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Jointless Structure and Under-Actuation Mechanism for Compact Hand Exoskeleton

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Abstract— **It is important for a wearable robot to be compact and sufficiently light for use as an assistive device. Since human fingers are arranged in a row in dense space, the concept of traditional wearable robots using a rigid frame and a pin joint result in size and complexity problems. A structure without a conventional pin joint, called a jointless structure, has the potential to be used as a wearable robotic hand because the human skeleton and joint can replace the robot's conventional structure. Another way to reduce the weight of the system is to use under-actuation. Under-actuation enables adaptive grasping with less number of actuators for robotic hands. Differential mechanisms are widely used for multi-finger under-actuation; however, they require additional working space. We propose a design with a jointless structure and a novel under-actuation mechanism to reduce the size and weight of a hand exoskeleton. Using these concepts, we developed a prototype that weighs only 80 grams. To evaluate the prototype, fingertip force and blocked force are measured. Fingertip force is the force that can be applied by the finger of the hand exoskeleton on the object surface. The fingertip force is about 18 N when actuated by a tension force of 35 N from the motor. 18 N is sufficient for simple pinch motion in daily activities. Another factor related to performance of the under-actuation mechanism is blocked force, which is a force required to stop one finger while the other finger keeps on moving. It is measured to be 0.5 N, which is sufficiently small. With these experiments, the feasibility of the new hand exoskeleton has been shown.**

Keywords-component; assistive deivice, exoskeleton, under-actuation, hand, jointless structure

I. INTRODUCTION

Many wearable robots designed to help paralytic patients have been developed in recent years. They can be divided into two classes: robots for rehabilitation and robots to assist in daily tasks. Rehabilitation therapy requires considerable repeated labor, which robotic technology can reduce. Several studies have shown that rehabilitation using conventional robots gives better results compared with the results of therapy by therapists [1], [2]. Wearable robots or exoskeleton devices for rehabilitation have also been developed [3]-[5]. These devices can help patients recover motor function by exercising the impaired body part. However, many patients still have disabilities even after completing their rehabilitation therapies. These patients need an assistive device to overcome the disabilities. Wearable robots have been developed to assist in daily tasks [6], [7].

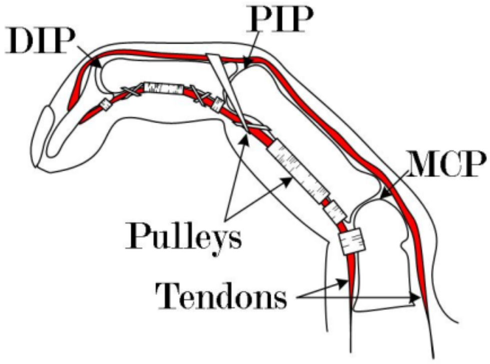

Fig. 1. Schematic of human finger anatomy.

The main causes of physical disability are spinal cord injuries (SCIs) and stroke. The number of people who suffer a stroke with neurological impairment has been estimated to be 3 million in the U.S., and approximately 550,000 new cases occur each year. The number of people who suffer SCIs in the U.S. has been estimated to be 262,000 in 2009, and approximately 12,000 new cases occur every year. The use of the hands is essential when interacting with environment to grasp and manipulate objects. Around 80% of stroke survivors have paresis in their arms and hands [8]. In SCI patients, around 55% exhibit tetraplegia that includes hand paralysis [9].

Many previous researchers have attempted to assist such patients with wearable robotic hands. Several wearable robotic hands have been developed to assist in rehabilitation [10], [11] or daily life motions [12], [13] for these patients. Most wearable robotic hands are composed of conventional pin joints and rigid frames to support the patients' hands and to transmit actuation forces. Additionally, the conventional pin joint structure of wearable robotic hands is convenient for tracking the motion of the fingers, and can prevent unwanted motions such as hyperextension and adduction-abduction. However, the problem with the pin joint structure is its size and complexity, which arises for several unavoidable reasons. This will be explained in more detail in Section 2.

