Exo-Glove: A Soft Wearable Robotic Hand for Stroke Survivors

Benny Cherian[1], Clins Dominic[2], Vysakh G[3], K R Vishakh[4]

[1]Professor, Dept. of EEE, MA Engineering College, Kothamangalam, Kerala, India
[2,3,4] Btech Student, Dept. of EEE, MA Engineering College, Kothamangalam, Kerala, India

---***---

Abstract - *This project presents the development of polymer-based tendon-driven wearable robotic hand, Exo-Glove. The proposed glove is soft, adjustable, allows unconstrained motion of the wrist and leaves the palm free for object grasping and manipulation. In the proposed design, both flexion and extension motions of the thumb and three fingers (excluding the little finger) are supported by respective bidirectional actuators. Exo- Glove is developed to use two motors, one for thumb and the other for index/middle finger, and under-actuation mechanism to grasp various objects. In order to realize Exo-Glove, various design features and following fabrication process were developed to adjust different hand size, to protect injury, to enable ventilation, and to embed Teflon tubes for wire path. Mechanical properties of Exo-Glove was verified with a healthy subject through wrap grasp experiment using mat-type pressure sensor and under-actuation performance experiment with developed test set up. Finally, performance of the Exo-Glove was verified with grasping various shape of object, including under-actuation needed objects.*

Key Words: **Cable-driven glove, exoskeleton, wearable robot, stroke patients, tendons.**

1. INTRODUCTION

The human hand is one of the most important systems we have for interacting with the environment, as it provides sensory and haptic feedback, as well as the ability to manipulate objects. Studies have shown that, on average, a person performs 1500 grasps with the hand per day. However, there is millions of people worldwide suffering from hand function impairment, and this number is constantly growing. Hand functioning and coordination may be compromised by various causes, the most common of which include traumas and injuries such as spinal cord injury, degenerative diseases, stroke, various motor disabilities and muscle weakness associated with aging. For example, the studies suggest that in stroke survivors, hand is the most likely limb to be affected. If ones hand function is compromised, it may significantly limit the number of daily tasks that the person can perform and result in a lower quality of life. For this reason, therapists and doctors have been developing various approaches and methods to restore normal functionality to impaired parts of the body.

The most common approach to improve the hand functionality is rehabilitation through physical therapy. However, the number of people with hand impairment in modern society is constantly growing, partly because of the growth in older population. As a result, it is not always possible to provide every patient with a sufficient level of therapist involvement. Additionally, the large number of repetitive exercises involved in each therapy session makes the job of doctors monotonous and does not fully exploit their qualifications and experience. To decrease the burden on specialists, engineers have developed various robotic devices to automate the therapy. These devices do not only ease the therapists workload, but also help to improve therapy conditions for the patients. Experimental studies have confirmed that the use of robotic systems for post-stroke and post-trauma physical therapy under doctors supervision improves motor functions of the patients.

This paper proposes a fully portable and wearable hand assistive system designed to support ADL. The developed device is a glove-type exoskeleton that actuates four fingers and a thumb. The proposed glove supports both flexion and extension. In addition, it allows for free motion of the wrist and has one of the highest output power-to-weight ratio among existing portable glove systems. The weight of the whole system is 340 g. The glove is capable of performing both a precision grip and a power grip.

The Exo-Glove employs a soft tendon routing system inspired by the human musculoskeletal system. The developed force transmission components are firmly attached to the body even though they consist of fabrics, with the exception of a thin anchor. All the elements of the routing system, including the actuator, are designed for operation without pretension, resulting in improved safety, comfort in use, and system efficiency. We developed a new adaptation mechanism for the soft tendon routing system by modifying the conventional differential mechanism. This reduced the complexity of the system and enhanced the handling of various objects.

2. REQUIREMENTS AND CHALLENGES FOR HAND ASSISTIVE SYSTEM

This section describes major requirements for the devices intended for hand assistance in ADL. As a result of the analysis of available literature and consultations with rehabilitation specialists and doctors, the main requirements for hand assistance devices could be summarized as follows:

i. **Bidirectionality:** The system should preferably support both finger flexion and extension and be capable of controlling each finger separately.

ii. **Wearability**: The device should be wearable (which implies complete portability) so that the user can move around freely while wearing the device.

iii. **High Power-to-Weight Ratio**: The system should be light and compact while capable of generating sufficient output force and velocity, which implies an exoskeleton with a high power-to-weight ratio.

iv. **Free wrist and palm**: The device should allow object grasping and should not impose any constraints on the mobility of other joints of the arm, such as the wrist.

v. **Safety and comfort**: The device must be safe and comfortable for the wearer.

