Abstract—Grasping objects is a natural thing for most people whose hands have normal function. Losing hand function disturbs all aspects of our daily life and work. Wearable device which can restore the hand function reasonably are significant for persons suffer from this problem. To this end, we propose a design of a soft robotic glove which highly replicates the biomechanical features of a human hand in this paper. Shape Memory Alloy (SMA) actuators were selected as artificial muscles to provide forces required for the hand motions. The performance of the soft robotic glove was investigated experimentally. The muscle glove is able to generate natural hand motions and grasp postures. The results confirmed our biomimetic design concept.

I. INTRODUCTION

Manual activities with repetitive or excessive hand movement as well as high force demands on hand are common in industrial production. They are the main risk factors for work-related musculoskeletal disorders of hand which lead to dysfunction of the hand [1], [2]. This will disturb daily work and life in every aspect. Therefore, some support or assistive devices for hand which can preventively complement or enhance the hand function are necessary for manual workers. In some situation, the normal hand function is constrained by the working condition, e.g. the finger cannot apply sufficient press force on a button when it is not easily accessible, and that is quite common in manufacturing. Another example is, people cannot apply sufficient grip force to the object or loss the dexterity of the fingers due to a thick glove, like astronaut or worker with special glove. Similar demands can be seen in daily life by people who lose the normal function of their hand completely or partially, e.g. elderly people with weak muscles, people doing rehabilitation or people with other handicap (older and young people with e.g. rheumatism).

Some wearable robotic devices have been developed for hand rehabilitation. Most of them contains rigid structure or elements like exoskeletons in [3], [4]. Those devices are characterized by bulkiness and can cause misalignment which leads to discomfort and injury. To address these issues, some soft robotic gloves have been developed recently. They restore hand motions by attaching soft elastomeric actuators directly to the finger [5], [6] or using cable drive and motor [7], [8]. The available solutions can restore the hand functions somewhat, but are not able to reproduce the hand dexterity entirely which is very important for daily activities.

In this work we are interested in using a highly biomimetic design to replicate the high dexterity and efficient grasping of the hand for a wide application, not only for rehabilitation but also for preventive application in daily work. A high degree of power support is not our investigation here but for further works. In the following sections, we first interpret the important biomechanical features of the hand and detail the biomimetic design of the muscle glove. Second, we discuss the design and control of the SMA coil actuator. After this, we experimentally investigate the general performance of the muscle glove.

II. DESIGN OF ARTIFICIAL TENDON-PULLEY STRUCTURE

The muscle glove is a soft robotic glove aiming to support the user by handling and grasping objects in work and daily life. It uses a bio-inspired tendon-pulley structure and artificial muscles to realize an effective grasping and the high dexterity of the hand. A schematic drawing of the muscle glove is showed in Figure 1. The glove is attached with a sleeve that covers the upper arm. The actuators are distributed on the sleeve to providing the forces and act on the string via the strings. Every string connect with an actuator, which is not able to be illustrated in Figure 1. The bands in the glove area mimic the pulley structure of the hand and fasten the strings to the glove. In this section, we identify the function of muscles and connective tissues that are significant for hand motions and discuss the way to mimic those functions in to the muscle glove.

Figure 1. Schematic of the muscle glove (left hand, palmar side)

A. Hand Anatomy

A hand has five digits: one thumb and four fingers (index, middle, ring and little finger). Each finger has three phalangeal bones (distal, middle and proximal), one metacarpal bone and three active joints which are distal interphalangeal joint (DIP), proximal interphalangeal joints (PIP) and metacarpophalangeal joints (MCP) (see Figure 2). Both DIP and PIP joints have 1 DOF (flexion and extension), while the MCP joint has 2 DOFs (flexion and extension, abduction and adduction).

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The thumb has two phalanges and one metacarpal bone, with one interphalangeal joint (IP), metacarpophalangeal joints (MCP) and carpometacarpal joints (CMC). The IP and MCP have only 1 DOF for flexion and extension. The CMC covers 3 DOF of the thumb: flexion and extension, abduction and adduction, opposition and reposition. The opposition of thumb is significant for hand functions, especially for grasping.

