A Paediatric 3D-Printed Soft Robotic Hand Prosthesis for Children with Upper Limb Loss

Conference Paper · July 2020

DOI: 10.1109/EMBC44109.2020.9176848

Alireza Mohammadi
University of Melbourne

Jim Lavranos

Peter Choong
University of Melbourne

A Paediatric 3D-Printed Soft Robotic Hand Prosthesis for Children with Upper Limb Loss

Alireza Mohammadi[1], Jim Lavranos[2], Ying Tan[1], Peter Choong[3] and Denny Oetomo[1]

***Abstract*— Designing prosthetic hands for children is challenging due to the limited space for electronics and the need of reducing the cost to cater for the constant growth of their hand. In this paper, we proposed an anthropomorphic hand prosthesis for children, using monolithic design and 3D printing of soft/compliant materials. The use of monolithic soft robotic structure provides a lightweight and compact design required in paediatric hand prostheses. The use of 3D printing also allows fabrication of customised products manufactured at low volumes in a cost-effective way which is of interest in prosthetic hand for children. The proposed hand/arm design has a total weight of 230gr including battery and actuation and control systems and a size similar to the biological hand of 5-7 years old children. The hand can provide two grasp types: pinch/tripod and power (cylindrical and spherical) and controlled by using two surface electromyography electrodes. The capability of the proposed hand prosthesis is demonstrated through grasping objects with different shapes and sizes.**

I. INTRODUCTION

Congenital limb loss and upper extremity differences are estimated to occur in approximately 15 individuals per 100,000 live births in the United States alone [1]. Replacement of an upper limb with a functional prosthetic hand has the potential to return some of the limb functionality and improve the ability for independent living of children. According to various research investigations, the earlier children are fitted for a powered prosthesis, the lower is the rate of prosthetic hand rejection in the following years of their life [2], [3]. However, children with limb loss, especially the ones in their early and middle childhood, are underserved with the prosthetic hand options.

The challenges in fitting actuation and control systems in a small size while maintaining the weight at the comfortable level to wear is one of the main reasons for limited options of myoelectric hand prostheses for children. Additionally, constant growth of children requires a frequent replacement of their hand prostheses which is not affordable for many families due to the cost of commercial myoelectric prostheses. Currently, there is only one commercial myoelectric hand prosthesis for children, which is Electrohand 2000 from OttoBock [5]. The Electrohand 2000 has a single grip type for performing tripod grasp (with maximum opening width of 35mm) and it costs about 14,000 USD.

Fig. 1. The proposed anthropomorphic soft robotic prosthetic hand for children

Due to theses limitations, researchers recently have focused on developing hand prostheses for children using technologies that can potentially address these limitations. 3D printed hand prostheses are amongst the most common assistive hands for children [4]. However, these hands are body-powered which requires actuation by other parts of the body, through harness cable fastened to the body of amputees or using functional wrist. A 3D-printed hand prosthesis with myoelectric control has been developed in [5] for children. This hand has one grip type and while it has an anthropomorphic design, the rest position of the hand is closed which makes the appearance unnatural. In [6], a myoelectric prosthetic arm with soft robotic grippers similar to Shape Deposition Manufacturing (SDM) Hand [7] has been developed for children. While the hand does not have an anthropomorphic design (it is a robotic gripper with three fingers) and only provides one grip type, the soft structure of the hand provides a safer mechanism in comparison to the conventional rigid-material systems.

Soft robotic systems and mechanisms have shown great potential in enabling lightweight and compact designs, as well as benefits that can be exploited in the design of hand prostheses, such as safe interaction with humans and

*This project is funded by the Valma Angliss Trust and The University of Melbourne.

[1]Alireza Mohammadi and Denny Oetomo are with the Department of Mechanical Engineering, The University of Melbourne, Parkville, VIC 3040, Australia {alirezam,yingt,doetomo}@unimelb.edu.au

[2]Jim Lavranos is with the Caulfield Hospital, Caulfield, VIC 3162, Australia jim.lavranos@gmail.com

[3]Peter Choong is with the Department of Surgery of University of Melbourne at St Vincent's Hospital, Fitzroy, VIC 3065, Australia pchoong@unimelb.edu.au

environment and adaptation to the shape of the objects [8]. The use of 3D printing in fabrication of soft robotic systems also allows manufacturing of customised products at low volumes in a cost-effective way which is of interest in fabrication of hand prostheses. Combining the advantages of soft robotic systems with capabilities of 3D printing methods resulted in an anthropomorphic soft robotic prosthetic hand (called X-Limb) introduced by authors in [9], [10]. This hand is designed in a monolithic fashion which allows 3D printing of the entire hand with soft material. Monolithic design and manufacturing eliminates a good portion of the need for assembly and the associated inadvertent misalignments. X-Limb is designed for adults and the results of its performance demonstrated its capability in grasping a wide range of objects with a simple control interface.