These requirements are summarized graphically in Fig-1. It is challenging to satisfy all of the requirements in one exoglove system, with the major hurdles being limited space, trade-off between positioning accuracy and compactness and weight, and the need of efficient and easy-to-maintain actuators.

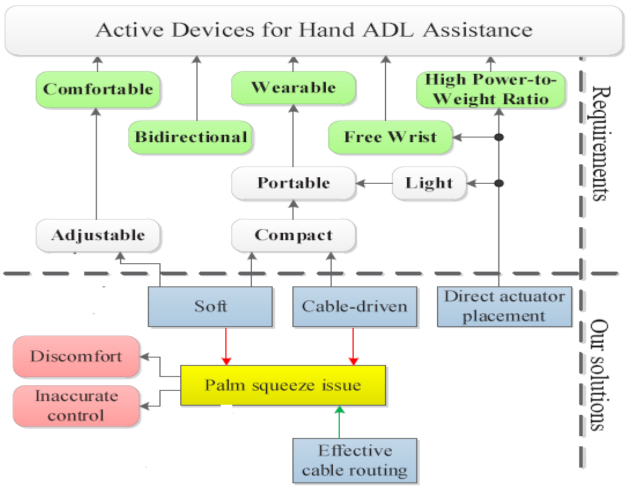

Fig -1: General requirements for devices for hand assistance in ADL and our solutions.

A number of wearable hand robots have been developed, most of them consisting of serially connected rigid links and joints that assist body motion by applying force to the body part to which they are attached. The positioning of these links and joints differs with the body part to which the robot is attached. The frames of hard exoskeleton robots for the legs or arms can be positioned along the sides of the limbs, but the closeness of the fingers means that the frames for a hand robot must be placed along the finger tops. To match the axes of the finger and the exoskeleton, many wearable hand robots use linkages and rack-and-pinion mechanisms.

One way to overcome the limitations of a rigid wearable hand robot is to dispense with frames and, instead, attach actuators directly to the fingers. In this design, the function of the rigid frame of a conventional robot is performed by the finger bones, and actuation can be accomplished by mechanical tendons, air, or other soft actuators. In the literature, these robots are referred to as soft wearable robots, soft exoskeletons, exosuits, or exotendons. Such robots do not have joint alignment problems, and they are compact and lightweight because of their simple structure and the materials used to make them. Several soft wearable robots for the hand have been developed, the majority of which use tendon drives. The tendon drive system does, however, pose some design challenges as follows.

- Tendons that are attached to the body without the use of an exoskeleton apply shear forces to the attachment points. If the tendons are attached by means of a soft material, the shear forces can move the attachment point and obstruct force transmission.

- In conventional tendon drive systems, pretension is necessary for good performance of the robot. However, in soft wearable robots, pretension can cause discomfort or injury, as well as hampering efficiency because of increased friction along the tendon path.

- Conventional adaptation mechanisms that enable objects of differing shapes to be grasped by simple control use multiple rigid mechanical components. Soft wearable robots for the hand require a new adaptation mechanism to accomplish the same task.

Firstly, the human hand has a high number of degrees of freedom and a significantly limited space for hardware installation. Therefore, actuators should either be installed remotely from the hand or be very compact and light in the case of direct installation on the palm. Both of these cases are challenging, since remote actuation requires an efficient force transmission mechanism, while compact actuators might not produce sufficient power.

Secondly, the need for a light device calls for the use of either a light-weight rigid or a soft frame. However, having rigid mechanical links is undesirable because they need to be well-aligned with human joints and often lead to a bulky structure. On the other hand, having a soft frame may introduce undesirable deformations of the frame and cause additional parasitic motions.

