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FLEXION AND EXTENSION CAPABLE MOTOR TENDON ACTUATED EXOSUIT GLOVE WITH OPEN PALM

Georgia S Patterson, Tyler D Zell, David E Parker, Jack L Grieve, Samuel C Watson, Vishesh Vikas
Agile Robotics Lab,
The University of Alabama
Tuscaloosa, Alabama, USA

ABSTRACT

Patients suffering from medical conditions resulting in hand impairment experience difficulty in performing simple daily tasks, like getting dressed or using a pencil, resulting in a poorer quality of life. Rehabilitation attempts to help such individuals regain a sense of control and normalcy. In this context, recent advances in robotics have manifested in multiple designs of hand exoskeletons and exosuit gloves for assistance and rehabilitation. These designs are typically actuated using pneumatic, shape memory alloys and motor-tendon actuators. The proposed Motor Tendon Actuated Exosuit Glove (MTAEG) with an open palm is a soft material glove capable of both flexion and extension of all four fingers of the human hand. Its minimally invasive design maintains an open palm to facilitate haptic and tactile interaction with the environment. The MTAEG achieves flexion-extension motion with joint angles of 45° at the metacarpal joint which is 57% of the desired motion; 90° at the proximal interphalangeal joint which is 100% of the desired motion; and 50° at the distal interphalangeal joint which is 96% of the desired motion. The paper discusses the challenges in achieving the desired motion without the ability to directly model human tendons, and the inability to actuate joints individually.
Keywords — Soft robotics, motor-tendon actuation, cable-driven actuation, rehabilitation, exosuit

1. INTRODUCTION

1.1 Hand Rehabilitation

Daily routine activities like getting dressed or lifting small objects, require substantial hand manipulations and functionality. For many individuals, who have endured an injury or a medical condition (e.g. a stroke), hand impairment can make performing these activities very difficult, resulting in a reduced quality of life [1]. Every year, hundreds of thousands of individuals suffer from strokes resulting in severe central nervous system (CNS) and spinal cord injuries (SCI). The National Spinal Cord Injury Statistical Center estimates that in 2018 there were as many as 358,000 people suffering from SCI [2]. Rehabilitation is the primary solution for these individuals to help resume control and normalcy in daily life. Physical rehabilitation and therapy have proven to be successful methods of promoting motor recovery [3,4].

In this context, robotic exosuits and skeletons are being developed to facilitate rehabilitation and assist individuals at home [5–7]. Due to the complex motor and sensory requirements, modern robotic exoskeleton technologies for the hand have not progressed as much as those used for upper and lower limbs of the body, leaving greater opportunities for advancement in the field [4]. While the current designs are a great step forward, there exists scope for improvement in areas that include functionality, portability, and tactile interaction. The motor-tendon actuated soft material Exo-Glove is functional and portable, however, the actuators inside the palm of the glove limit tactile and haptic interaction[8]. The proposed research presents the design and fabrication of an exosuit glove that can flex and extend an individual's fingers for therapeutic and rehabilitative purposes. The glove design is free of mechanisms, tendons, braces, or actuators on the palm of the hand. This portable design increases functionality by allowing the user to experience tactile and haptic feedback.

Functionality. The performance of daily activities requires individuals to be capable of feeling objects. This need for sensory input limits the methods of motion that can be used in the design [9]. Due to the number of joints in the hand and the requirement of touch-sensory input, achieving this desired motion can be a difficult task. Currently in literature, about 44% of the hand assistance devices are capable of assisting in both extension and flexion of the fingers [1]. One of the major design criteria for the proposed exosuit gloves requires the palm of the hand and the underside of the fingers to be actuator-free so as to enhance user's ability to feel objects and quality of interaction.

Portability. Another problem facing the design of an exosuit glove is weight and portability. Many current therapeutic hand devices require a power source such as a wall outlet, limiting their use with activities of daily living. The complexity of many devices also creates an excessive amount of weight that the user must support. This can cause pain for many users and create issues for those with very limited arm or hand strength [4].

