Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 1393-1399

ECCOMAS Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

DEVELOPMENT OF A HAND EXOSKELETON WITH TUNABLE STIFFNESS AND EFFICIENT ENERGY FOR ENHANCEMENT OF GRIP ENDURANCE AND STRENGTH

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Abstract: The wearable hand exoskeletons have been widely used in labor assistance, rehabilitation and assistance for activities of daily living (ADL) in recent decades. However, most of the hand exoskeleton designs are actively actuated, which requires high energy consumption in finger motion, especially in the process of holding a load. In this paper, a novel lower-power-consumption hand exoskeleton which is semi-actively driven by magnetorheological (MR) actuators is proposed and manufactured. The primary feature of the MR actuator is that it has highly controllable stiffness, which facilitates the exoskeleton to perform flexible motion yet high gripping force and endurance. In addition, the MR exoskeleton innovatively uses human hand as an active actuator to restore the hand kinetic energy into a flywheel in the MR actuator and then release the inertia energy to further enhance the user's grip strength without consuming any external power. Experimental results showed that the subject wearing the proposed hand exoskeleton performed approximately 500% enhancement in grip endurance and 41.2% increase in the grip strength.

Key words: Hand exoskeleton, MR actuator, low energy consumption, enhancement of grip strength and endurance.

1 INTRODUCTION

Hand is one of the most important organs that makes our human beings achieve what it is today. As the end effectors for people to interact with the world, hands enable human to complete very complicated tasks such as completing heavy works like gripping, lifting, carrying, etc. and fine works like needle threading and writing. To execute those tasks, gripping is the most fundamental yet the most important function of the hand as it is required in almost every aspect of human daily life. However, due to the limitation of muscle size and strength of the forearm, our hands will be inadequate when required to handle heavy loads or keep gripping for a long time. Current solutions to solving this limitation mainly rely on the

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9911.448489

hand exoskeletons.

Based on the actuator types of current hand exoskeletons, the main actuation designs for them can be divided into four categories [1]: DC-motor-based design [2], servo-motor-based design [3], pneumatic-based design [4], and shape-memory-alloy-based (SMA-based) design [5]. Each actuation type has its own advantages and disadvantages, though, one common challenge faced by all these methods is how to further improve the grip strength and extend the endurance.

To solve the above issues, this paper presents the design of a wearable MR hand exoskeleton. The proposed hand exoskeleton overcomes the defects faced by current four types of actuation mechanism, and more importantly, it is very capable of providing improved grip force and prolonged grip endurance due to the controllability. Besides, the mechanical transmission of the actuator can realize the energy storage from the muscle-driven finger's motion and then generate extra grip strength.

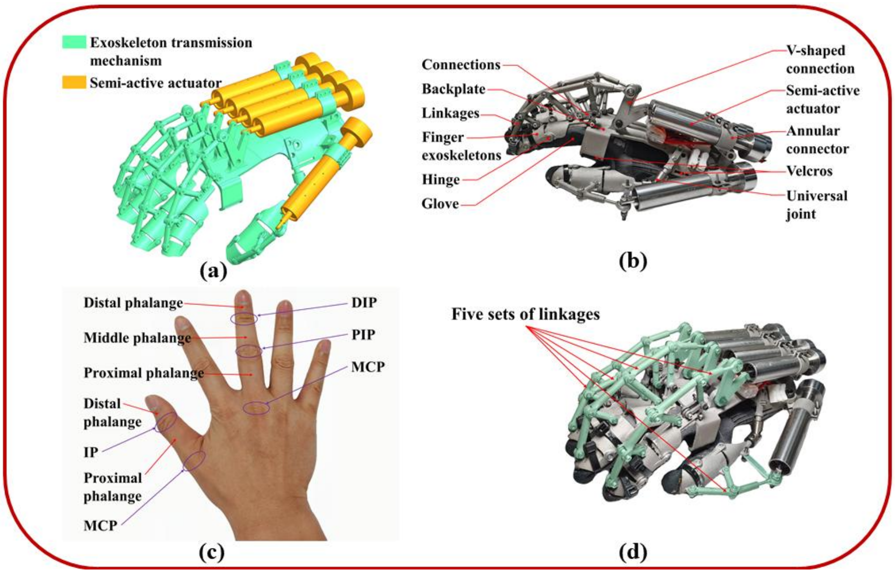

Figure 1: The composition of the MR hand exoskeleton. (a) 3D model of the hand exoskeleton; (b) the prototype of the hand exoskeleton; (c)phalanges and joints of human hand; (d)schematic of the transmission mechanism.