The objective of this paper is to develop an anthropomorphic soft robotic hand prosthesis based on the design in [9] for pre-schoolers and children in their middle childhood stage (5-7 years of age). The hand design should have an anthropomorphic appearance (Fig. 1), soft structure, multi-grasping functionality for grasping wide range of objects and the size and weight similar to the natural hand and arm of 5-7 years old children.

II. Materials and Methods

A. Design Requirements

For children in their middle childhood, this is the age that they become more independent and their physical, social and mental skills develop quickly [11], therefore, they need a capable and comfortable hand prosthesis for performing their daily activities and also safe interaction with other children and the environment.

The average hand and forearm weight for 5-7 years old children are 120±8 gr and 320±7 gr, respectively [12]. The size of the average hand and forearm size for these children are [13]: elbow-hand length 30.2±3.9 cm, forearm length 16.7±2.3 cm, hand length 12.6±1.5 cm and hand breadth 5.9±0.6 cm. Therefore, the weight and size of the proposed prosthetic hand and forearm should be similar to the biological hand of 5-7 years old children.

In order to comprehensively reflect the functionality and dexterity needed by children with upper-limb loss in design of the hand, it is required to realise these needs in the form of grasp types. In the proposed prosthetic hand design, the objective is to realise the two most commonly used grasps: power grasp (cylindrical and spherical) and pinch/tripod grasp. These two grasps will cover more 70% of the daily activities as reported in [14], [15].

B. Fabrication

The proposed hand is specifically designed and customised for fabrication using 3D printing of soft materials. The fingers are designed using flexure joints and hinges with a monolithic structure similar to [9] as shown in Fig. 2. The morphology of the flexure joints has a significant effect on their stiffness. The relative stiffness of the metacarpo phalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of the fingers specifies the trajectory of the fingertip . In the proposed hand design, stiffness of the finger joints adjusted to provide the required grasp types. In addition, a membrane constructed as part of the monolithic structure of the mechanism to cover the flexure joint (Fig. 2(b)). The membrane encloses the entire finger and its actuation cable. This prevents the cables from being caught on external objects during grasping, enabling more streamlined design similar to human fingers for prosthetic hand applications and potentially water-proof design.

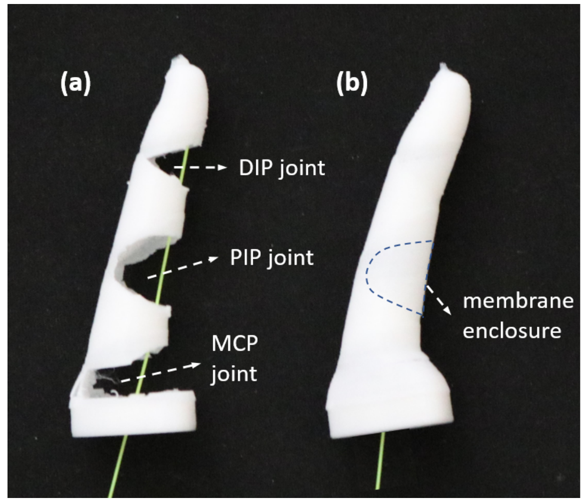

Fig. 2. The 3D printed finger of the proposed soft prosthetic hand: (a) Flexure joints of the finger; (b) Joints with membrane enclosure

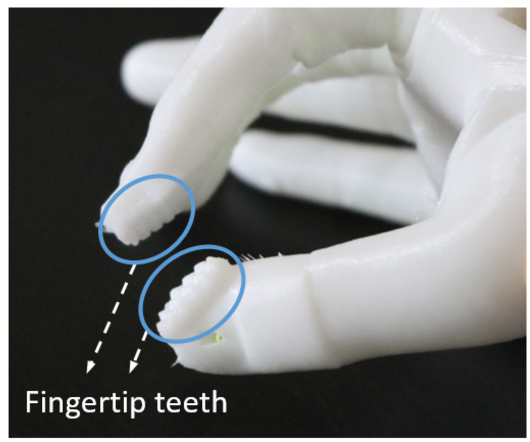

Fig. 3. 3D printed fingertip teeth to provide stable pinch grasp

In order to have a stable pinch grasp while keeping the mechanism simple, a designed-in uneven surface such as teeth can be added to the fingertips of the index and thumb fingers, as shown in Fig. 3. This will increase the contact surface area and provide more robust and stable pinch grasp for tasks such as doing shoe laces.