The proposed Motor Tendon Actuated Exosuit Glove (MTAEG) open palm design is the first-of-its-kind. The tendons are capable of bi-directional motion, inducing both flexion and extension allowing for complete rehabilitation motion. The glove can achieve flexion and extension in all four fingers.

1.2 Defining Human Motion and Comfort

The hand consists of two types of bones, namely, phalanges and metacarpals. The phalanges are found in the fingers with each finger having three phalanges of varying lengths. The longest phalanges, i.e. proximal phalanges, connect to the metacarpal bones that make up the palm of the hand and can be felt along the back of the hand. The first joint, located closest to the fingertip and farthest from the body of the hand, connects distal and medial phalanges and is known as distal interphalangeal (DIP) joint. The second joint, in the middle of the finger connecting the medial and proximal phalanges, is the proximal interphalangeal (PIP) joint. The third joint, the "knuckle" connecting the proximal phalanges to the metacarpal bones, is the metacarpophalangeal (MP) joint [10].

Standard practice when working with bio-mechanics is to measure joints using relative measurements. Relative angles are measured between two segments of the human body. These are more often used in clinical settings than other methods as they provide a more practical indicator of function and joint position. All the angles seen in this work are relative to the respective parts of the finger and the back of the hand, as depicted in Fig. 1 [11,12].

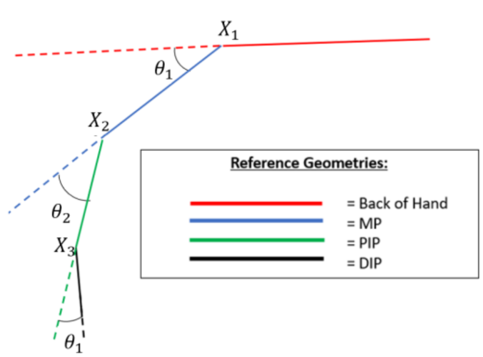

FIGURE 1. REFERENCE GEOMETRIES OF THE HUMAN HAND

Fig. 1 displays the actual MP, PIP, and DIP as solid lines and the geometries off of them as dashed lines. These reference geometries are utilized to calculate angles and lengths of the kinematic system utilized for actuation.

In addition to the joint angle measurements, the type of motion must also be defined. The main motion the MTAEG aims to achieve is that of flexion, and conversely, extension. Flexion refers to the motion of curling the fingers towards the palm of the hand while extension refers to the straightening of the finger away from the palm. MTAEG is not trying to achieve either abduction nor adduction. Each of these joints has a median joint angle that is finger dependent, Table 1.

TABLE 1: MEDIAN JOINT ANGLES

Joint	Median Angle
MP	79° - 97°
PIP	87° - 90°
DIP	52° - 68°

The MTAEG design strives to achieve these angles in the respective joints thus creating a fist of the user's hand. This is a basic motion in rehabilitation and is independent of whether it is intermittent or continuous motion [11–13].

Passive motion, a therapeutic exercising technique in which the joints are moved by an external force, requires no force to be generated on the part of the patient. Instead, motion is performed by a therapist, machine, or other source. It is the type of motion solely generated by the MTAEG [14]. The MTAEG, therefore, is designed to assist the user in fully flexing and extending the fingers and grasping objects used in activities of daily living.

For severe cases of hand immobilization, it is best to begin rehabilitation by using the glove with small intermittent passive motions (IPM) that reduce discomfort as much as possible and gradually return finger strength. The glove can then be used to gradually return continuous passive motion (CPM) to the hand [15]. Joint immobilization is known to cause pain, swelling, stiffness and muscular atrophy [16]. In a study comparing the results of using IPM as opposed to no IPM, in 50 people, with the IPM there is a 36% increase in "excellent" improvement and an 8% increase in "good" results. The study concluded that IPM is a successful technique to improve flexor tendon strength in the hand [17]. When CPM is studied in comparison to IPM, CPM improves the rehabilitation process by stimulating the pluripotential mesenchymal cells to differentiate more into the articular cartilage. By enhancing the nutrition of this cartilage, patients report more comfort in movement and displayed accelerated tendon and tissue repair. In a group study performed on patients with intraarticular fractures, only 30% had healed using IPM whereas 80% of the patients healed at a quicker rate using CPM [17]. IPM and CPM have been shown to reduce patient recovery time, decrease pain during the recovery and prevent future complications. The MTAEG will provide these types of motion to assist in the rehabilitation process.