2 DESIGN, PROTOTYPE AND WORKING MECHANISM OF THE MR HAND EXOSKELETON

As shown in Figure 1(a), the hand exoskeleton can be divided into two parts: exoskeleton transmission mechanism, and semi-active actuator. Figure 1(b) shows the detailed structure of the exoskeleton and the transmission mechanism. The exoskeleton includes two parts: the backplate and the finger exoskeleton which consists of five individual finger exoskeletons. Each individual finger exoskeleton is composed of three customized parts which cover distal phalange, middle phalange and proximal phalange, respectively. The details about phalanges and joints of human hand can be seen in Figure 1(c). The adjacent parts of each finger exoskeleton are connected by two hinges which are placed at each side of the joint and exactly accommodate the rotation center of their corresponding finger joint. The backplate is mainly used for fixation of the parts including the finger exoskeletons, linkages and actuators.

In order to keep the fingers and their exoskeletons in synchronous movement, a glove is used as the medium of connection between the exoskeletons and the fingers. The glove is adhered to the finger exoskeletons using modified acrylate adhesive for ease and comfort wearing. To make the backplate fixed closely to the back of the hand, two Velcro® bands are used as fasteners which connect the platform and the user's hand tightly at palm and wrist.

For the transmission mechanism, it consists of five sets of linages (see Figure 1(d)) which are placed on top of each individual finger exoskeleton and move in the same plane where each finger flexes and extends. When the finger exoskeletons flex or extend, the linkages will drive the screw shafts of the actuators to move forward or backward linearly. In the meanwhile, the output force from the actuators will also be transmitted to the fingers through the linkages.

When the user needs to perform the griping operation, the exoskeleton will first be driven to the gripping gesture by hand muscles, and then the actuator will be powered on so that the magnetic circuits can be generated. As a result, the holding torque of the MRG bearings will increase greatly, which restricts the linear motion of the screw shaft. In this situation, the actuators are very stiff, locking the finger exoskeletons and the linkages at the current position, which provides supporting forces to the user's fingers and enables the fingers to hold gripping longer. When the user wants to loosen the object, the actuators will be powered off and the holding torques of the MRG bearings decreases. In this way, the finger exoskeletons and the linkages can move freely so that the user is able to move his/her fingers with dexterity again.

Under the situation where larger grip force is required, the semi-active actuator needs to be powered off. Then the user is required to perform a fast grip on the object, which drives the screw shaft of the actuator to perform a fast linear movement which then is converted to the fast rotation of the nut, the inner sleeve and the flywheel. This transmission process facilitates the actuation energy from the hand muscle transformed to the kinetic energy in the nut, inner sleeve and the flywheel. When the grip operation completes, the linear motion of the screw shaft is forced to stop, while the stored kinetic energy will keep pushing the screw shaft forward, facilitating the finger exoskeleton to generate an extra gripping force.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Experiment of grip endurance

Lifting is a very important activity completed by hands in daily life, which requires the fingers to keep grasping firmly and sometimes for a very long time. However, hand muscles cannot keep lifting at high strength for a long time because of their easy fatigue characteristics. The proposed MR hand exoskeleton can provide assistance to this situation. In this section, controlled trials were conducted to assess seven subjects' maximum endurance time of lifting a load of about 20 kg. Please refer to Figure 3(a) where the subject is not wearing the exoskeleton. The experimental trial was conducted on only one of the subjects with the hand exoskeleton due to the single adaptation of the exoskeleton.

All the subjects were required to first finish the controlled trials. Only one hand was allowed to grip the load, and then the subjects have to stand straight and lift up the load in front of them (as shown in Figure 3(b)) as long as possible without any other contact between their bodies and the load. Each trail would end when the subject failed to keep lifting due to hand fatigue and then the maximum endurance time was recorded. After completing the controlled trials, subject 1 of the seven subjects was chosen to continue the experimental trail. An important condition that adequate rest must be guaranteed between these two trails has to be satisfied. All the requirements were the same as in controlled trials except that the subject wears the MR hand exoskeleton.

The measured maximum endurance time for these trials are presented in Figure 3(c). The average maximum endurance time of the seven subjects without wearing the MR hand exoskeleton is 2.55 minutes, approximately a quarter of that with the exoskeleton. For the same subject, the maximum endurance time under the assistance of the MR hand exoskeleton is 3.88 times of that with bare hand. In theory, the subject who wore the hand exoskeleton could keep the lifting for much longer if the muscular fatigue in arm and back would not happen. These measurement data and comparisons between them demonstrate that this MR hand exoskeleton is very effective on extending the endurance time of the hands when they have to work at high strength for a long time. Therefore, this MR hand exoskeleton will protect the hands from over fatigue or even muscle damage.