Compact size and light weight are important for a wearable robot to be used widely as an assistive device. To make a

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wearable robotic hand compact, the structure of the transmission should be small. Thus, a wearable robotic hand without joints is desirable. As shown in Fig. 1, a human finger contains a skeleton and joints actuated by tendons. Wearable robots can use the human skeletal structure as a rigid frame combined with the joint structure of conventional robots. If an artificial tendon structure can be implemented on the human hand, a wearable robotic hand with a human hand can perform a grasp. We developed a prototype using gloves and wires; our design was inspired by the human tendon mechanism.

By reducing the number of actuators, the entire wearable robot structure can be made smaller. In particular, for a robotic hand design, an under-actuation mechanism is required since the hand has over 20 degrees of freedom (DOFs). Although a small number of actuators is used, the fingers should adapt to the surface of objects by the under actuation mechanism, which produces a stable grasp. There are two different types of passive adaptation by under-actuation when a robotic hand grasps objects. The first is under-actuation of one finger, and the second is under-actuation over more than two fingers. When only one finger is under-actuated, the finger can adapt to a two-dimensional (2-D) curved surface such as a cylinder, whereas multi-finger under-actuation can adapt to a three-dimensional (3-D) curved surface such as a sphere. Sphere-shaped surfaces frequently appear in common objects such as bulbs, wine glasses, and knobs.

The under-actuation mechanism is generally used in the robotic hand field. Some robotic hands use only one-finger under-actuation [14], [15]. For multi-finger under-actuation, a robotic hand generally uses a differential mechanism. Kamikawa *et al.* [16] proposed a differential mechanism using a linkage, and Dollar *et al.* [17] developed an under-actuated prosthetic hand using a multiple pulley.

The one-finger under-actuation mechanism is used often in the field of wearable robotic hands [12], [18], [19]. However, multi-finger under-actuation has not yet been applied to a wearable robotic hand. For a wearable robotic hand, all structures of the under-actuation mechanism must be located outside the wearable robot because the human structure is located inside, whereas a conventional robot transmission can be placed in the interior. In addition, differential mechanisms generally require additional working space for the transmission. Therefore, it is difficult to implement an existing multi-finger under-actuation mechanism in a wearable robotic hand without an increase in overall size. We propose a mechanism that does not require additional working space. The details of the mechanism are described in Section 2.

We made a prototype using two novel concepts that result in small size and light weight, and we evaluated the concepts using simulation and experimental data. The rest of the paper is organized as follows. A jointless structure and under-actuation design is described in Section 2. We report the results of force measurements in Section 3. Our conclusions are given in Section 4.

II. Design Concept and Prototype

In this section, we present two main design concepts of our hand exoskeleton. One is jointless structure, and another is under-actuation mechanism for adaptive grasping.

A. *Jointless wearable robotic hand design*

With a jointless design concept, the problems from conventional pin joint structures can be avoided. The problems of a conventional pin joint wearable robot for hands are as follows. First, each finger is located close to the other fingers. Since the frame and pin joint structures can interfere with nearby fingers, the structures should not be located on the side, near the other fingers (see Fig. 2(a)). Therefore, many wearable robotic hands have frame and joint structures on the back side of the hand. Generally, it is hard to make the rotational axis of the structure coaxial with that of the human finger joint. To match the two axes, many wearable robotic hands employ a linkage (e.g. double parallelograms) or rack-and-pinion mechanisms (see Fig. 2(b)) [10]-[12], [19]. Second, the human finger joint's center of rotation is not fixed while the fingers move. In contrast, a conventional pin joint is generally fixed. Therefore, a designer should consider the change of the human finger joint axis for comfort and wearability, and to prevent damage to the fingers. These problems make it difficult to design a wearable robotic hand hard that is small and simple.