Safety aspect of rehabilitation devices is inferred through pain or discomfort. Rather than creating broad mathematical definitions of comfort for the average person, it is more useful to study how comfort and discomfort can be perceived and explained. When describing pain, both intensity and unpleasantness are common standards. Intensity refers to the degree of pain the subject experiences as well as to the intensity of the forces, stresses and strains that cause discomfort. Unpleasantness relates to the individual's tolerance of the pain and often depends on the location of the discomfort. These dimensions may then be specified further using a scale with the classes of sensory quality, affective quality and overall pain evaluation. These terms, however, are not defined numerically rather by descriptors. Sensory and affective quality descriptors are related as is shown in Table 2. [18]

TABLE 2: SENSORY QUALITY AND AFFECTIVE QUALITY DESCRIPTORS

Sensory	Affective
Extremely intense	Excruciating
Intense	Agonizing
Moderate	Awful
Mild	Distressing
Weak	Unpleasant
Extremely Weak	Bearable

Research done to determine where the most sensitivity in the hand lies was performed by sectioning a hand into grids and slowly applying pressure to each point in the grid. Studies illustrate that typically the fingers hold the highest Pain Pressure Threshold (PPT), followed by the middle of the hand and the thumb. Furthermore, non-dominant hands experience a lower PPT than dominant hands. All three regions on the hand output very similar PPT values when compared to the rest of the body. This means that the overall sensitivity and therefore comfort of one's hand is relatively equal when compared to other body parts such as the head or torso. The PPT variance seen in the hand is minimal on that entire body scale, but it is still important in designing devices for optimal hand comfort. [19]. Studies have also shown that the most sensitive section of each finger is the DIP, with the least sensitive being the PIP, while the MP fell in between the two in PPT [20]. The knowledge from qualitative dimensioning of user pain can serve as feedback enabling adjustments in device design to best suit the user needs.

2. MOTOR TENDON ACTUATED EXOSUIT GLOVE

2.1 Design Constraints

The following design constraints were applied with the goal to create a comfortable (soft and flexible) and portable glove that assists with rehabilitation:

1. *Open palm design to allow for sensory input*. No soft tendons, tendon braces, motors, pulleys or other design components were placed on the palm of the glove. All mechanical systems were placed on the back of the hand, the side of the fingers or the back of the forearm.
2. *Portability.* Non-pneumatic actuation, namely, tendon-based actuation, was used. Pneumatic actuators have been successful in generating both extension and flexion of the fingers on a human hand. However, they also have their limitations [21]: (a) pressure-based actuators are at a risk of pressure losses, (b) often have significant noise associated with them, and (c) pose control challenges due to difficulty in pump regulation and non-linearities in the system [22,23]. Geared DC motors were used to actuate the tendons on the MTAEG. DC motors are efficient, easy to control and light weight. [23]

2.2 Fabrication of the MTAEG

Testing Model. In order to test the MTAEG prior to clinical evaluation on human subjects, a silicone model of a human hand was created. A negative of a human hand was created using an alginate material. This was then used as a mold to cast the silicone hand, Fig. 2. It is noteworthy that a silicone hand is a perfectly proportional model vs. other types of materials such as foam, plastic, rubber, etc. Further, the silicone has the most similarity to the composition of human muscles due to its platinum-based properties [24]. While bones and joints are lacking, if the correct motion can be achieved on the model, then it follows that motion would work on an actual human hand. Additionally, the authors have personally verified that the desired motion is achieved if tested with a hand containing bones and joints.