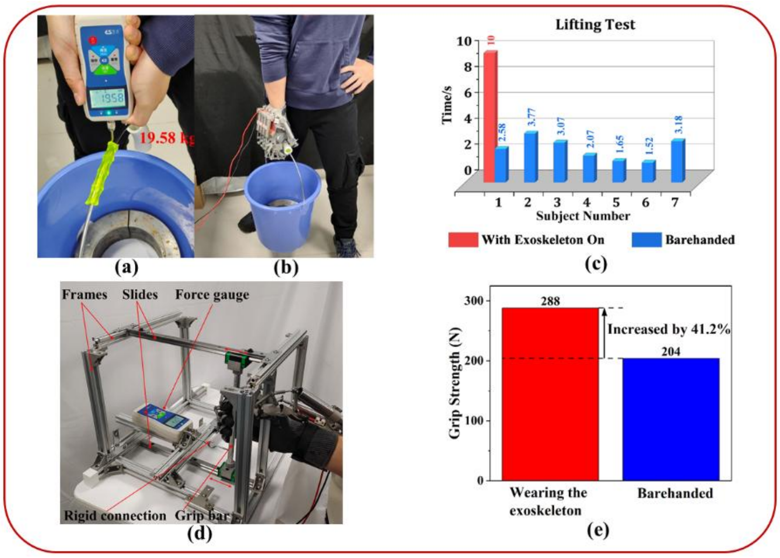

Figure 3: Experiments on the MR hand exoskeleton. (a) weight of the load; (b) the subject lifting a load of about 20 kg with the exoskeleton; (c) endurance times of seven subjects in the lifting test; (d) the framework for tests of grip endurance and grip strength enhancement; (e) comparison of average maximum grip strength for wearing and not wearing the exoskeleton.

Table 1: Maximum grip strength for wearing and not wearing the exoskeleton.

Whether to wear hand exoskeleton	Grip force (N)	Average (N)
Yes	284	288
	316	
	276	
	277	
No	197	204
	213	

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	202	

3.2 Performance on grip strength enhancement

The effect of the proposed MR hand exoskeleton on enhancing the grip strength was tested and measured in this part. The subjects were required to perform fast gripping on the same framework described in Figure 3(d) and the maximum grip strengths were recorded. Four replicates of experiments were conducted for the situations of wearing and not wearing the hand exoskeleton, respectively. This process is conducted without any power provided to the MR hand exoskeleton. The results are presented in Table 1 and Fig.3 (e) with the average maximum grip strength calculated. From Figure 3(e) where the average maximum grip strength is plotted, it can be seen that the average maximum grip strength with the hand exoskeleton has increased by 41.2% compared to that without the exoskeleton. The measured enhancement of the grip strength is 84 N which is about 91% of the theoretical value. The loss may result from the rotary friction of the bearings and the transmission process. These results verify that the muscle-actuation energy can be converted into the extra gripping force on the finger without consuming any external power.

3.3 Comparison of power consumption between the MR hand exoskeleton and other exoskeletons

In the lifting and grip endurance tests, each MR actuator was working at the current of 0.4 A, which is proved to be highly effective in extending the user's grip endurance time. To calculate the power of the hand exoskeleton at the second state, we measured the resistances of the electromagnetic coils using a digital multimeter and the average of the measured resistances was 12.5 Ω. According to the principle of electricity, the power of each MR actuator can be calculated as follows:

$$(\mathbf{0.4\ A})^{2} \times \mathbf{12.5\ \Omega} \quad \mathbf{2\ w}$$

where P_0 is the power of each MR actuator. Since 5 MR actuators were used for actuation of the five fingers, the total power of the MR hand exoskeleton is 10 watts. Besides, we made a comparison of power consumption and the assisted force between the actuators on the MR hand exoskeleton and other exoskeleton actuators, and the result can be seen in Table 2. Obviously, the MR hand exoskeleton is highly energy efficient but the assisted force of the MR actuator is much higher than other exoskeletons.

Table 2: Comparison of power consumption and force generation between the actuators of the MR hand

exoskeleton and other exoskeletons.

Actuator Type	Power Consumption	Maximum Force Output
MR actuator	2 w	over 400 N
SMA actuator [6]	14.5 w	53.4 N
Linear actuator [7]	3.3 w	50 N

4 CONCLUSION

This paper successfully designs and manufactures a novel semi-actuated hand exoskeleton. Owing to the highly-tunable-stiffness property, the user can achieve great improvement in grip endurance at high stiffness, while remaining finger dexterity at low stiffness. Furthermore, the actuator is designed to be high in rotary inertia and can store the energy of finger motion as the rotation energy of the flywheel; then the inertia energy can be released to enhance the user's grip strength. The experimental results show that the stiffness of the actuator can be tuned by 563% when changing the current in the electromagnetic coil, which proves that the actuator has excellent performance in keeping large holding capability while maintaining its flexibility during motions. A dynamic test on the MR actuator shows that the actuator can generate an inertia force of 132 N when the speed of the screw shaft is 80 mm/s. The performance of the hand exoskeleton is also tested. The subject wearing the exoskeleton showed great enhancement in grip endurance which is up to 200 seconds while the endurance of the one who is not wearing the exoskeleton is only about 40 seconds. The subject's grip strength achieved 288 N grip force on average with the exoskeleton on, which increased by 41.2% compared with the one without wearing the exoskeleton.

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