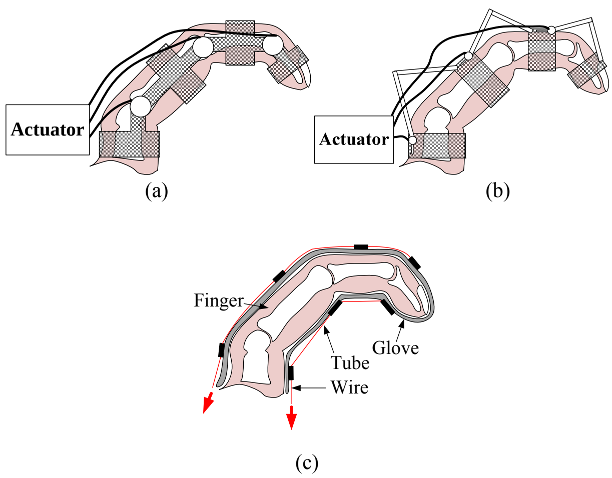


Fig. 2. Design concepts of wearable robotic hand: (a),(b) conventional joint design, and (c) jointless design.

For compactness, the human finger structure is considered in our mechanism. As shown in Fig. 1, human fingers consist of bones, joints, and connective ligament tissue that are actuated by muscles and tendons. A tendon connects the muscles and finger bone, passing through an annular pulley structure. This structure is a kind of tunnel that makes a path for the tendon. There are three joints in each finger; these are actuated directly, or by muscles through tendons. Most of the actuation force is transmitted through a flexor digitorum profundus tendon when simple tip pinch, pulp pinch, and grasp motions are performed [20]. We use a tendon drive mechanism that actuates all three joints using a single flexion wire. This approach was inspired by flexor digitorum profundus tendons that perform simple grasp and pinch motions. As shown in Fig. 2(c), the proposed wearable robot design uses two wires as tendons for extension and flexion. The tubes attached to the glove play the role of the human anular pulley structures that transmit tendon forces to the bone and keep the tendon from deviating from its route. Because the user is able to easily wear the glove, the glove is used as a base for the attachment of the actuation wire. The main issue of removing the frames

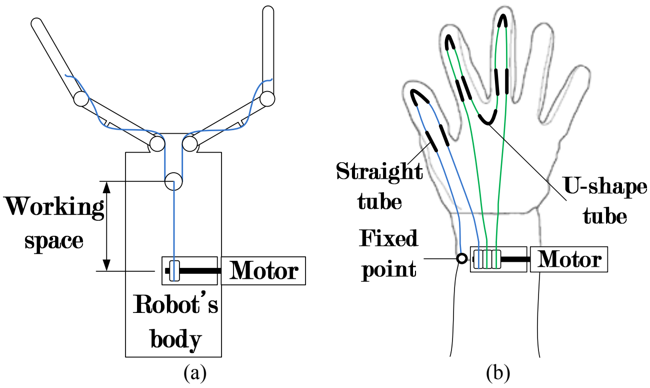


Fig. 3. Schematics of under-actuation mechanism over multi-fingers: (a) differential mechanism used in robotic hand, and (b) proposed mechanism.

is that the human joint has to sustain the tension forces by the motor, but unlike the exoskeletons for upper and lower body, hand exoskeletons require small forces such that the human hand joints can sustain the direct external forces from the motor.

B. Differential mechanism for multi-finger under-actuation

Robotic hands that are under-actuated for only one finger cannot adapt to the 3-D surface of an object if they use only one actuator. Therefore, each finger should be actuated respectively to adapt to spherically-shaped objects. In a robotic hand, a differential mechanism is used for multi-finger under-actuation for better adaptation.

Fig. 3(a) shows an example of a differential mechanism used in a robotic hand [17]. It consists of a moving pulley and wire. The length of the flexion wire is constant and the ends of the wire are fixed at the fingertips. The wire is pulled at the middle point to flex the finger. Because the moving pulley is used to pull the wire, the pulled stroke and the tension of the wire can be distributed to both fingers. However, to pull the moving pulley, a large working space is required. The working space is generally located inside of the body of the robot to simplify the exterior. In the case of a wearable robot, the working space of the moving pulley must be located outside of the robot, since the human body is located inside the robot.