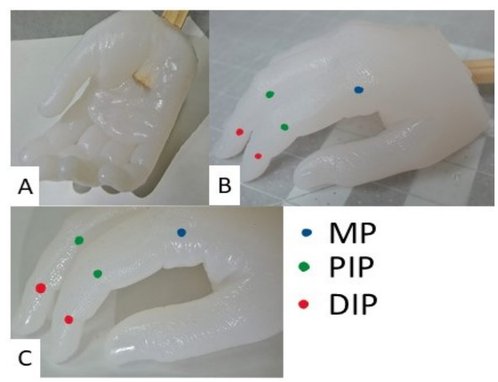

FIGURE 2. SILICONE HAND MODEL FROM THE BOTTOM (A) THE TOP (B) AND THE THUMB, INDEX, AND MIDDLE FINGER (C)

Materials. To create a soft, flexible and easy-to-use MTAEG, a basic polyester glove was used to rout the tendons. The glove fabric (88% polyester, 12% spandex) allows user comfort and motion while providing adequate support for mounting tendons and bracing. The palm of the hand was covered by the fabric of the glove, which can be removed in future iterations of the project with ease. The tendon-cable was a unique 4-strand braided cord, which allowed zero stretch and could withstand weights up to 10 lbs [23]. The tendon bracing mount was designed to safely guide tendons as force was applied. The mount was constructed from nylon which allowed the brace to conform to the back of the hand while still supporting the tendons.

Tendons. The tendons were sewn onto the fingers of the polyester glove. In order to produce extension, the tendon was anchored directly above the fingernail and above each successive joint in the finger, Fig. 3. This design was chosen because it reflects the extensor tendons naturally seen in the back of the human hand. To generate flexion of the finger, a single continuous tendon was run along both sides of the finger, Fig. 4. Typically, flexion of human fingers is caused by the flexor tendons which run across the palm and along the bottom of the fingers [25]. However, due to the design constraints, mirroring these tendons was not an option. To produce flexion in the fingers without having tendons run along the palm, the MTAEG models the bones in the fingers as a three-member kinematic system which allows for dynamic analysis of the forces seen on each link of the finger. Fig. 5, 6, and 7 demonstrate this kinematic system in relation to the reference geometry previously displayed in Fig. 1.

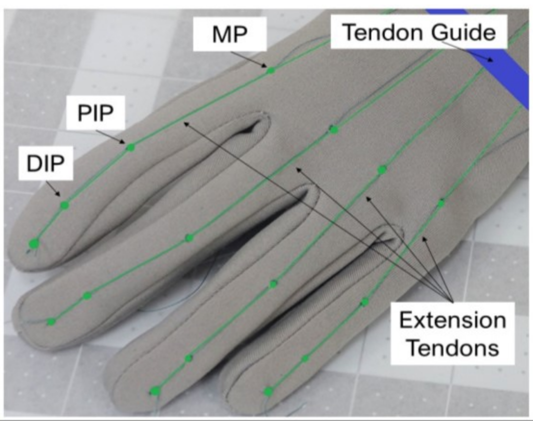

FIGURE 3. EXTENSION TENDONS RUN ACROSS THE BACK OF EACH FINGER AND ANCHORED OVER EACH JOINT

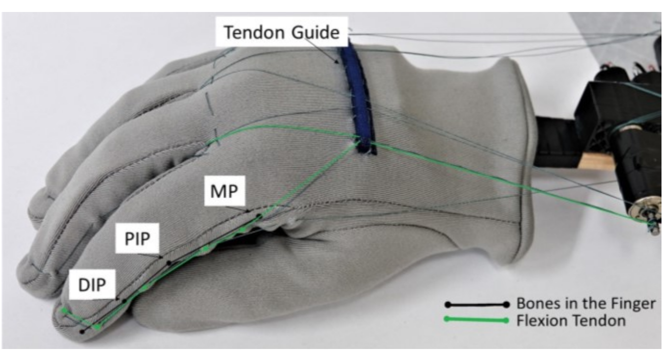

FIGURE 4. FLEXION TENDONS RUN ALONG THE SIDE OF EACH FINGER

In Fig. 5, 6, and 7, the brown lines represent the bones as a 3-member kinematic system, while the green lines represent the tendons utilized to actuate the MTAEG design. The relative angular (θ_i) values displayed in Fig. 6 are the median values of the data shown in Table 1 [18]. Utilizing trigonometric equations with our known values in relation to Fig. 6, all lengths and angles can be calculated.