The 3D printing method that we used is the Fused Deposition Modeling (FDM) technique. The flexible and soft material used for fabrication of the proposed hand is TPU90 (Thermoplastic Polyurethane with Shore Hardness 90A).

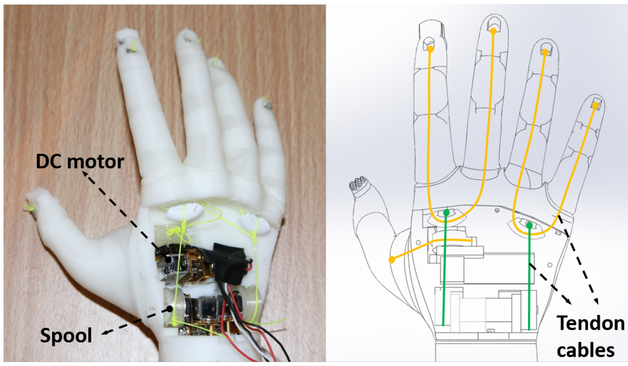

Fig. 4. Actuation and force transfer mechanism

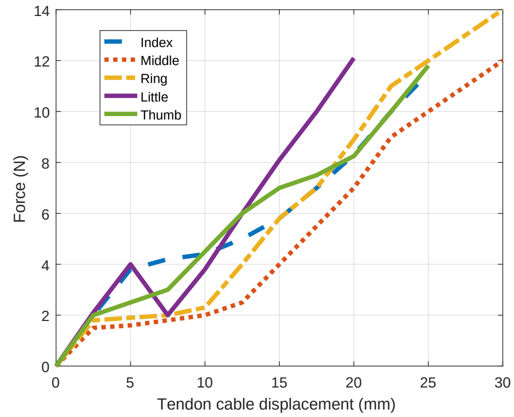

Fig. 5. Force vs cable displacement of different fingers of the proposed hand

C. Actuation and Control Systems

Considering the size requirement for the proposed paediatric hand prosthesis, the overall size of the X-Limb in [9] needs to be reduced by about 30%. As a result, the five degrees of actuation for individual finger movements of the X-Limb cannot be directly used for the paediatric version. In order to realise the two required grasp types (pinch/tripod and power grasps) for the paediatric version, at least three degrees of actuation is required: one for thumb, one for index and middle fingers and one for ring and little fingers.

As shown in Fig. 4, the index and middle fingers are co-actuated with one motor using a cable-driven mechanism and pulleys. With this mechanism, we can reduce the number of required actuators and also ensure that when one of fingers in contact with an object, the other finger will continue moving until both fingers have made contact. Similar mechanism is used for co-actuation of the ring and little fingers.

The actuation system consists of three geared DC micro-motors (6V HPCB Micro Metal Gearmotor, Pololu Inc.), see Fig. 4. Tendon cables are wrapped around small spools and connected to the motors. The diameter of these spools and gearhead ratio of the motors can be adjusted for the desired speed of the finger flexion and grasp force. To this end, we need to find the required displacement of the tendon cables and corresponding force for flexion of the fingers. A single-axis force testing machine with an appropriate load cell is used to find the maximum tendon cable displacement and the corresponding cable force for full flexion of the each finger. The results in Fig. 5 show that maximum tendon cable displacement and required tendon cable force for thumb, index, middle, ring and little fingers are (25mm,12N), (25mm,11N), (30mm,12N), (30mm,14N) and (20mm,12N), respectively. In little finger, this force reduces once the bend is initiated as the membrane buckles and forms a fold. This is due to the relative thickness of the joint thickness and membrane thickness in the little finger in comparison to the other fingers. Since the fingers should move from fully extended to fully flexed position in one revolution of the spool, the diameter of motors spools and minimum required motor torques are:

$$D_{\text{Thumb}} = 25/\pi \approx 8mm, \tau_{\text{Thumb}} = 48Nmm,$$
$$D_{\text{Index/Mid}} = (25+30)/\pi \approx 18mm, \tau_{\text{Index/Mid}} = 207Nmm,$$
$$D_{\text{Ring/Lit}} = (30+20)\pi \approx 16mm, \tau_{\text{Ring/Lit}} = 208Nmm.$$

As a result, the minimum required torque at the output of the motor gearhead is about 0.2Nm. Considering the grasp speed of 1 sec, the speed of the output shaft the motor gearhead should be 60rpm. The actuators of the proposed prosthetic hand are three DC motors with no-load speed of 30,000 rpm and stall torque of 1Nmm with gearhead of 500:1 providing output torque of .4Nm and speed of 60rpm.