Figure 2. Schematic of hand skeleton (modified from [9])

B. Artificial Tendon-Pulley Structure

As the tendon connects the muscle to the bone, the string connects the actuator to the glove via the band (see Figure 1). But unlike the direct contact between tendon and bone, the pull force along the string is applied indirectly on the finger surface via the glove. The point of application of the pull force is then no more on the side which the string connects to, but on its opposite side of the hand. For example, a string for flexion is attached to the palmar side, but the pull force along the string is actually applied on the dorsal side. In order to achieve a large torque at the finger joint, the insert point of the string should be on the relevant phalanx but as far as possible from the axis of the rotation. The strings should be loadable for large pull force and inelastic for an effective force transfer. For a high wear comfort the string should also be thin and light. We used nylon string with a diameter of 0.35 mm and a maximum load for 3.5 kg.

The main strings which are dominant for grasping are illustrated in Figure 1. Table I shows an overview of these strings, the muscles and phalanges they connect with and the joint motions they are responsible for. The string group 1, 2 and 3 are located on the palmar side of the four fingers (index, middle, ring and little finger) and mainly responsible for finger flexion. The string group 1 mimic the tendons of flexor digitorum profundus muscle (FDP) which insert to the distal phalanges and cause the flexion of DIP directly and the flexion of PIP and MCP indirectly. Together with the three strings of thumb, this group of strings are significant for holding a gripping shape in proportion to the object’s form. The second string group are bound to the middle phalanges of the fingers and represent the flexor digitorum superficialis (FDS) tendon. They are responsible to flex the PIP joints, and the MCP joints as well. The FDS strings remain irrelevant for precision handling but play an important role in power grip [10], [11]. Unlike the hand anatomy, it is unfavorable to locate the actuators directly in the palm area of the glove. Therefore, all the actuators which represent the intrinsic muscles are attached to the sleeve as extrinsic artificial muscles and extended to their insert point on the glove via strings, e.g. No. 3, 5 and 6. As extension of interosseous (IOs) the string group 3 connect to the proximal phalanges and enables the flexion of the MCP joints. Thanks to the FDS and IO strings, the PIP and MCP joints can flex independently. In power grip, they help to hold tightly onto object’s form and enhance the grip power.

Opposition is a special motion of the thumb, which enables all forms of grip, except hook grip. A perfect representation of the opposition motion is always a big challenge for the systems which support the hand motion. The muscle glove use three strings to realize the complex motion of the thumb. The string 4 and 5 work mainly for the flexion and opposition of the thumb, while the string 6 serve for abduction and support the other two in opposition. Different from the strings of the fingers they do not go exactly along the middle line of the thumb, but start a little bit away from the middle line and go across the palm to the wrist (see Figure 1). Those special routes of the three strings enable them to rotate the CMC joint in a proper way. The string 4 and 5 are involved in both precision handling and power grip. The string 6 abort the thumb from the palm for grasping big objects.

### Table I. Overview of the strings on palmar side (see Figure 1)

<table>
<thead>
<tr>
<th>String Nr.</th>
<th>Relevant Muscle(s)</th>
<th>Digit</th>
<th>Phalanx</th>
<th>Joint Motions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>flexor digitorum</td>
<td>fingers</td>
<td>distal</td>
<td>DIP, PIP and MCP flexion</td>
</tr>
<tr>
<td>2</td>
<td>flexor digitorum</td>
<td>middle</td>
<td>PIP and MCP flexion</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>interosseous</td>
<td>proximal</td>
<td>MCP flexion</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>flexor pollicis</td>
<td>distal</td>
<td>IP and MCP flexion, CMC opposition</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>flexor pollicis</td>
<td>proximal</td>
<td>MCP and CMC flexion, CMC opposition</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>abductor pollicis</td>
<td>proximal</td>
<td>MCP flexion, CMC abduction</td>
<td></td>
</tr>
</tbody>
</table>

On the dorsal side of the glove there are strings for extension and reposition of the digits (see Figure 3). The main characteristics and functions of those strings are listed in Table II. The string group 7 and 8 are the main extensor string for the fingers. They divide into two slips over the phalanges in consideration of the wear comfort, but still stay above the rotation axis of DIP, PIP and MCP joint to ensure extension effect. The two extensor strings of thumb 9, is responsible to move it back to its neutral position.