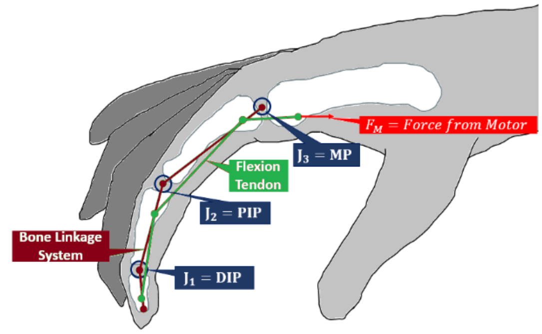

FIGURE 5. KINEMATIC SYSTEM ON HAND TO GENERATE FLEXION

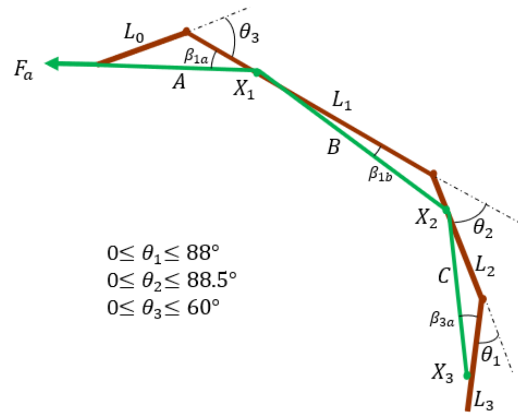

FIGURE 6. KINEMATIC SYSTEM ANALYSIS OF FLEXION

Actuation. In order to determine what motor would successfully actuate the fingers, analysis was performed on the kinematic mechanism model of the finger. For the flexion tendon the following analysis was performed based on the system seen in Fig. 6.

The angles being measured, θ_n, are converted to interior angles, α_n, to simplify calculations through Eq. 1, 2, and 3.

$$\alpha_1 = 180° - \theta_1 \tag{1}$$
$$\alpha_2 = 180° - \theta_2 \tag{2}$$
$$\alpha_3 = 180° - \theta_3 \tag{3}$$

The tendon lengths, A, B, and C are determined as

$$A = \sqrt{L_0^2 + J_1^2 - 2L_0J_1\cos(\alpha_1)} \tag{4}$$

$$B = \sqrt{(L_1 - J_1)^2 + J_2^2 - 2(L_1 - J_1)(J_2)\cos(\alpha_2)} \tag{5}$$

$$C = \sqrt{(L_2 - J_2)^2 + J_3^2 - 2(L_2 - J_2)(J_3)\cos(\alpha_3)} \tag{6}$$

A is the tendon length from the initial tendon mounting point on the hand to the tendon mounting point X_1, B is the tendon length between the tendon mounting points X_1 and X_2, and C is the tendon length between the tendon mounting points X_2 and X_3.

J_1 is the distance from the MP joint to the tendon mounting point M_1, J_2 is the distance from the PIP joint to the tendon mounting point M_2, and J_3 is the distance from the DIP joint to the tendon mounting point M_3,