To minimize the working space of the pulley, we propose a novel structure for a differential mechanism that does not need additional working space. The structure consists of tubes and wire. The core element in the differential mechanism shown in Fig. 3(a) is the moving pulley, which pulls the wire and changes its direction without restricting the movement of the

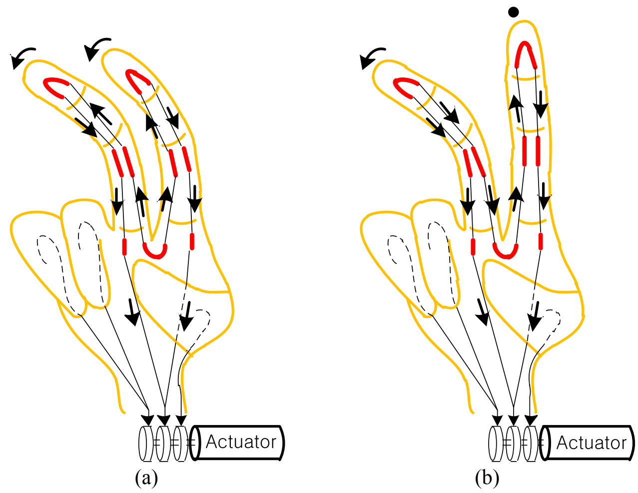


Fig. 4. Movement of the wire in the proposed mechanism: (a) two fingers move identically, and (b) the index finger is fixed while the middle finger

wire. In our mechanism, the U-shaped tube replaces the pulley since the pulley can interfere with the grasp by its movement and thickness.

A conceptual schematic diagram of the proposed mechanism is shown in Fig. 3(b). Three U-shaped tubes are placed on the index, middle fingertip, and between the fingers, respectively. Two straight tubes are attached to each proximal phalange in parallel to make a path for the wire.

In our differential mechanism, the end points of the wire are fixed at the spooler. To flex the fingers, the motor spools the wire and the total length of the wire is decreased. The shortened length and the tension of the wire can be distributed to both fingers because the path between the wires, consisting of tubes, does not restrict the wire.

In each mechanism, the total amount of finger flexion depends on the pulled length of the moving pulley and shortens the length of the flexion wire. The reaction with the environment determines the proportion of the amount of flexion, thereby enabling passive adaptation.

Fig. 4(a) and (b) show the movement of our mechanism according to the environment: (a) shows the case in which two fingers move at same rate, and (b) shows the case in which the index finger is fixed by the environment as the middle finger is flexed. To actuate more fingers together, a similar configuration can be used over more fingers. The differential mechanism was not applied to the thumb in our design.

The proposed mechanism replaces bulky differential mechanism with simple tubes attached on the surface of the hand; this approach reduces the overall system size drastically. However, the length of wire that slides on the tube surface is long, path is curved, and the wire slides on the edges of the tubes as shown in Fig. 4(a) and (b). Therefore the friction is much larger than the conventional differential mechanisms. We measure fingertip forces to show that despite the increased friction, enough fingertip forces are generated.

C. Prototype

A prototype of the wearable robotic hand was built using the proposed jointless concept and the differential mechanism. The prototype drives only the index finger, the middle finger, and the thumb. Only the index and middle fingers were connected to the differential mechanism.

This prototype uses a glove for a base to which wires were attached. The flexion wires were attached to a single actuator to flex the fingers, and the extension wires were attached to linear springs to generate extension force. Ni-Ti alloy 200 μm in diameter was used as the actuation wire. The glove was tested on the hands of healthy subjects. Stainless steel tubes with a diameter of 500 μm were attached to the distal, proximal phalanges, and palm to make paths for the wires. Instead of attaching a tube to the middle phalanges, tubes on the distal and proximal phalanges were attached close to the joints connected to the middle phalanges to prevent the tubes from interfering with motion when the fingers are flexed.

