A 3D-printed soft hand exoskeleton with finger abduction assistance

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Min Li
Xi'an Jiaotong University

Yueyan Zhuo
Xi'an Jiaotong University

Bo He
Xi'an Jiaotong University

Ziting Liang
Xi'an Jiaotong University

A 3D-printed soft hand exoskeleton with finger abduction assistance*

Min Li, Yueyan Zhuo, Bo He, Ziting Liang, Guanghua Xu, Jun Xie, Sicong Zhang

***Abstract*— Most existing hand rehabilitation devices provide no assistance to finger abduction motions and do not control finger joints motion separately that impairs the assistance for complex motion. In this paper, we describes the design and fabrication process of a soft material 3D-printed pneumatic hand exoskeleton with finger abduction assistance and separate finger joints' flexion motion control. The performance evaluations showed that the device can carry out several kinds of grasping motion with the combination of finger flexion and abduction. Compared to existing devices, the device provides the assistance to finger abduction motions and controls finger joints motion separately, which provides better assistance to complex hand motions in rehabilitation.**

I. Introduction

The loss of hand motor ability, which may be caused by traffic accidents, industrial accidents or stroke, will inhibit activities of daily living (ADL). Appropriate training can promote the recombination of central nervous system and recover patients' limb function [1]. But in traditional physical therapy, therapists need to conduct one-to-one treatment, which is labor intensive and costly. As a result, patients are difficult to get enough treatment.

Rehabilitation robots, which have been gradually applied in clinical rehabilitation, have proven to be effective to help patients to regain the ability to control the limb motion [2]. For rehabilitation robots, soft devices are safer, lighter and less expensive than rigid devices [3]. Traditional fabrication procedures of soft devices are mainly based on casting and molding, which are complicated. The design of mold requires professional knowledge and the mold may be often reworked because of structure modification. Fortunately, the 3D printing technology opens a new way for fabrication. The 3D printing technology can fabricate complex 3D model in the computer directly. The 3D printing technology can greatly save the time and energy of fabrication [3].

Finger abduction motions are necessary in ADL. Without the finger abduction, we cannot perform complex motions such as cross grasp shown in Figure 1. Only by combining the finger flexion and the abduction can we provide better assistance in rehabilitation and ADL. However, the existing finger rehabilitation robots are mainly concerned with the assistance of the finger flexion motion while there is currently no device assisting the abduction motion between fingers [4]-[7]. What's more, most pneumatic devices cannot control finger joints motion separately, which impairs the assistance for complex motion [8], [9].

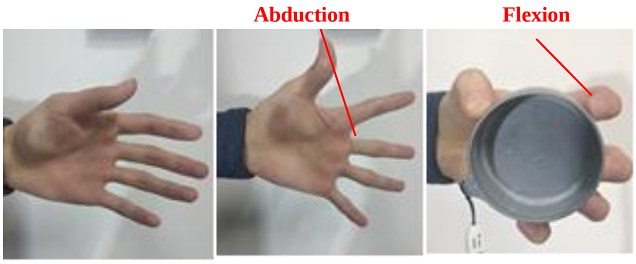

Figure 1. Cross grasp motion sequence of human hand

To provide better assistance to complex hand motions in rehabilitation, this paper presents an exoskeleton design with abduction actuators that provide finger abduction assistance and flexion actuators that are divided into two separately controlled sections. This exoskeleton was fabricated using 3D printing technology. The performance evaluations were conducted to investigate whether the actuators can assist patients to perform the flexion motion and the abduction motion.

II. Design and Fabrication

A. Design requirements

The actuator is designed for continuous passive motion (CPM) rehabilitation training, which has proven to be helpful for patients with dyskinesia caused by nerve damage [10]. The rehabilitation motions are flexion and abduction. To decrease the motion interference, the size of actuators should not exceed the size of fingers, the maximum width and height of actuators are both 20 mm [9].