L_0 is the distance from the initial tendon mounting point on the hand to the MP joint, L_1 is the finger length from the MP joint to the PIP joint, and L_2 is the finger length from the PIP point to the DIP point. The angles β between the finger phalanges and each tendon path are determined as

$$\beta_{1a} = \sin^{-1}\left(\frac{L_0 \sin(\alpha_1)}{A}\right) \tag{7}$$

$$\beta_{1b} = \sin^{-1}\left(\frac{J_2 \sin(\alpha_2)}{B}\right) \tag{8}$$

$$\beta_{2a} = \sin^{-1}\left(\frac{(L_1 - J_1) \sin(\alpha_2)}{B}\right) \tag{9}$$

$$\beta_{2b} = \sin^{-1}\left(\frac{L_3 \sin(\alpha_3)}{C}\right) \tag{10}$$

$$\beta_{3a} = \sin^{-1}\left(\frac{(L_2 - J_2) \sin(\alpha_3)}{C}\right) \tag{11}$$

Using these angles, the perpendicular force, F_{p,x_n}, produced by the tendon at each mounting location is determined as

$$F_{p,x_1} = F_a(\sin(\beta_{1a}) + \sin(\beta_{1b})) \tag{12}$$

$$F_{p,x_2} = F_a(\sin(\beta_{2a}) + \sin(\beta_{2b})) \tag{13}$$

$$F_{p,x_3} = F_a(\sin(\beta_{3a})) \tag{14}$$

Using these perpendicular forces, the torque, τ, created by the tendon mounting point with regards to the previous joint are determined as

$$\tau_{MP} = F_{p,x_1}(J_1) \tag{15}$$

$$\tau_{PIP} = F_{p,x_2}(J_2) \tag{16}$$

$$\tau_{DIP} = F_{p,x_3}(J_3) \tag{17}$$

A similar analysis was performed on the extension tendon in order to determine the torque seen at each joint as a function of θ_1, θ_2 and, θ_3. Figure 7 shows the extensor tendon in relation to the bones of the finger.

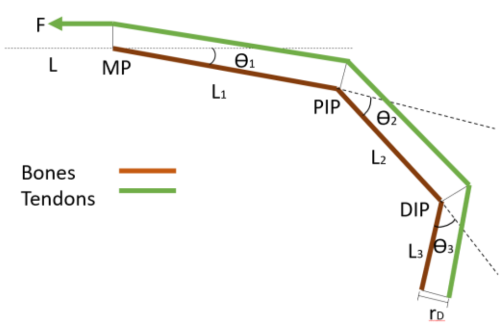

FIGURE 7. KINEMATIC SYSTEM ANALYSIS OF EXTENSION

The torque seen at the end of finger is the cross product of F, the force generated from the motor, and r_D, the distance from the center of the bone and the tendon mounting location shown in Eq. 18. The torque seen from the DIP, PIP, and MP joints can been seen in Eq. 19, 20, and 21 respectively. The total torque experienced by the hand can be seen in Eq. 22 where L is the distance from the MP joint to the final anchor point of the tendon.

$$\tau_{DIP} = F(\mathrm{r}_D) \tag{19}$$

$$\tau_{PIP} = F(r_D + L_2\sin\theta_3) \tag{20}$$

$$\tau_{MP} = F_a(r_D + L_2\sin\theta_3 + L_1\sin\theta_2) \tag{21}$$

From this position analysis, the forces and torques seen on each segment can be found for any given location as a function of theta, the position of the finger.

Additionally, data was taken from a 1999 Virginia Polytechnic Institute report on average finger strength and a 2004 Journal of Hand Therapy article regarding relative strength of each finger [26,27]. This information was used to verify that the overall torque seen from the motor-pulley combination was adequate to actuate the MTAEG. In the Virginia Polytechnic Institute report, 100 volunteers aged 18 to 65 went through a series of finger strength tests, including grip strength and extended index finger lateral downward press. The average grip strength and lateral press average strength were found to be 43.05 N and 370.67 N, respectively. [26].

The Journal of Hand Therapy article studied loss of grip strength in people who had lost the function of various digits and found the following: on average, index, middle, and the combined strength of the two ulnar fingers contribute 25%, 35%, and 40% total to overall grip and hand strength [28]. Combining this with the average grip strength gives an average index curling strength of 92.67 N.