Lastly, selecting suitable actuators and transmission mechanisms is another challenging issue. Hydraulic and pneumatic actuators are often used in robotic systems due to their high power density and easy power transmission. However, they are demanding in terms of maintenance, since one needs to prevent air or oil leakages, water ingress, oxidation, and other undesirable factors. Conversely, conventional electric motors, in combination with mechanical gears and power transmission systems, can be quieter, cheaper, more durable and require less maintenance. In addition, electric batteries which can power the motors are generally more compact than pressure pumps used by pneumatic and hydraulic actuators. However, mechanical transmission mechanisms (gears, belts, Bowden cables) that are required to transfer power from the motors to the end-effector often suffer from low efficiency, mechanical complexity, alignment issues, and other problems.

All of these challenges need to be addressed to design an assistive device suitable for ADL applications.

3. GLOVE DESIGN

The Exo-Glove transmits the tension of the tendon to the body in a manner inspired by the human hand, for which tendons transmit muscular forces to induce flexion and extension of the fingers.

Three components are required for human tendons to function properly: 1) an insertion, 2) the origin of the muscles, and 3) a pulley. Muscles are connected to tendons, and tendons are connected to their insertion points and to the origin point of the muscles. The pulley is the annular ligament that determines the path of the tendons.

Based on the structure of the human hand, the Exo-Glove has two tendons for each finger and the thumb, several types of straps that together form the pulley, and supporting structures that form the origin of the muscles. These components are designed to transmit normal forces to the body. To generate an appropriate finger trajectory for different users, the tendon path of the routing system can be adjusted by changing the length and position of the fabric straps.

3.1 Muscle Insertion Point: A Fingertip Thimble

In soft wearable hand robots, special interfaces attach the tendons to the digits. The Exo-Glove uses a glove interface. One of the problems of using a glove interface is that it stretches. As can be seen from Figure 2(a), the part of the glove near the attachment point is stretched in the proximal direction when the flexor tendon is pulled.

To solve this problem, the tendons are attached to the finger by a thimble-like strap made from inextensible fabric, as shown in Figure 2(b). When the flexor tendon is pulled, the strap pushes the back and tip of the phalange, minimizing deformation of the attachment points.

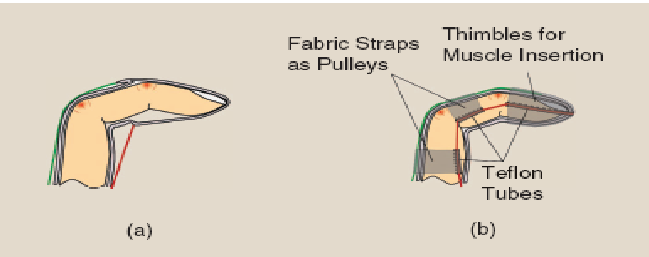

Fig -2: (a) A case in which the tendon is directly attached to the glove. (b) A case in which the tendon is attached through a thimble-like strap and is fixed near the finger by straps.

3.2 Pulleys: Inextensible Fabric Straps and Teflon Tubes

In the hand, the annular ligaments attached to the bone act as pulleys, and they determine the path of the tendons, as without the pulleys, the tendons would separate from the finger, a phenomenon referred to as bowstringing. The Exo-Glove pulleys are made from fabric straps and a Teflon tube and are indicated in gray, as shown in Figure 4.3(b). The straps are attached to the dorsal side, with their two ends located on the left and right sides of the phalanges. Both ends of the straps are rolled up and stitched to hold the Teflon tubes that minimize friction when the flexor tendons move. The straps are made inextensible to maintain the moment arms of the tendons. The positions of the straps determine the moment arms and are crucial for generating the required force and posture.

3.3 Origin of Muscles: Tendon Anchoring Support

To control the fingers while also isolating them from the movements of the wrist and elbow joints, the Exo-Glove uses a Bowden cable such as that used in the transmission of a bicycle brake. One end of the outer sheath of the cable is fixed to the actuator side, and the other end is fixed between the metacarpophalangeal joint and wrist joint. The inner tendon is then connected to the finger. As shown in Figure 3, the actuation can be transmitted to the fingers regardless of the movement of the proximal joints. This is similar to the way that the actuation of a brake lever can be transmitted to the brake regardless of the movement of the handle. Without the Bowden cable, it would be necessary to place the actuator on the back of the hand.