In order to comfortably support finger flexion and extension motion, the soft actuator needs to generate enough force to perform finger motions following the range of motion of a natural finger. According to the finger structure, the thumb has interphalangeal (IP) joint and metacarpophalangeal (MCP) joint, while the other fingers have distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint, and metacarpophalangeal (MCP) joint. To support the hand flexion, the degree of freedom (DOF) of the thumb is set in the IP joint and the MCP joint; the DOFs of other fingers are set in the MCP joints, the PIP joints and the DIP joints. To support the hand abduction, there are DOFs between fingers.

For the thumb, the motion of IP joint is relatively independent to the motion of the MCP joint, the two are controlled separately in this paper. For other fingers, since there is the constraint relationship between DIP joints and PIP joints of fingers [11], and the MCP joint are relatively independent, so other flexion actuators are respectively controlled with two air tubes, which control the DIP joint and the PIP joint together and control the MCP joint separately.

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M Li (corresponding author), Y Zhuo, B He, Z Ling, G Xu, J Xie, and S Zhang are all with State Key Laboratory for Manufacturing System Engineering, Department of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049 China (e-mail: min.li@mail.xjtu.edu.cn).

Moreover, each abduction actuator is controlled by an air tube. So, the actuator can perform more complicated motions through the combination of flexion and abduction.

According to the information provided by therapists of Xijing Hospital, the adequate flexion range is 2/3 of the maximum flexion range of patients to ensure the patient's motion is within the safe range. For thumb, the flexion range of the MCP joint is 0~33° and the flexion range of the IP joint is 0~53°. For the other fingers, the flexion range of the MCP joint is 0~60°, the flexion range of PIP joint is 0~73° and the flexion range of DIP joint is 0~53°. Between thumb and index finger, the abduction range is 0~50°, while the abduction range between other fingers is 0~25°.

Furthermore, the force generated by actuator should be greater than 7.3N to perform the appropriate movement [9]. The device mounted on hands should not be heavier than 0.500kg for practical requirements [12].

B. Concept and design

The device is composed of the flexion actuators and the abduction actuators. The flexion actuators are located at the back of fingers, which consist of rigid parts on the knuckles and the soft parts on the joints. The rigid parts limit radial expansion and inhibit the linear growth of the actuator bottom to improve bending effect.

The soft parts adopt the single-air cavity structure for flexion deformation. The abduction actuators with soft structure also have asymmetrical cavity structures for abduction deformation. When the input gas fills the actuator cavity, the actuator makes deformations and helps finger perform flexion and abduction motion because of different stiffness. When the pressure is negative, the actuator returns to its original state under the vacuum pressure and restoration of the material. According to the above design requirement, we used SolidWorks to establish 3D models. The flexion actuators and the abduction actuators are shown in Fig. 2.

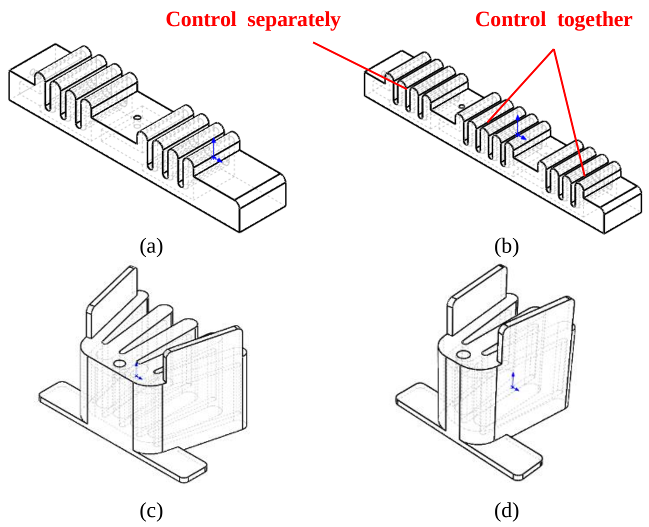


Figure 2. Flexion actuators and abduction actuators: (a) Thumb flexion actuator, (b) Index flexion actuator, (c) Thumb/Index abduction actuator, and (d) The other abduction actuator

C. Fabrication

The actuators were made of the NinjaFlex 85A TPU. A LulzBot TAZ 6 Aerostruder printer with a slice software Cura-LulzBot 3.2.21 was used.