Using the dimensions of the hand model and predetermined tendon placement points, the previous equations were used to determine the minimum torque created around each joint for a given applied force. Motors were selected accordingly.

Tendons were attached to the motor drive shaft of the predetermined motors. One motor was designated per tendon in an effort to minimize the actuator size and weight as it allowed for smaller motors. With this design a total of 8 motors are needed per hand. Because the motors only weigh 17 grams, having a total weight of 136 grams, this number of motors is not a problem. With these equations, it was determined that a motor-pulley combination able of providing the 10 lbf each tendon was rated for would be sufficient to hold a closed fist.

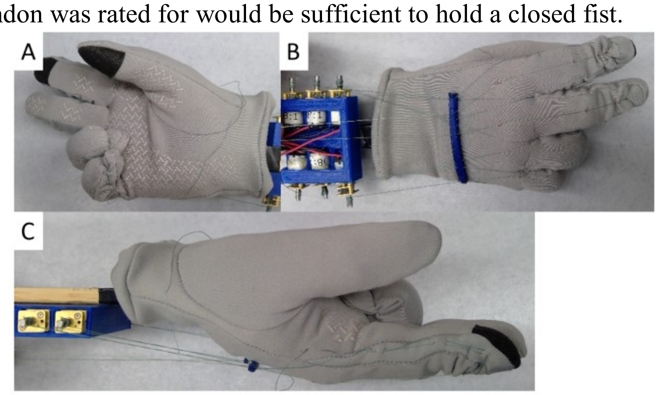

FIGURE 8. EXTENSION TEST OF THE INDEX AND MIDLE FINGER WITH THE BOTTOM, TOP, AND SIDE VIEW SEEN IN (A), (B), AND (C) RESPECTIVLY.

3. PERFORMANCE TESTING

3.1 Prototype Testing

Extension. Extension was created by exerting a force on extensor tendons as seen in Fig. 3. When the fingers are curled, the extensor tendon is actuated via an independent motor and the finger will straighten. This extension can be seen in Fig. 8.

Due to having a limited number of motors in the lab, only the index and middle fingers were tested with both extension and flexion. However, all the fingers were individually tested to assure the proper extension motion.

Flexion. Flexion testing was accomplished by using the motors to actuate each finger of the hand model individually, and collectively. Each finger had its own flexion tendon and motor so as to allow for a variety of movements. The individual finger flexion can be seen in Fig. 9 and the collective flexion can be seen in Fig. 10.

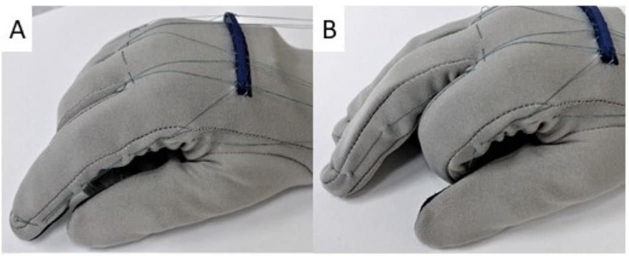

FIGURE 9. CURLING TEST OF THE INDEX FINGER WITH THE EXTENDED STATE (A) AND THE FLEXED STATE (B)

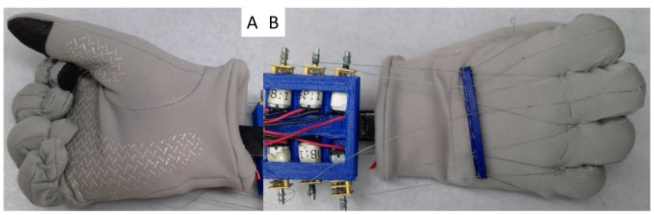

FIGURE 10. FLEXION TEST OF ALL FINGERS SEEN FROM THE BOTTOM (A) AND THE TOP (B)

A separate tendon was run along both the pinky and index fingers and across the hand in order to produce adequate curling of the MP joint.