As shown in Fig. 5, on the ventral side of the hand, flexion wires were connected to the actuator on the wrist. On the dorsal side, extension tendons were connected with a spring on the wrist to extend the fingers. A Faulhaber 1226 006B BLDC motor with a 12/4 (256:1) gear head was used to generate a torque of 450 mNm. The spooler, which has a diameter of 10 mm, was connected to the motor to actuate the tendons. The maximum force that motor can generate is 60 N, which can generate enough fingertip force to do ADL(activity of daily living) as we show it in next section. The maximum speed the wire can be spooled is 81mm/sec. With this rate, the finger is fully flexed within 1 second. The motor was controlled using a CompactRIO system (NI cRio-9014) with LabVIEW 9.0 software (National Instruments Corporation).

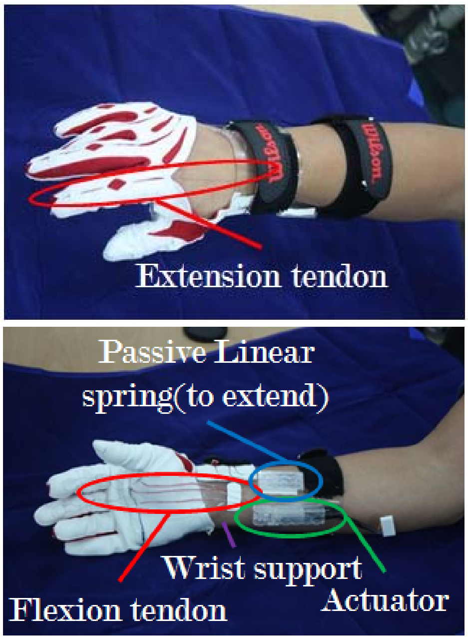


Fig. 5. Prototype of wearable robotic hand.

III. Fingertip Force Measurement

The fingertip force was measured to show that despite the friction of the tendons, the mechanism produces enough forces to be used as a hand exoskeleton. In this section the measurement system is introduced and the results are presented.

A. Fingertip force measurement system

To measure the fingertip force of the index and middle finger, an experiment was set up as shown in Fig. 6. Two load cells were used for the force measurement; one recorded the fingertip force and the other recorded the tension in the flex wire. According to the direction of the fingertip force, a load cell to measure the fingertip force was installed at an angle of $\theta = 50°$. The position of the load cell was 47 mm vertically and 40 mm horizontally from the center of the MCP joint. For accurate measurement, the load cell, which measured the wire tension, was placed on a linear guide and pulled by a servo-motor. To evaluate the proposed wearable robot design with multi-finger under-actuation, the measurement was conducted for two different designs called design 1 and design 2 (Fig. 7).

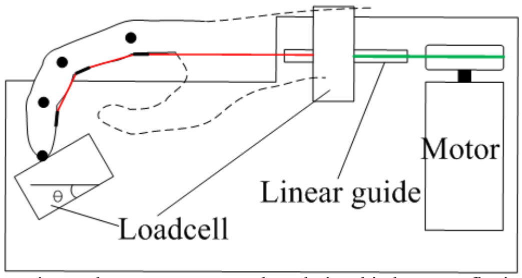
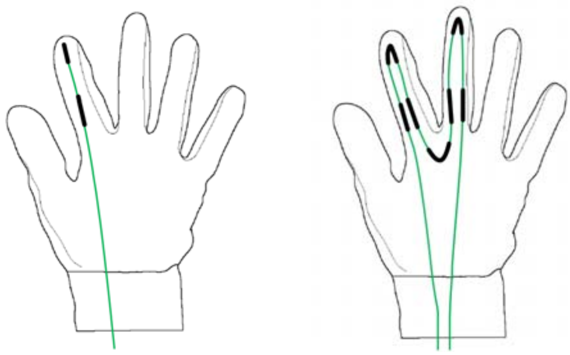


Fig. 6. Experimental setup to measure the relationship between flexion tension and fingertip force.



(a) (b)

Fig. 7. Two designs used in the experiment: (a) design 1 and (b) design 2.