All three motors are controlled with an Arduino Micro microcontroller board and an H-bridge motor driver. The motor driver can supply up to almost 3A continuous current to one brushed DC motor at 6V, and it can tolerate peak currents up to 5A per channel for a few seconds. The controller, motor drivers and a 7.4V-1000mAh LiPo battery are embedded in the forearm.

The hand is controlled by using two sEMG (surface electromyography) electrodes (OYMotion Analog EMG Sensor from OYMotion Technologies, Inc.) for opening and closing the hand. To switch between power and pinch/tripod grasps the hold-open signals of EMG (holding the hand open command for certain amount of time) are used as per current practice in the commercial hand prostheses. A combination of user command and position-control has been used for performing different grasping tasks. In each grasp type, the corresponding fingers of the hand will move to the predefined position while receiving the EMG signal from the user. The finger flexion and extension will stop either when user stops sending the EMG signal (stop contracting their muscle) or predefined torque of the motor is achieved.

III. Results and Discussions

The size of the final design is a hand with breadth of 6cm and length of 12cm which satisfies the size requirement. The weight of the proposed paediatric hand prosthesis including the actuators and sensors is 110gr, the weight of the forearm

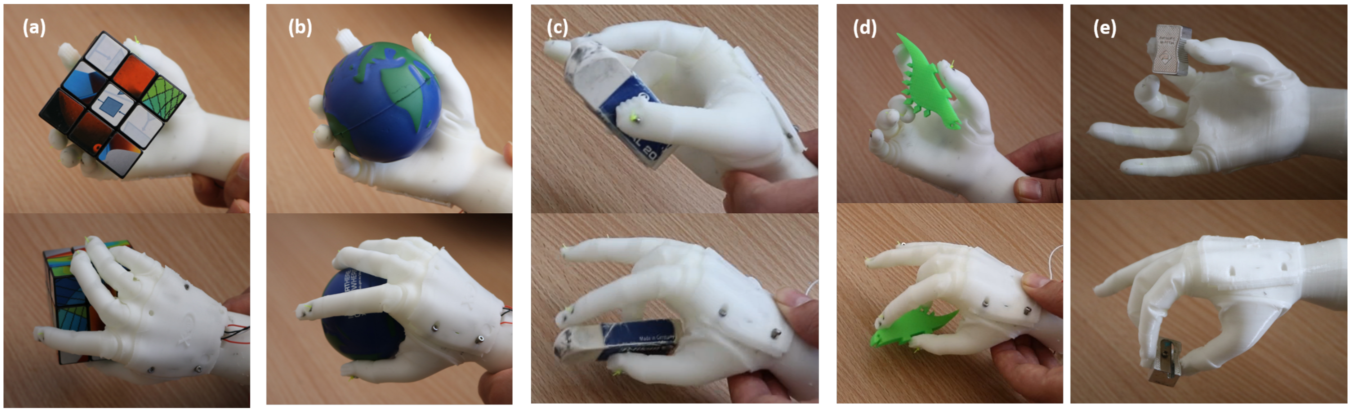

Fig. 6. Grasping examples using the proposed paediatric soft hand prosthesis: (a) Power grasp of a Rubik's cube with 57mm on each side; (b) Power grasp of a stress ball with 65mm diameter; (c) Tripod grasp of an eraser; (d) Tripod grasp of a toy with irregular shape; (e) Pinch grasp of a small sharpener

including the controller and motor drivers is 65gr and the weight of the battery is 55gr. Therefore, the overall weight of the arm is 230gr and this is 30% less than an average forearm of 5-7 years old children. The bill of material cost of the hand is about 70 USD. As shown in Fig. 6, the designed soft robotic prosthetic hand has an anthropomorphic appearance and human-hand-like morphology. The hand grasp speed which is defined as the finger flexion speed or the time required for full flexion of the hand is 1.2 sec.