3.2 Numerical Analysis

Through testing of the tendon prototypes outlined in section 3.1, it was determined that adequate median joint angles were produced by the MTAEG design. The measured MTAEG joint angles as compared to Table 1 [12], are shown in Table 3:

TABLE 3: THEORETICAL MEDIAN JOINT ANGLES VS. MTAEG MEASURED JOINT ANGLES

Joint	Theoretical Angle	Measured Angle
MP	79° - 97°	45°
PIP	87° - 90°	90°
DIP	52° - 68°	50°

The PIP joint is actuating exactly as desired. The observed angle of 90° is perfectly within the desired range. The DIP joint, while being close to the desired range at 50° falls just short of the desired range. This could be due to error in the measurement method. In order to measure angles, the reference lines seen in Fig. 1 were marked and measured which leaves room for several degrees of error. Another issue to consider is the fact that the glove does allow for a bit of motion when the force is applied. Since the glove is fabric it can stretch and slide along the hand in an undesirable fashion. This can result in the forces not being perfectly transposed on the fingers. The MP joint was the most difficult to actuate. The MP joint is a fully encased joint with no external access seen on the hand. As such it was difficult to mount tendons on the side of each MP joint. During experimentation it was determined that by curling the index and pinky finger in conjunction, the MP joint will naturally follow. Thus, in order to generate full curl, all the fingers were actuated together. The loss of forces and torque transmission to the fingers remains the focus of successive design iterations.

4. DISCUSSION AND FUTURE RESEARCH

4.1 Discussion of the project results.

As tested, finger flexion and extension on the MTAEG glove is successful. The extension tendons, modeled after a pre-existing biological tendon, were able to duplicate the natural human motion of extending different fingers of the hand. Both the index and middle finger were tested in conjunction with flexion and the ring and pinky fingers were tested independently. In regard to flexion, while the current design meets the design criteria and possesses adequate force to induce motion in the finger, questions regarding optimization still exist. By modeling the fingers as three-member kinematic systems the necessary preset tendon mounting locations are determined to generate basic motion. In the future, the design will look to optimize the torque being used by adjusting the tendon placement along the fingers to more efficiently actuate basic motion, and potentially move to more complex motion. By verifying both flexion and extension, the MTAEG is showing that rehabilitation can be assisted with minimal, soft robotic designs.

4.2 Future Research

Force Efficiency. In the future, forces acting upon the hand model from the glove need to be measured to verify the mathematical model used for forces. Verifying this model is an important step in proving that this device is safe for human trials. Additionally, during construction of the glove, the positioning of where the tendons travel outside and inside glove resulted in a varying amount of actuation effectiveness. Having force measurements available will allow the tendon positioning to be optimized.

Feedback Control. Currently, the MTAEG does not utilize positional or force feedback in its control loop. This will be necessary for safety - preventing a user's finger from being improperly actuated in a harmful manner. The feedback will also be needed if control of actuation speed or position beyond fully curled or extended is desired. This feedback is also a necessary feature in the pursuit of human trials to ensure that safety mechanisms are in place to prevent the incorrect actuation of the glove.

Portability. Additionally, it is intended that a battery will be used to power the motors in the future. This will remove the reliance upon a power supply and allow for greater mobility of the patient being rehabilitated. Further iterations of the MTAEG aim to provide a mounting solution for the battery, as well as the motor controllers and microcontrollers, to prevent mobility impediment due to power or data tethers.

Design Optimization. There is room for design optimization. Currently the design is using one motor per tendon, but, in the future, we are looking to optimize this and reduce the overall number of motors required. Another aspect of optimization will be with the glove itself. Currently, a full glove is used. It would be better to have a smaller design such as straps on each joint for mounting the tendons and no extra fabric.

The MTAEG has shown the potential of a tendon-based soft robotic device for hand rehabilitation and adds minimal weight to the hand. It allows for tactile feedback along the underside of the hand and fingers to maximize the effectiveness of rehabilitation exercises. While solutions to various problems encountered have been discussed, the greatest benefit seen is the ability to actuate motion in a human hand from tensile based, soft motor tendons.

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