Since the actuator printed with default printing parameters in Cura-LulzBot 3.2.21 cannot fulfill our design requirements, the printing parameters were adjusted as Table I.

When assembling the actuator, the rigid parts of flexion actuators were fixed with the Velcro, the air tubes were glued with flexion actuators and abduction actuators. After the silicone sealant (RTV108) was completely solidified, the actuators were assembled on the gloves. The mass of actuator is 0.172 kg, which is lighter than our target weight 0.500 kg.

TABLE I. PRINTING PARAMETERS OF LULZBOT TAZ 6

Printing parameters	Value
Lay Height	0.1 mm
Initial Lay Height	0.5 mm
Line Width	0.5 mm
Wall Thickness	1.0 mm
Infill Density	100%
Infill Overlap Percentage	20%
Printing Temperature	230 ℃
Initial Printing Temperature	230 ℃
Final Printing Temperature	230 ℃

III. PERFORMANCE EVALUATIONS

Performance evaluations were conducted to validate our design. The human subject is a 23-year-old male with the actuator on his left hand, and performed the angle test, the force test and the rehabilitation motion test. The air source is an air compressor and the electromagnetic proportional valve (IVT0030-2BL) is controlled by Arduino UNO, so that the air supply system can generate the required air pressure.

A. Range of flexion motion evaluation

In this experiment the flexion actuators were pressurized to 0.30 MPa, while the measured pressures were recorded.

A VICON motion capturing system was used to capture the position of infrared marker ball and record the finger motion. The infrared marker ball position in Vicon system is shown in Fig. 3. The maximum flexion angles of the flexion actuator are shown in Table II.

Figure 3. Infrared marker ball position in Vicon system

As the data shown in Table II, with the help of the flexion actuator, the flexion range of the thumb and the pinky finger met the requirements, the flexion range of the index, the middle and the ring finger respectively reached 78.72%, 82.67% and 85.36% of the requirement, which proved that the actuator has potential to help the patient in training.

TABLE II. MAXIMUM FLEXION ANGLE OF FLEXION ACTUATOR

Finger	MCP/°	PIP/°	DIP/°	IP/°	Total/°
Thumb	34.19	NA	NA	54.20	88.39
Index finger	36.29	49.50	61.14	NA	146.94
Middle finger	41.91	78.07	58.43	NA	178.40
Ring finger	50.98	56.96	51.39	NA	159.34
Pinky finger	41.07	82.40	78.56	NA	202.04

B. *Force of flexion motion evaluation*

There was a 40 mm diameter polylactic acid (PLA) cylinder next to the actuator and the actuator was pressurized to 0.30 MPa for grasping the cylinder. The actuator was attached to table by a vise, and the cylinder was pulled up by hoisting mechanism until the actuator released the cylinder.

We used a force sensor (BBTGTJL-1) in the evaluation, and the test system is shown in Fig. 4. Since the index finger actuator has the same structure as the ring finger actuator, we made the evaluation for the two together. In this paper, these experiments were repeated three times. The maximum force of each finger actuator is shown in Table III.

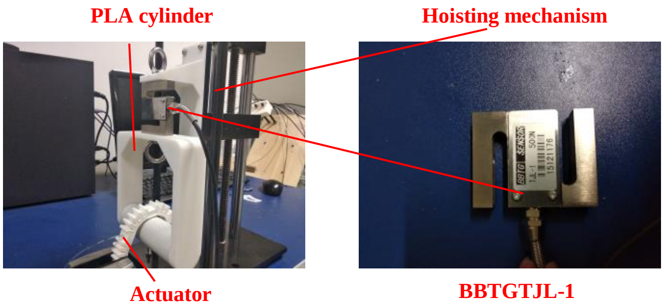


Figure 4. Force test system of flexion actuator

TABLE III. MAXIMUM FORCE OF RIGID AND SOFT INTEGRATION FLEXION ACTUATOR

Finger	Force /N	Friction /N
Thumb	8.93	3.53
Index finger	8.90	3.52
Middle finger	8.90	3.52
Ring finger	8.90	3.52
Pinky finger	9.23	3.65
Total	44.86	17.74

According to the results, the maximum force generated by each flexion actuator was greater than 7.3 N, which is enough force for daily activities. Considering the friction coefficient of the PLA cylinder is 0.395 [13], the friction force generated by the actuators was 17.74 N to help the user to grasp and lift the objects. Since the objects of daily living weigh less than 1.5 kg [14], the actuator is able to provide assistance in daily living.