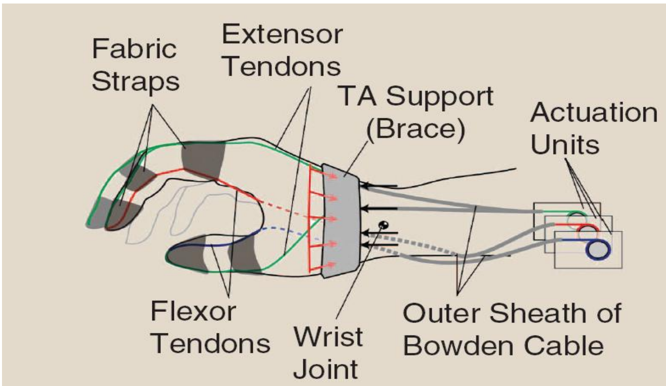

Fig -3: Tendons along with actuating units.

In most soft devices, the actuator is fixed by straps and wrapped around the body, which always applies pressure to the skin. To avoid applying continuous pressure, the Exo-Glove uses a thin, rigid brace customized to the shape of the hand to anchor the tendons. When the tendon is actuated, the actuator and the outer sheath of the Bowden cable are forced toward the finger. The brace blocks the Bowden cable from moving toward the finger by applying a normal force to the hand while actuated, thereby firmly fixing the tendon. No pressure is exerted on the hand when the tendon is released.

3.4 Operation of the Soft Tendon Routing System

In a conventional tendon drive system, pretension is necessary to maintain joint stiffness and ensure a short response time. Pretension is achieved by an antagonistic tendon arrangement. However, in a soft tendon routing system, pretension should be avoided for the following reasons.

- It results in the application of unnecessary force on the joints and skin, causing discomfort and possible injury for the wearer.
- It severely interferes with finger movement, thereby decreasing the effectiveness of the device.

To reduce or eliminate the pretension and friction problem, the tendon should be fully released or even pushed by the actuator. However, slackening occurs when the tension is loosened, and this may cause the tendon to derail from the spool that is connected to the motor, resulting in system failure. The slack prevention mechanism, shown in Figure 4, maintains actuator tension and prevents tendon derailment when tension is removed. A roller and idler are used to maintain the tension. The roller is connected to the spool through a one-way clutch so that the roller rotates when the spool unwinds the tendon and stops when the spool winds the tendon.

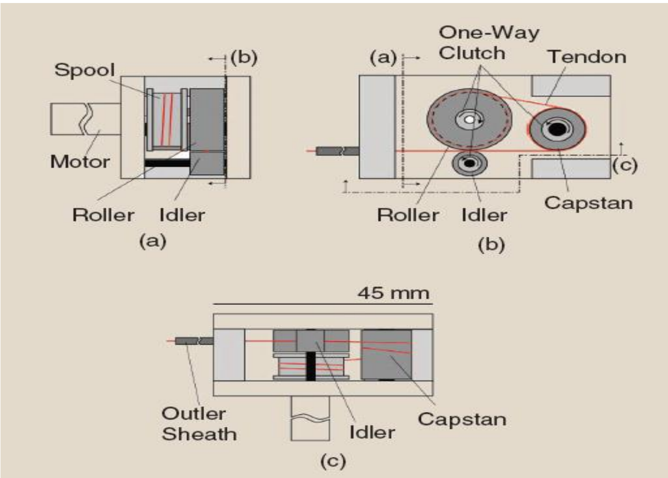

Fig -4: The actuation system.

3.5 Key Features of the Glove

The developed glove has the following key features:

Bidirectional action: The proposed exoskeleton glove supports both finger flexion and extension motions for a thumb and 3 fingers, leaving out the little finger. Each finger is controlled independently and is driven by a pair of cables, one of which is responsible for flexion and the other one for extension. In such a configuration, the cables act in a fashion similar to human tendons and force each finger to move in the desired direction when the cable is being pulled by the motor. This design allowed us to use only 4 actuators, which were installed directly on the dorsal side of the palm. This approach helped to overcome the first challenge for the devices for hand support devices described above, namely, the limited space.