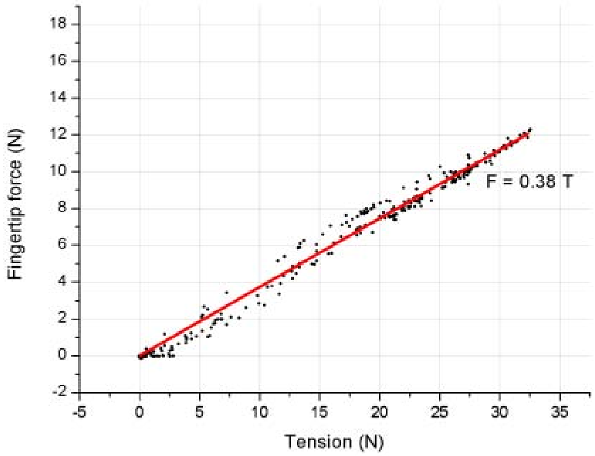
B. Fingertip force

The fingertip force was measured while the flexion wire was actuated. Because the wire breaks at a tension of 40 N, the flexion tension applied was smaller than 35 N in the experiment.

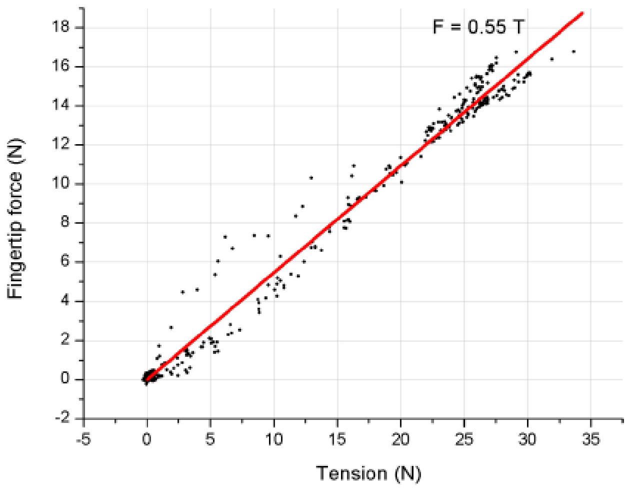
Fig. 8(a) shows the fingertip force of design 1 and Fig. 8(b) shows that of design 2. The force in design 1 was larger than that in design 2 since the flexion stroke in design 2 was twice as long. The fingertip force should be twice of design 1 without friction effect. However, due to the effect of the friction force, the fingertip force in design 2 decreased by about 75% compared to design 1.

Because the jointless structure cannot support the axial and shear forces applied to the finger joints, large flexion wire tension can damage the human finger. Generally, the tension of human's tendon, which is main source of the axial and shear force, reaches two or three times that of the fingertip force when performing a general pinch or grasp [20]. Compared to the tension of a human tendon, the wire force level, which is below two times of fingertip force in the case of design 2, is acceptable for people without disease in the joint such as arthritis.

The fingertip force of design 2 exceeded 18 N. This amount of fingertip force is enough to perform daily tasks. Smaby *et al*. [21] measured the pinch force while performing several daily tasks (opening and closing zippers; inserting and removing a plug, a key, and an ATM card; using a fork; and using a remote control button). In their results, most tasks required less than 10.5 N except inserting and removing a plug (about 30 N).



(a)



(b)

Fig. 8. Relationship between flexion wire tension and fingertip force. (experimental result) (a) design 1 (b) design 2.

C. *Blocked fingertip force*

When the index finger moves and the middle finger is blocked while performing the grasp motion, a blocking force is generated at middle finger's fingertip because of flexion wire tension caused by joint stiffness of the index finger and friction force at the tubes. In this case, the flexion wire was actuated as shown in Fig. 4(b). For better adaptation performance, the blocked force should be small; this maintains the object's static condition until all fingers contact the surface of the object. The red line in Fig. 9 shows the measured blocked force with flexion wire tension. Because of the inertial force of the index finger and stiction, the tension in the flexion wire increased rapidly at first up to 0.5 s. After 0.5 s, the tension was maintained at about 3 N and the blocked force was below 0.5 N. The blocked force was comparatively small considering that the required force to push the remote control button was about 1 N [21].