Figure 3. Schematic of the strings on dorsal side (left hand)
Inspired by the pulleys of the digits, the muscle glove use inelastic bands to keep the strings close to the digits to enable effective flexion. The bands provide the channels where the strings can go through and ensure them not to slide out of their proper courses. Moreover, some of the bands define the connecting point between the strings and the glove. They are the first bands on each phalanx from the fingertip and act as extensions of the strings which transfer the pull force from the string to the finger. For a better realization of the functionalities mentioned above the bands should be inelastic to protect from stretch when the string are pulled. However, the band on wrist is an exception. It is elastic in radial direction for easy put on and take off. The band structure in palm area is designed with ergonomic consideration for reminding restriction of intrinsic muscles, especially the thenar muscles, during hand movements. The two cross bands enable effective wrist motion which caused by the two wrist strings (A and B).

III. ARTIFICIAL MUSCLE

As mentioned above, every string should be driven separately in order to achieve the high dexterity of the hand. In consideration of the high demand on actuator, the classical actuators like motors and cylinders are no more suitable for such a mobile wearable system. Shape memory alloy (SMA) coil actuator is chosen here for the glove as artificial muscle because its possibility to be made in low mass and small size.

A. design of the SMA coil actuator

The SMA coil actuator is comprised of NiTi wire which wound into string. Although the SMA wire is thinner and can provide higher recovery force, but its stroke length is very small which is not sufficient for our application. We are interested in SMA spring actuator which can produce large stroke and maximum contract force under the conditions of a wearable system. For this purpose, following parameters will be decided: the working temperature of the SMA wire, the wire thickness, diameter and length of the spring.

The SMA wire for the glove should be easily deformed in room temperature and be activated at a temperature which is acceptable for the wearable application. In available commercial NiTi wire we only find one with an austenite start temperature of 55 °C can meet this condition in some measure. Therefore the sleeve, to which the SMA coil actuators are attached, is made from thermal insulation textile to protect the user from overheat.

Thick wire can produce large force but result in bulk actuator. An ideal wearable actuator for the glove should be as tiny as possible and can produce adequate force as well.

This work does not propose to create super power for the hands but to support the user to a certain degree in the daily life. So we prioritize to minimize the wire thickness, as long as that can generate enough power. The selected NiTi wire is available in three thickness: 0.21 mm, 0.32 mm and 0.5 mm. SMA wire with 0.25mm and 0.305mm have been shown good performance in wearable application [12], [13]. The 0.32 mm wire is thus chosen for the glove.

With a fixed wire diameter (d) the mean spring diameter (D) is proportional to the spring index (C = D/d) which determine the strength of the spring. The spring strength is increased by reducing the spring index. Within this reason, the mean diameter of the spring should be minimized, that also meets the size requirement of the actuator. However, this leads to a reduced stroke. But maximizing the force and minimizing the size of the actuator is more preferred. We made the spring with 1.8 mm outside diameter which match the lower limit of the index (C ≥3) as well.

The muscle glove requires sufficient stroke length to achieve full flexion and extension of the fingers. To maximize stroke length with fixed number of spring coils (n), the free spring length (L0) should approximate to the product of wire diameter and number of spring coils (nd), i.e., the spring coils should be wound next to each other as closely as possible. In this case, a shorter spring (i.e. less spring coils) can generate more force then the longer one for the same linear displacement. To maximize the force we select a reasonable L0 whose allowable active stroke can just meet the requirements of FDP string of middle finger, which needs larger stroke length than other strings. According to several tests, we find out that the activation stroke should be better keep in 200% of the free spring length for repeatable application. Otherwise, unrecoverable extension of the free spring length will appear after few cycle loading. A maximal stroke length of 83 mm is needed for the FDP string of a 95 mm-long middle finger (measured from fingertip to MCP joint) to allow a full flexion from full extension. However, the most repeated activation stroke is about 50 mm, from neutral position (the fingers are slightly curved when they are relaxed) to full flexion. The free length of SMA spring actuators for the muscle glove is thus determined of 40 mm in this work. It can be adjusted for other sizes of glove or hand.

B. control of the SMA coil actuator

A microcontroller is used to generate PWM signal with certain duty cycle to control the SMA actuators. The low energy efficiency of SMA coil actuator hinders its wide application. PWM have been proven good performance by reducing the energy consumption of SMA coil actuator and the control of its stroke [14]. Logic level power MOSFETs operated by PWM signal from microcontroller is used to modulate the voltage applied to the SMA coil actuators. By changing the duty cycle of the PWM signal the power applied to the SMA actuator is regulated.