Wearability: To make the system light and compact, we chose a soft structure as the framework of the glove. In addition, efficient transmission allows the use of miniaturized motors to provide the required power, which also positively contributes to the light weight of the overall device. To minimize lateral deformations of such a soft exoskeleton and maintain accurate control, we designed an additional lightweight plate and installed it inside the glove to give the framework around the palm more support. Lastly, an effective cable routing architecture helps to minimize undesired palm squeeze. As a result, compact size and low weight of the device make it portable and wearable, while the rigid plate helps to maintain high positioning accuracy of the fingers. This approach helped to address the second challenge, a trade-off between accuracy of the device and its weight and compactness. For more details on the rigid plate and cable routing.

High power-to-weight ratio: Achieving this feature required implementation of light yet powerful actuators and minimizing power losses in the transmission mechanism. Electric DC motors were chosen as actuators, as they are compact and simple in maintenance. To improve the efficiency of the mechanical transmission between the motors and the fingers, we decided to install the actuators directly on the dorsal side of the hand and to transfer the force by low-friction cables made of a composite material, without the use of any intermediary mechanisms, such as Bowden cables. With this design, the actuators are easy to maintain, and the device is mechanically simple, quiet and does not suffer from misalignments of the tendons. As a result, we were able to address the third challenge, namely, implementation of efficient and easy-to-maintain actuators.

Free wrist: Installing the motors directly on the hand preserves full mobility of the other joints of the arm, such as the wrist. Therefore, they can be either left free during the operation of the glove or assisted independently by another device, if needed.

Comfort: The overall soft structure of the glove and adjustable Velcro straps around the fingers allow easy donning and doffing, as well as adjustment, of the system on hand of different sizes and shapes.

4. EVALUATION OF GLOVE PERFORMANCE

4.1 Glove Prototype

A prototype of the glove was composed of three layers which included an elastic glove, a rigid plate and the exoskeleton itself (motors, tendons, and guides). Two gear motors with a 84:1 gear reduction ratio, were used as actuators. The artificial tendons were Bowden cables lines with a diameter of 0.6 mm. All other parts (motors mounts, frame, motor pulleys, tendon guides) are enclosed in a box.. The angles between the phalanges were measured using resistive flex sensors (SpectraSymbol SEN- 10264, length 5.5 cm). The overall weight of the wearable prototype glove is 340 g. The glove is driven by a control unit which includes an Arduino Uno microcontroller board. The device is powered by a conventional 11.1-V Li-Po battery. Accordingly, the developed prototype is completely untethered from any control station.

A fully mobile version of the glove is shown in Figure 6.

Fig -5: (a) Dorsal and (b) Palmer view of the prototype

Fig -6: Subjet holding the prototype

Arduino uno is the main control unit of this project. It continuously receives analogue data from flex sensor. Flex sensor in placed in the wrist of the paralyzed hand. The flex sensor acts as a potential divider and hence, when the sensor get bend with a sufficient angle, there occurs a corresponding change in their internal resistance. So different voltage level (0-5 V) is obtained at the input of arduino uno. H bridge is used for rotating gear motor in both direction. Two H bridge units are used for driving two motors. The Flex Sensor patented technology is based on resistive carbon elements. As a variable printed resistor, the Flex Sensor achieves great form-factor on a thin flexible substrate. When the substrate is bent, the sensor produces a resistance output correlated to the bend radius the smaller the radius, the higher the resistance value. The resistance of the flex sensor changes when the metal pads are on the outside of the bend. The sensor is connected to the analog input pins of the microcontroller while the motors are connected to the pulse-width-modulation (PWM) pins used for digital output. As the motor it rotates and the tendons placed in the palmer side are tightened at the same time those on the dorsal side are released hence achieving flexion of the hand. In order to obtain the extension of hand, the same process could be repeated. This time flex sensor is bend in the opposite direction hence actuating the gear motors: tendons placed in the palmer side are released while those on the dorsal side are tightened.