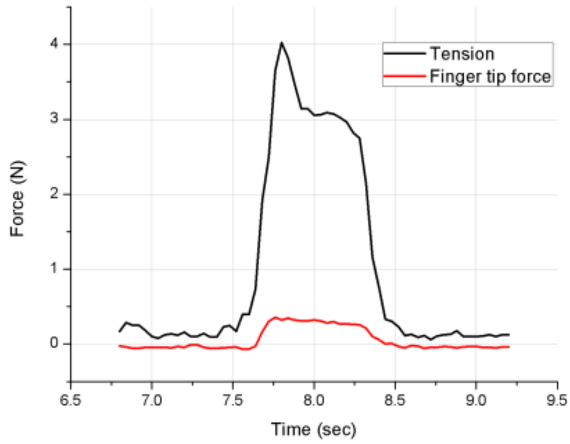


Fig. 9. Blocking force.

IV. CONCLUSION

We proposed a novel concept for a hand exoskeleton with under-actuation mechanism. The proposed design is a jointless structure with a novel differential mechanism. The structure is suitable for use in a simple and compact wearable robotic hand.

The relationship between fingertip force and flexion wire tension was derived experimentally. This relationship can be used to control the fingertip force of the wearable robotic hand with tension sensing. We proved by experiment that the prototype could generate enough fingertip force to complete general daily tasks. As shown by the results, the tension of the wire was less than the general tension of the human tendon while applying a pinch grip, which means that only a small force was applied to the human finger joints. When the actuation was performed with one finger blocked, the tension and the blocked force was small enough to adapt to a common object.

The 200 μm NiTi alloy wire used in our prototypes will break when tension above 40 N is applied. After several uses, a kink appeared in the wire since the concentrated force was applied to the wire at the tube edge. Therefore, the wire should be changed to a material with a small friction coefficient, a large yield strength, and a small Young's modulus for better performance and durability.

During the experiment, loosening of the glove occurred. Because this can change the expected relationship between the fingertip force and the wire tension, it should be eliminated, or estimated by making a proper model. To make a proper finger dynamic model to estimate trajectories and fingertip forces, the joint stiffnesses of the human body must be measured, especially in the case of stroke patients who have much stiffer joints. For stroke patients, finger extension is much harder than flexion [22]. In future research, this extension must be considered. Although there are few issues with the design, the proposed design concept has a potential to reduce the size and weight of hand exoskeletons which is an important factor for a wearable robots to be used widely.

REFERENCES

[1] C.D. Takahashi, L. Der-Yeghiaian, V. Le, R.R. Motiwala, and S.C. Cramer, "Robot-based hand motor therapy after stroke," *Brain*, vol. 131, pp. 425-437, Feb. 2008.

[2] D.J. Reinkensmeyer, J.L. Emken, and S.C. Cramer, "ROBOTICS, MOTOR LEARNING, AND NEUROLOGIC RECOVERY," *Annual Review of Biomedical Engineering*, vol. 6, 2004, pp. 497-525.

[3] K. Westlake and C. Patten, "Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke," *Journal of NeuroEngineering and Rehabilitation*, vol. 6, 2009, p. 18.

[4] S.J. Housman, K.M. Scott, and D.J. Reinkensmeyer, "A Randomized Controlled Trial of Gravity-Supported, Computer-Enhanced Arm Exercise for Individuals With Severe Hemiparesis," *Neurorehabilitation and Neural Repair*, vol. 23, 2009, p. 505.

[5] T. Nef, M. Mihelj, G. Kiefer, C. Perndl, R. Muller, and R. Riener, "ARMin - Exoskeleton for Arm Therapy in Stroke Patients," *2007 IEEE 10th International Conference on Rehabilitation Robotics*, Noordwijk, Netherlands: 2007, pp. 68-74.