We made two tests to find out the best setting of the PWM signal for quick response and high energy efficiency of the actuator. The tests were set up for position control of a single SMA spring actuator which matches the design we mentioned above. A rubber stretch sensor is used to send the linear displacement (δ) to the controller. Both the SMA coil actuators are operated by PWM signal from microcontroller is used to modulate the voltage applied to the SMA coil actuators. By changing the duty cycle of the PWM signal the power applied to the SMA actuator is regulated.
actuator and the rubber sensor are fixed on one end, and connect to each other on the other end. The actuator is tested at 5V and with a fixed stroke range from 58mm to 10mm. At the beginning of the tests, the rubber is released but straight. In steady state, the rubber sensor is stretched with 4.8cm and produced a force of 1.5 N.

In the first test, the SMA actuator was stimulated by PWM signals with duty cycle from 50% to 90%. The test duration was 15 s and the PWM signal was applied at the beginning. The responses are shown in Figure 4. The actuator react faster by increasing duty cycle. We select 90% duty cycle for activation PWM signal.

In the second test is aiming to find out the proper duty cycle to keep the SMA actuator in steady state after entering austenite phase. The test duration was 50 s. According to the results from the first test, a PWM signal with 90% duty cycle was applied at the first 4 seconds for a full activation. After that the duty cycle was turned down to different value. The results are shown in Figure 5. It shows already a balance between heating and cooling process by 20% duty cycle.

IV. EXPERIMENTAL EVALUATION

In order to evaluate our design concept we experimentally investigated the performance of the muscle glove by free movement and grasping, especially the functionalities of the strings mentioned in section II. The glove was tested by a healthy female subject with left hand. By the experiments the seat for the subject is set to a reasonable height so that she can put her left forearm completely relaxed on.

A. Free movement performance

The focus here is to evaluate the different finger motions by comparing the range of motion (ROM) conducted by the glove and the user’s muscles. Figure 6 shows the comparison by finger flexion involving different finger joints. The left row shows flexion of DIP, PIP and MCP joints. The middle row includes PIP and MCP joints. In the right row is only MCP flexion. The three kinds of flexion, from left to right, was done by FDP, FDS and IO strings of the glove. The independent motions of PIP and MCP are significant for many activities, like typing and pressing the button. It also enables us to adapt the grasping posture properly to different objects. The flexion degree of MCP and DIP joint made by the glove is almost the same by a natural motion. The PIP joint flexed a little bit less by the muscle glove.

Thumb abduction, opposition and flexion are significant for all kinds of grips except hook grip, in which the thumb is not involved. Thus it is important to investigate the thumb motion of the glove. According to the pair comparisons in Figure 7 the muscle glove generated the main motions of the thumb and its ROM are very close to the ROM of natural motions. Moreover, the cooperation of fingers and thumb is checked by 6 gestures (see Figure 8). Although the little finger was not driven by the glove, it moves slightly with the other fingers due to the inherit collaboration with ring finger.

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B. Grasping performance

In order to test the grasping performance of the glove, we used a healthy female subject with left hand. The subject was asked to hold different objects with the glove and without the glove, respectively. The results are shown in Figure 9. It shows a balance between heating and cooling process by 20% duty cycle.
B. Grasping performance

To examine the grip force generated by the muscle glove, a Kern hanging scale CH is used to measure the hook grip force. The scale has a handle loop (15.03 mm deep and 9.46 mm thick) for hand-held on one side and a steel hook on the other side. The scale is aligned with the subject’s arm and fixed on the hook. By measuring the subject took a firm grasp of the handle and pull. Nine SMA coil actuators for three fingers (index, middle and ring finger) are involved in hook grip. Every finger is driven by three actuators which are connected to the FDP, FDS and IO string of the finger. A hook grip force of about 11 N is measured by the scale.

To exclude intentional grasping of the subject, we used surface EMG sensors (Myon, Switzerland) to measure the activity of the flexion muscles on forearm. The EMG signal was recorded at a frequency of 2000 Hz. The FDP and FDS muscle locate deeply under the skin and their activities cannot be detected directly using surface EMG, but is detected as crosstalk over neighboring muscles. To get a reference measure, electrodes were placed over palmaris longus and flexor carpi ulnaris muscles for this test. Records were taken in three conditions: relaxed, grasping with muscle force (inactive muscle glove) and grasping with active muscle glove. Every recording took 10 s. The recordings during grasping only started when the force reached about 11 N. The results can be seen in Figure 9, Figure 10 and Table III. In both qualitative and quantitative analysis differences were recognized obviously between the muscle activities with and without the support from the glove. The EMG signal from palmaris longus by grasping with the glove has almost the same amplitude as of the signal in relaxed state. A slight activity is detected over flexor carpi ulnaris with active glove, which may be caused by unintentional motion of the subjects. However, the support effect of the muscle glove is obvious.