4.2 Glove Usability Test

To check the usability of the developed exoskeleton glove, it was first tested in a series of indoor object grasping experiments. The wearer was able to successfully grab and hold rigid objects such as a) cricket ball, b) bottle, c) comb, d) glass, e) box and f) table tennis ball. Objects were selected to include different shapes of object and different sizes of objects with the same shape, and two objects that require under-actuation in order to be grasped. In addition, the human subjects could perform a precise pinching grasp to hold miniature objects, such as the table tennis ball in Fig. 7(f). The subject was asked to voluntarily change the orientation of the hand and arm path according to the state of the objects. Glove could execute both a precision grip and power grip, and therefore can be used to cover a large range of the prehensile activities of human hand. Simple actuation control and under-actuation allowed the subject to grasp all the objects in a first trial without any practice. Fig. 7 shows the grasp of various objects with Exo-Glove.

Fig. 8 presents a sample pattern of the index finger joint angles observed during the object grasping tests. In this experiment, the proximal phalanx (Θ_1) was initially blocked by the object (a stiff cricket ball), as shown in Fig. 8 (a). Therefore, after the motion starts at approximately 0.4 sec, whole flexor contraction is directed exclusively into actuation of the intermediate and distal phalanges (the left-most dashed line in the graphs in Fig. 8). After the finger completely envelops the object at the time instance of around 0.7 sec (the middle dashed line on the graphs corresponding to the case (b) on the diagram below), the phalanges cannot flex freely anymore because of high object's stiffness. However, since the motor is still

Fig -7: Versatile object grasping: a) cricket ball, b) bottle, c) comb, d) glass, e)box and f)table tennis ball contracting the flexor, the tension force acting on the cable increases, which results in the motion of the proximal phalanx that deforms the object (this period of time marked as (c) on both the graphs and kinematical structure at the bottom) and compression of the soft parts of the glove. This motion starts at 0.7 sec and finishes at approximately 1 sec. During this period of time, a certain deviation between the experimental and theoretical curves can be observed. Theoretical curve only reflects the displacement of the cable caused by the motion of finger joints (angles Θ_1- Θ_3). Since after 0.7 sec all phalanges are already in contact with the object, all of their displacement contributes to the deformation of mentioned object. For clarity, the region corresponding to object deformation is filled with red color in the flexor contraction plot in Fig. 8. At the same time, a certain part of excessive tendon tension contributes to stretching of the soft parts of the, and because of this the actual contraction of the cable is larger than the one calculated from current joint angles. This motion region is filled with blue color in Fig. 8. If needed, the issue of undesired stretching of the glove will be addressed in the future versions of the device. However, in the current state of the glove, the error between theoretical and actual tendon contraction curves can be used by the control system as an indicator of external disturbance (e.g. an object). These experiments demonstrated that the glove could generate sufficient grip force when grasping objects. Prevention of excessive grasping forces can be solved at the control level. For instance, the flexion can be stopped once certain value of motor torque is reached or if some triggering mechanism (e.g., force sensors at the fingertips) is activated.

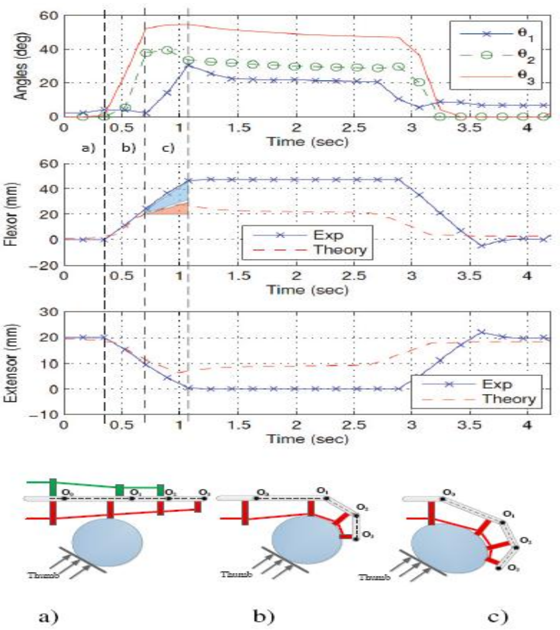

Fig -8: Wrap of index finger around an object: Proximal (Θ_1), intermediate (Θ_2), and distal (Θ_3) phalanges' angles (top); experimental and theoretical contractions of the flexor (second row) and extensor tendons (third row). Finger configurations (bottom row, left to right): t=0 s, t=0.7 s, t=1.0s.