C. *Range of abduction motion evaluation*

The maximum abduction angle generated by abduction actuators were recorded during the increase of pressure from 0.10 MPa to 0.40 MPa (see Fig. 5).

The measuring instrument used in this evaluation was an electronic protractor. The maximum abduction angles in different motion are shown in Table IV.

Figure 5. Abduction actuator display.

TABLE IV. MAXIMUM ABDUCTION ANGLE IN DIFFERENT MOTION

Motion	Thumb/ Index finger	Index finger/ Middle finger	Middle finger/ Ring finger	Ring finger/ Pinky finger
Initial angle	34.4°	21.3°	20.4°	19.1°
Abduct seperately	69.4°	37.7°	34.6°	34.0°
Abduct together	51.3°	31.5°	27.6°	31.1°
Ideal angle	50.0°	25.0°	25.0°	25.0°

As data shown, the abduction actuator can assist the patient to abduct respectively or together and has the possibility of assisting the patient in rehabilitation.

D. *Force of abduction motion evaluation*

We recorded the force generated by abduction actuators when the actuators were pressurized from 0.10 MPa to 0.40 MPa.

There was a force sensor (Nano17) to measure the force. The force test system is shown in Fig. 6, and the maximum force of abduction actuator in different pressure is shown in Table V.

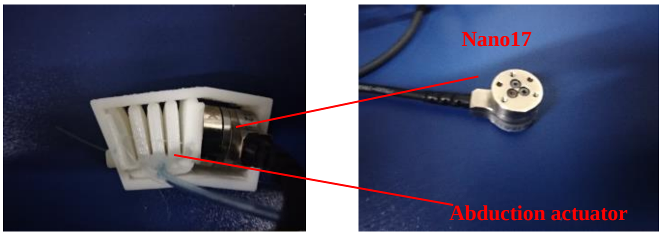


Figure 6. Force test system of abduction actuator

TABLE V. MAXIMUM FORCE OF ABDUCTION ACTUATOR IN DIFFERENT PRESSURE

Pressure	Thumb/Index finger	Others
0.10 MPa	2.60 N	1.20 N
0.20 MPa	5.90 N	4.10 N
0.30 MPa	10.30 N	7.30 N
0.40 MPa	15.00 N	10.70 N

The result showed that the maximum force generated by each abduction actuator is greater than 7.30 N, which can generate sufficient abduction force between the fingers and provide abduction assistance.

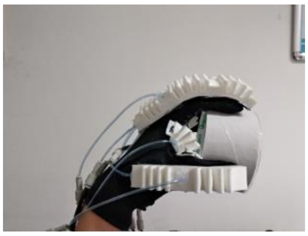
E. Rehabilitation motion evaluation

To evaluate the ability of the device to perform rehabilitation motion and assistance in ADL, tripod grasp, strong grasp, cross grasp and precision pinch were chosen as the target rehabilitation motions. The objects examined for performing rehabilitation motions have different sizes and stiffness characteristics (an eraser, a cup and a tape).

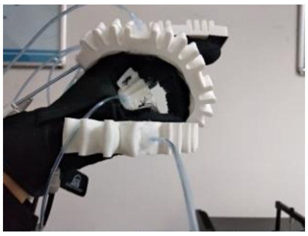
The actuators were pressurized to perform flexion and abduction motions, with the combination of which the exoskeleton can help the human subject to perform complex motions. Moreover, the ability of controlling finger joints motion separately makes the device can carry on the motions need high flexibility. The ability of the robot to perform rehabilitation motions through the control of its internal pressure is demonstrated in Fig. 7.

(a)

(b)



(c)



(d)

Figure 7. Rehabilitation motion: (a) tripod grasp, (b) strong grasp, (c) cross grasp and (d) precision pinch.