[6] E. Rocon, J.M. Belda-Lois, A.F. Ruiz, M. Manto, J.C. Moreno, and J.L. Pons, "Design and validation of a rehabilitation robotic exoskeleton for tremor assessment and suppression," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, 2007, p. 367.

[7] J.E. Pratt, B.T. Krupp, C.J. Morse, and S.H. Collins, "The RoboKnee: an exoskeleton for enhancing strength and endurance during walking," *IEEE International Conference on Robotics and Automation*, 2004, pp. 2430-5.

[8] P.W. Duncan, W.B. Stason, H.P. Adams, A.M. Adelman, D.N. Alexander, D.S. Bishop, L. Diller, N.E. Donaldson, C.V. Granger, and A.L. Holland, *Post-Stroke Rehabilitation: Clinical Practice Guideline*, Aspen Publishers, 1995.

[9] Spinal Cord Injury Facts and Figures at a Glance – Feb 2010, NSCISC, Available : http://www.nscisc.uab.edu

[10] A. Wege and G. Hommel, "Development and control of a hand exoskeleton for rehabilitation of hand injuries," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Alberta, 2005, pp. 3046-3051.

[11] J. Wang, J. Li, Y. Zhang, and S. Wang, "Design of an Exoskeleton for Index Finger Rehabilitation," *31st Annual International Conference of the IEEE EMBS*, Minnesota, 2009, pp. 5957-5960.

[12] M. DiCicco, L. Lucas, and Y. Matsuoka, "Comparison of Control Strategies for an EMG Controlled Orthotic Exoskeleton for the Hand," *the 2004 IEEE International Conference on Robotics & Automation*, New Orleans, 2004, pp. 1622-1627.

[13] Y. Hasegawa, Y. Mikami, K. Watanabe, Z. Firouzimehr, and Y. Sankai, "Wearable handling support system for paralyzed patient," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Nice, 2008, pp. 741-746.

[14] B. Massa, S. Roccella, M.C. Carrozza, and P. Dario, "Design and development of an underactuated prosthetic hand," *Proceedings- IEEE International Conference on Robotics and Automation*, Washington DC, 2002, pp. 3374-3379.

[15] M.C. Carrozza, C. Suppo, F. Sebastiani, B. Massa, F. Vecchi, R. Lazzarini, M.R. Cutkosky, and P. Dario, "The spring hand: development of a self-adaptive prosthesis for restoring natural grasping," *Autonomous Robots*, vol. 16, 2004, pp. 125-141.

[16] Y. Kamikawa and T. Maeno, "Underactuated five-finger prosthetic hand inspired by grasping force distribution of humans," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Nice, 2008, pp. 717-722.

[17] A. Dollar and R. Howe, The SDM Hand as a Prosthetic Terminal Device: A Feasibility Study, *IEEE 10th International Conference on Rehabilitation Robotics*, Noordwijk, 2007, pp. 978-983.

[18] T. Kline, D. Kamper, and B. Schmit, "Control System for Pneumatically Controlled Glove to Assist in Grasp Activities," *9th International Conference on Rehabilitation Robotics*, 2005, Chicago, 2005, pp. 78-81.

[19] A. Chiri, F. Giovacchini, N. Vitiello, E. Cattin, S. Roccella, F. Vecchi, and M. Carrozza, "HANDEXOS: Towards an exoskeleton device for the rehabilitation of the hand," IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009, St. Louis, pp. 1106-1111.

[20] K.N. An, E.Y. Chao, W.P. Cooney, and R.L. Linscheid, Forces in the normal and abnormal hand, *Journal of Orthopaedic Research*, vol. 3, 1985, 202-211.

[21] N. Smaby, M.E. Johanson, B. Baker, D.E. Kenney, W.M. Murray, and V.R. Hentz, Identification of key pinch forces required to complete functional tasks, *Journal of Rehabilitation Research and Development*, vol 41, 2004, 215-224.

[22] D.G. Kamper and W.Z. Rymer, Quantitative features of the stretch response of extrinsic finger muscles in hemiparetic stroke, *Muscle & Nerve*, vol 23, 2000, 954-961.