5. CONCLUSIONS

A polymer-based tendon-driven soft wearable robotic hand, Exo-Glove Poly, was proposed and detailed design features of the components were described. The Exo-Glove is most suitable for people who are incapable of closing or opening their hands but are able to use other joints of the upper limb, including the wrist, elbow, and shoulder joints. Because the conventional elements of a hard exoskeleton are unsuitable for the soft structure of the proposed device, the Exo-Glove employs a new design inspired by human finger anatomy. Owing to the inherent features of the soft structure, no joint alignment was required between the device and the human body, which enhances the simplicity of the device.

One of the biggest advantages of the proposed exoskeleton glove is its power-to-weight ratio, which is the highest among existing portable systems for hand assistance. At the same time, the glove can support the flexion and extension of 4 fingers (excluding the thumb) while enabling the wrist to move freely. The use of a cable-driven soft structure, the direct placement of actuators and the optimal cable routing which mimicked real human hand anatomy allowed the development of a compact, bidirectional, and powerful exoskeleton glove. The resulting weight of the entire system is 340 g which makes it portable i.e., the entire hardware could be carried by the patient.

The performance of the glove was experimentally verified in a series of versatile object grasping tests, where the task was to pick up and hold objects of various sizes, shapes, and hardness. The wearers could successfully grasp objects weighing 300 grams and with diameters of up to 90 mm as well as miniature objects. When powered by a conventional 3000-mAh battery, the glove could operate continuously performing grasping task for 4 hours.

REFERENCES

[1] J. Z. Zheng, S. De La Rosa, and A. M. Dollar, "An investigation of grasp type and frequency in daily household and machine shop tasks," in Robotics and Automation (ICRA), 2011 IEEE International Conference on. IEEE, 2011, pp. 4169–4175.

[2] C. A. Trombly, Occupational Therapy for Physical Dysfunction. Lippincott, Williams and Wilkins, 1989.

[3] S. Rathore, A. Hinn, L. Cooper, H. Tyroler, and W. Rosamond, "Characterization of incident stroke signs and symptoms: findings from the atherosclerosis risk in communities study," in Stroke, 2002, vol. 33, 2002, pp. 2718–2721.

[4] G. J. Snoek, M. J. IJzerman, H. J. Hermens, D. Maxwell, and F. Biering-Sorensen, "Survey of the needs of patients with spinal cord injury:impact and priority for improvement in hand function in tetraplegics,"Spinal cord, vol. 42, no. 9, pp. 526–532, 2004.

[5] E. H. Kim, M. C. Jang, J. P. Seo, S. H. Jang, J. C. Song, and H. M. Jo,"The effect of a hand-stretching device during the management of spasticity in chronic hemiparetic stroke patients," Annals of rehabilitation medicine, vol. 37, no. 2, pp. 235–240, 2013.

[6] C.-Y. Yeh, J.-J. J. Chen, and K.-H. Tsai, "Quantifying the effectiveness of the sustained muscle stretching treatments in stroke patients with ankle hypertonia," Journal of Electromyography and Kinesiology, vol. 17, no. 4, pp. 453–461, 2007.

[7] 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," Mechatronics, IEEE/ASME Transactions on, vol. 17, no. 1, pp. 136–146, Feb 2012.

[8] S. Moromugi, K. Kawakami, K. Nakamura, T. Sakamoto, and T. Ishimatsu,"A tendon-driven glove to restore finger function for disabled," in ICCAS-SICE, 2009. IEEE, 2009, pp. 794–797.

[9] H. In, B. Kang, M. Sin, and K.-J. Cho, "Exo-glove: A wearable robot for the hand with a soft tendon routing system," Robotics Automation Magazine, IEEE, vol. 22, no. 1, pp. 97–105, March 2015.

[10] F. Vanoglio, A. Luisa, F. Garofali, and C. Mora, "Evaluation of the effectiveness of gloreha (hand rehabilitation glove) on hemiplegic patients. pilot study," in XIII Congress of Italian Society of Neurorehabilitation, 18-20 April, 2013.

[11] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," J. Neuroeng. Rehabil, vol. 11, no. 3, pp. 10–1186, 2014.