To demonstrate the capability of the proposed hand prosthesis in using two grasp types, a sample of objects with different shapes and sizes are used: a Rubik's cube with 57mm on each side, a stress ball with 65mm diameter, an eraser, a 3D printed toy with irregular shape and a small pencil sharpener, as shown in Fig. 6 and the accompanied multimedia in YouTube (`https://youtu.be/TOFy_0TReHM`). The results of power grasps in 6 (a) and Fig. 6 (b) show that low stiffness of MCP joints in index and middle fingers can provide enough flexibility to be abducted and wrap around the large Rubik's cube and the stress ball. Fig. 6 (c) and Fig. 6 (d) show that in tripod grasp both index and middle fingers continue to move until both fingers have made the contact with the object, therefore, it is able to grasp the objects with an irregular shape. In the pinch grasp, as shown in Fig. 6 (e), only the index finger is in contact with the object and the fingertip feature of the index and thumb fingers (see Fig. 3) increased the interaction between fingertip and the object for a stable grasp.

IV. Conclusions

In this paper, we proposed design and fabrication of a soft prosthetic hand for children at their mid-childhood. The fabrication process of the proposed hand takes advantages of monolithic design and 3D printing of soft materials. This resulted in a light-weight, low-cost and customizable hand prosthesis for children. The hand performance in grasping objects with various shape and size showed its capability to potentially address the current limitations of the hand prostheses for children. The future work will focus on testing the hand with children with upper-limb loss.

References

[1] C. Behrend, W. Reizner, J. A. Marchessault, and W. C. Hammert, "Update on advances in upper extremity prosthetics," *The Journal of hand surgery*, vol. 36, no. 10, pp. 1711–1717, 2011.

[2] M. Toda, T. Chin, Y. Shibata, and F. Mizobe, "Use of powered prosthesis for children with upper limb deficiency at hyogo rehabilitation center," *PloS One*, vol. 10, no. 6, e0131746, 2015.

[3] M.-A. Kuyper, M. Breedijk, A. Mulders, M. Post, and A. Prevo, "Prosthetic management of children in the netherlands with upper limb deficiencies," *Prosthetics and orthotics international*, vol. 25, no. 3, pp. 228–234, 2001.

[4] M. B. Burn, A. Ta, and G. R. Gogola, "Three-dimensional printing of prosthetic hands for children," *The Journal of hand surgery*, vol. 41, no. 5, pp. e103–e109, 2016.

[5] L. Ccorimanya, R. Watanabe, M. Hassan, Y. Hada, and K. Suzuki, "Design of a myoelectric 3d-printed prosthesis for a child with upper limb congenital amputation," in *IEEE Conference of Engineering in Medicine and Biology Society (EMBC)*, 2019, pp. 5394–5398.

[6] D. De Barrie, R. Margetts, K. Goher *et al.*, "Simpa: Soft-grasp infant myoelectric prosthetic arm," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 699–704, 2020.

[7] A. M. Dollar and R. D. Howe, "The highly adaptive sdm hand: Design and performance evaluation," *The international journal of robotics research*, vol. 29, no. 5, pp. 585–597, 2010.

[8] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Science Robotics*, vol. 1, no. 1, 2016.

[9] A. Mohammadi, J. Lavranos, P. Choong, and D. Oetomo, "X-limb: a soft prosthetic hand with user-friendly interface," in *International Conference on NeuroRehabilitation*. Springer, 2018, pp. 82–86.

[10] A. Mohammadi, J. Lavranos, H. Zhou, R. Mutlu, G. Alici, Y. Tan, P. Choong, and D. Oetomo, "A practical 3d-printed soft robotic prosthetic hand with multi-articulating capabilities," *PLoS ONE*, doi: 10.1371/journal.pone.0232766, 2020.

[11] M. R. Weiss, "Psychological skill development in children and adolescents," *The Sport Psychologist*, vol. 5, no. 4, pp. 335–354, 1991.

[12] R. H. Krishnan, V. Devanandh, A. K. Brahma, and S. Pugazhenthi, "Estimation of mass moment of inertia of human body, when bending forward, for the design of a self-transfer robotic facility," *J. Eng. Sci. Technol*, vol. 11, no. 2, pp. 166–176, 2016.

[13] R. G. Snyder *et al.*, "Anthropometry of infants, children, and youths to age 18 for product safety design. final report." 1977.

[14] C. M. Light, P. H. Chappell, and P. J. Kyberd, "Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: normative data, reliability, and validity," *Archives of physical medicine and rehabilitation*, vol. 83, no. 6, pp. 776–783, 2002.

[15] A. Mohammadi, J. Lavranos, R. Howe, P. Choong, and D. Oetomo, "Grasp specific and user friendly interface design for myoelectric hand prostheses," in *2017 International Conference on Rehabilitation Robotics (ICORR)*, 2017, pp. 1621–1626.