen, Van Chon Trinh, Thanh Danh Le, et al. 2020. An adaptive fast terminal sliding mode controller of exercise-assisted robotic arm for elbow joint rehabilitation featuring pneumatic artificial muscle actuator. In *Actuators*, Vol. 9. Multidisciplinary Digital Publishing Institute, 118.

[18] NIH. 2013. *Cerebral Palsy: Hope Through Research | National Institute of Neurological Disorders and Stroke*. https://www.ninds.nih.gov/Disorders/Patient-Caregiver-Education/Hope-Through-Research/Cerebral-Palsy-Hope-Through-Research

[19] Toshiro Noritsugu and Toshihiro Tanaka. 1997. Application of rubber artificial muscle manipulator as a rehabilitation robot. *IEEE/ASME Transactions on mechatronics* 2, 4 (1997), 259–267.

[20] Pia Ödman, Barbro Krevers, and Birgitta Öberg. 2007. Parents' perceptions of the quality of two intensive training programmes for children with cerebral palsy. *Developmental Medicine & Child Neurology* 49, 2 (2007), 93–100.

[21] Kazunori Ogawa, Chetan Thakur, Tomohiro Ikeda, Toshio Tsuji, and Yuichi Kurita. 2017. Development of a pneumatic artificial muscle driven by low pressure and its application to the unplugged powered suit. *Advanced Robotics* 31, 21 (Nov 2017), 1135–1143. https://doi.org/10.1080/01691864.2017.1392345

[22] Evelyn J Park, Tunc Akbas, Asa Eckert-Erdheim, Lizeth H Sloot, Richard W Nuckols, Dorothy Orzel, Lexine Schumm, Terry D Ellis, Louis N Awad, and Conor J Walsh. 2020. A hinge-free, non-restrictive, lightweight tethered exosuit for knee extension assistance during walking. *IEEE transactions on medical robotics and bionics* 2, 2 (2020), 165–175.

[23] Dilip R Patel, Mekala Neelakantan, Karan Pandher, and Joav Merrick. 2020. Cerebral palsy in children: a clinical overview. *Translational pediatrics* 9, Suppl 1 (2020), S125.

[24] Peter Rosenbaum, Nigel Paneth, Alan Leviton, Murray Goldstein, Martin Bax, Diane Damiano, Bernard Dan, Bo Jacobsson, et al. 2007. A report: the definition and classification of cerebral palsy April 2006. *Dev Med Child Neurol Suppl* 109, suppl 109 (2007), 8–14.

[25] Lizzette J Salmeron, Gladys V Juca, Satesh M Mahadeo, Jiechao Ma, Shuangyue Yu, and Hao Su. 2020. An Untethered Electro-Pneumatic Exosuit for Gait Assistance of People With Foot Drop. In *Frontiers in Biomedical Devices*, Vol. 83549. American Society of Mechanical Engineers, V001T09A009.

[26] Marlene Sandlund, Katarina Dock, Charlotte K Häger, and Eva Lindh Waterworth. 2012. Motion interactive video games in home training for children with cerebral palsy: parents' perceptions. *Disability and rehabilitation* 34, 11 (2012), 925–933.

[27] Manon Maitland Schladen, Yiannis Koumpouros, and Peter Lum. 2021. Factors Mediating Use of Advanced Rehabilitation Technologies in the Home. In *International Conference on Applied Human Factors and Ergonomics*. Springer, 141–147.

[28] N Smania, M Gandolfi, V Marconi, A Calanca, C Geroin, S Piazza, P Bonetti, P Fiorini, A Consentino, C Capelli, et al. 2011. Applicability of a new robotic walking aid in a patient with cerebral palsy. *Eur J Phys Rehabil Med* 147, 2 (2011), 135–40.

[29] Goto Takashi, Das Swagata, Wolf Katrin, Lopes Pedro, Kurita Yuichi, and Kunze Kai. 2020. Accelerating Skill Acquisition of Two-Handed Drumming using Pneumatic Artificial Muscles | Proceedings of the Augmented Humans International Conference. *AHs '20: Proceedings of the Augmented Humans International Conference* (Mar 2020), 1–9. https://doi.org/10.1145/3384657.3384780

[30] Osman Ulkir, Gazi Akgun, and Erkan Kaplanoglu. 2018. Mechanical design and analysis of a pneumatic ankle foot orthosis. In *2018 Electric Electronics, Computer Science, Biomedical Engineerings' Meeting (EBBT)*. IEEE, 1–4.

[31] Pedro Valadão, Harri Piitulainen, Eero A Haapala, Tiina Parviainen, Janne Avela, and Taija Finni. 2021. Exercise intervention protocol in children and young adults with cerebral palsy: the effects of strength, flexibility and gait training on physical performance, neuromuscular mechanisms and cardiometabolic risk factors (EXECP). *BMC Sports Science, Medicine and Rehabilitation* 13, 1 (2021), 1–19.

[32] Yulin Wang and Benny Lo. 2021. A Soft Inflatable Elbow-Assistive Robot for Children with Cerebral Palsy. In *2021 IEEE 17th International Conference on Wearable and Implantable Body Sensor Networks (BSN)(IEEE BSN 2021). Athens, Greece*.

[33] Masataka Yamamoto, Yusuke Kishishita, Koji Shimatani, and Yuichi Kurita. 2019. Development of new soft wearable balance exercise device using pneumatic gel muscles. *Applied Sciences* 9, 15 (2019), 3108.

[34] Maria Zuurmond, David O'Banion, Melissa Gladstone, Sandra Carsamar, Marko Kerac, Marjolein Baltussen, Cally J Tann, Gifty Gyamah Nyante, and Sarah Polack. 2018. Evaluating the impact of a community-based parent training programme for children with cerebral palsy in Ghana. *PloS one* 13, 9 (2018), e0202096.