In addition, grasping tests with different objects and postures, according to the grasp taxonomy in [15], were conducted to evaluate the performance of our muscle glove. The grasp taxonomy realized by the muscle glove are shown in Figure 11 and Table IV. During the test, the objects were handed from the right hand to the left hand of the subject. The objects weight from 7.2 g to 380.6 g. The precision grasp with abducted thumb (7-10 in Figure 11) was carried out by FDP and FPL strings and their corresponding actuators. This is consistent with the statement “FDP muscle is predominant by precision handling” in [10]. An exception is grasp 14 (parallel extension), which was mainly realized by IO strings. The FDPs only assist the IOs. By grasp with abducted thumb (1-6 in Figure 11) the actuators connected to FDS and FPB strings were also active beside FDP and FPL. Thumb abduction in grasp 11-13 was achieved by a reasonable cooperation of flexion (FPB) and extension (EPL) strings.

| Table III. Mean values of the EMG signals in Figure 9 and Figure 10 |
|-----------------|------------------|------------------|
|                 | Still (mV)       | Grip with active glove (mV) | Grip with inactive glove (mV) |
| left palmaris longus | 0.0036           | 0.0063            | 0.0497            |
| left flexor carpi ulnaris | 0.0046           | 0.0353            | 0.1003            |

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| Table IV. List of realized grasp based on taxonomy in [4] (GRASP NUMBER CAN BE FOUND IN FIGURE 11) |
|-----------------|------------------|------------------|
| Thumb Abducted  | Power            | Precision        |
| 1: large diameter | 1: prismatic 3 finger | 8: writing tripod |
| 2: small diameter | 2: precision disk   | 9: precision disk |
| 3: medium wrap  | 4: power disk     | 10: precision sphere |
C. the impact of FDS and IO strings on grasp

As we mentioned in section II, FDS and IO muscles allow extra motions of PIP and MCP joint independent to the FDP muscle. This plays an important role in power grip, affecting on grasp posture and grip force. Thus, it is significant to investigate the impact of adding FDS and IO strings to our muscle glove. We conducted comparative experiments for grasp posture and grip force.

The grasp 1 and 2 in Figure 12 were realized by the muscle glove with inactive and active actuators connected to IO strings. The FDP actuators are active by all the four tests. Obviously, FDP and IO prevent the finger curling up by grasping and ensure sufficient contact surface between the hand and the objects. As a result, the efficiency of actuator force to grip force increase. We measured the maximum load by power grasping in two cases. Every finger is driven by two SMA coil actuators in both cases. In one case the two actuators were connected separately to FDP and FSD strings and can hold a maximum load of 806 g; in the other case, both actuator were attached to FDP string and the maximum loading is 711 g. The handle size for both cases is 51.32 mm and the coefficient of friction the glove and the object is under 0.3.

![Figure 12. Comparison of grasp with inactive (1, 2) and active (3, 4) IO or FDS actuator](image)

V. CONCLUSION AND FUTURE WORK

We designed and prototyped a muscle glove with SMA coil actuator for supporting precision handling and power grip. The design focused on two challenges of developing wearable support systems for hand: replicating the high dexterity and efficient grasping of the hand. To solve this problem, we implemented a tendon-pulley structure which mimics the important functionalities of the connective tissues in human hand. The performance of the glove was validated experimentally. The proposed motions of the thumb and the fingers can be good achieved by the glove. Its support effect was confirmed for grasping daily objects below 1 kg. The replication of FDS and IO enables a natural grasp posture and efficient force transfer.

In future work, we are planning to integrate sensors into the glove for an intuitive control of the motions and support force. Additionally, we will further explore the cooperation of the hand muscle and try to find out the best tension ratio between the FDP, FDS and IO muscles for maximum grip force. Moreover, we are going to optimize the actuator for large load application.

REFERENCES