IV. CONCLUSION

In this paper, we proposed a pneumatic hand exoskeleton with abduction actuators that provide finger abduction assistance and flexion actuators that are divided into two separately controlled sections to provide better assistance to complex hand motions in rehabilitation. This exoskeleton was fabricated using a 3D printing technology, which made the fabrication procedure simple and can realize customization easily. We test the device’s abilities through the range evaluation, the force evaluation as well as the rehabilitation motion evaluation on healthy subjects, which proves that the device has the potential to be applied in clinical rehabilitation.

In the future, we plan to improve the control system. In addition, the robustness and life cycle will also be investigated through fatigue tests. Moreover, clinical tests on patients will be conducted to further prove the feasibility of our exoskeleton design. To associate the motion intention of the patient with the motion of the robot to promote the recovery of stroke patients for better assistance, it is possible to use the electroencephalography (EEG) or the electromyography (EMG) signal as a control signal to ensure that patients get better rehabilitation training in our future study.

REFERENCES

[1] W. M. Jenkins, and M. M. Merzenich, "Reorganization of neocortical representations after brain injury: a neurophysiological model of the bases of recovery from stroke," Progress in brain research, pp. 249-266: Elsevier, 1987.

[2] E. Carmeli, S. Peleg, G. Bartur, E. Elbo, and J. J. Vatine, “HandTutorTM enhanced hand rehabilitation after stroke—a pilot study,” Physiotherapy research international, vol. 16, no. 4, pp. 191-200, 2011.

[3] P. Aubin, K. Petersen, H. Sallum, C. Walsh, A. Correia, and L. Stirling, “A pediatric robotic thumb exoskeleton for at-home rehabilitation: the isolated orthosis for thumb actuation (IOTA),” International Journal of Intelligent Computing and Cybernetics, vol. 7, no. 3, pp. 233-252, 2014.

[4] A. Chiri, F. Giovacchini, N. Vitiello, E. Cattin, S. Roccella, F. Vecchi, and M. C. Carrozza, "HANDEXOS: Towards an exoskeleton device for the rehabilitation of the hand." pp. 1106-1111.

[5] K. Tong, S. Ho, P. Pang, X. Hu, W. Tam, K. Fung, X. Wei, P. Chen, and M. Chen, "An intention driven hand functions task training robotic system." pp. 3406-3409.

[6] S. Ueki, H. Kawasaki, S. Ito, Y. Nishimoto, M. Abe, T. Aoki, Y. Ishigure, T. Ojika, and T. Mouri, “Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy,” IEEE/ASME Transactions on Mechatronics, vol. 17, no. 1, pp. 136-146, 2012.

[7] 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, 2002.

[8] H. K. Yap, J. H. Lim, F. Nasrallah, J. C. Goh, and R. C. Yeow, "A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness." pp. 4967-4972.

[9] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, “Soft robotic glove for combined assistance and at-home rehabilitation,” Robotics and Autonomous Systems, vol. 73, pp. 135-143, 2015.

[10] X. L. Hu, K.-y. Tong, R. Song, X. J. Zheng, and W. W. Leung, “A comparison between electromyography-driven robot and passive motion device on wrist rehabilitation for chronic stroke,” Neurorehabilitation and Neural Repair, vol. 23, no. 8, pp. 837-846, 2009.

[11] Kexin Xin, “Research on Some Key Technologies of Hand Function Rehabilitation Robot System [D]," Wuhan: Huazhong University of Science and Technology, 2010.

[12] P. Aubin, K. Petersen, H. Sallum, C. Walsh, A. Correia, and L. Stirling, “A pediatric robotic thumb exoskeleton for at-home rehabilitation: the isolated orthosis for thumb actuation (IOTA),” International Journal of Intelligent Computing and Cybernetics, vol. 7, no. 3, pp. 233-252, 2014.

[13] C Zheng, M X Wang, B Liu, et al., “Hydrophilic and mechanical properties of 3D printed polylactic levodopa as alternative material for bone regeneration," Chinese Journal of Tissue Engineering Research, vol. 22, no. 30, pp. 4800-4805.

[14] K. Matheus, and A. M. Dollar, "Benchmarking grasping and manipulation: Properties of the objects of daily living." pp. 5020-5027.