

Developing a Climbing Assistive Exoskeleton*

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Abstract— This paper presents a design of a climbing assistive exoskeleton (CAE) that reduces stress and strain on the fingers of a climber. Climbers routinely must support their entire body weight with their fingers. While human hands can accommodate climbing, experienced climbers are continuously testing the limits of their bodies, and hand injuries are both a frequent and severe occurrence. This device will help injured mountain climbers to continue training with reduced impact to their hand, and in turn increase climbing endurance and duration. Inexperienced climbers can also benefit from the device as they suffer from a lack of finger and hand muscle mass. This device will aid them in training safely and learn proper grips while developing their strength to be successful. The CAE is a glove-like device which can be slid on over the user's hand while climbing. The exoskeleton will have resistance bands going from the fingertips to the base of the hand, causing the hand to curl. This will create a constant passive force which will reduce the force normally directed through the pulleys and tendons while climbing. In the case of hand opening, the CAE has a motor that should assist the climber to overcome the passive force created by the bands. The glove is controlled through a microcontroller in real-time via feedback from electromyography sensors attached to the forearm of the climber. Our objective is to achieve a 20-40N reduction in force through the fingers while climbing per hand.

I. INTRODUCTION

Mountain climbing is one of the most physically demanding sports. Some studies show that up to 73% of climbing related injuries are to the wrist and hand [1]. Climbing can put a lot of strain on the pulleys and tendons of the fingers. It's imperative that climbers be mindful and careful with their tendons, and pulleys within their hands to continue doing their sport. There are 3 different grades of finger strains. Grade 1 is mild fiber damage which results in the climber feeling pain for a couple of days, but no serious recovery is needed. Grade 2 strain more fibers were injured, and the climber may need to let the injured finger/muscle recover for 2-3 months to heal all the way. Grade 3 Strain is a full rupture of the muscle or tendon. Grade 3 injuries may require surgery to reattach the damaged muscle and tendon [2]. The most common injury to climbers is a strain to the A2 pulley. The pulleys in the fingers are responsible for holding the tendon tight to the bone. Making tendons function as fulcrums curling the fingers when it contracts, curling the fingers. In the worst case with a grade 3 rupture, the tendon will rip through the Pulley [3]. Without the pulley, the tendon would take the path of least resistance and bulge out from the joint preventing the climber from properly curling their finger. The second most injured part of the hand is the tendons, particularly the Flexor

tendon. The tendon runs from the tip of the finger down the fingers, through the hand and attaches to the finger muscles in the forearm. When the muscle contracts, the tendon is pulled causing the finger to curl from the reduction in length. A study looking at 604 injured rock climbers found 247 (41%) of the injuries were finger related. Of those 247, 122 had pulley related injuries and 42 had tenovaginitis based injuries. The paper used 4 grades of injuries with the highest 4 being multiple ruptures. Of the pulley injuries there were 48 grade 1 injuries, 31 grade 2 injuries, 36 grade 3 injuries, and 7 grade 4 injuries [4].

To gather information about the climbing demographic their Needs from a product of this type, and how they deal with finger injuries. We sent a survey out to the club. From these interviews we found if climbers injure their hand and/or fingers depending on the severity of the injury they would stop climbing or explore some temporary solutions. If the injury is anything less than a rupture. They will choose to tape the injured finger to a neighboring finger creating a splint. The solution technically works but restricts mobility and does not stop the root cause. There are no products which aim to protect the tendons and pulleys in the hand while climbing for mountain climbers. The only products available for mountain climbers are regular gloves designed with climbing in mind. With rubber grips for the palmar side of the hand for grip. Some are also designed to keep the hand warm in cold conditions or to handle ropes.

The rest of the paper is organized as follows: section 2 presents the system design procedure that has been followed in this study and discusses the outcomes of this stage. System integration and implementation are shown in section 3 and section 4 concludes the paper.

II. SYSTEM DESIGN

A. System Requirements

Most exoskeletal systems are designed for rehabilitation or for augmenting human capabilities by controlling all movement of the hand. These exoskeletons tend to be immobile, and impractical for climbing due to size, weight, or the need for a base station [5]. Rehabilitation style devices focus on imitating human hand motor skills by using external actuators and motors to force the user's hand to perform mundane tasks [6], such as holding a cup of water or training hand movement through repetition after a stroke. Augmentation style exoskeletons aim to significantly increase grip strength or to handle all movement. Where the hand exerts little to no force in the moment while the exoskeleton does all the work. Rehabilitation types of exoskeletons have very little

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force, a fraction of the force and strength a healthy human hand can achieve. On the other hand, augmentation style exoskeletons suffer because of the number of motors, sensors, material, and power. Making the glove very heavy, and bulky both as breaking points for prospective mountain climbers [5]. In order to find a solution to our unique challenge of both weight and force, we needed a fresh perspective for exoskeleton technology. This design must be lightweight, power efficient and be designed in a way that the intended audience of climbers would feel intuitive to use. We set out to design a piece of exoskeletal technology that focused on allowing the user to have as close to or above the unaided capabilities a climber has, to perform the same strenuous acts with reduced stress on the tendons and pulleys, reducing the probability of injuring these parts. In summary, the system must meet the following requirements as outlined by our stakeholders, The device must: 1. not injure or endanger the climber, 2. be easy to use, 3. function under a load of 72.57kg, 4. must weigh under 2.36kg per hand, 5. have friction equal or greater than finger pads, 6. Operate the full duration of a climb ~10min, and 7. not shift on hand while equipped.

Based on these requirements, the team created different design alternatives and the winning design concept is adopted in this project. More details about the design concept is presented in the following subsection.

B. Design Concept

The first step was to determine the style of actuation that the device would be designed around. From our research we found that hand exoskeletons could be separated into different categories based on their method of actuation [5]. Of the ones we thought best fit our application, series elastic actuators, shape memory alloys, or tendon and/or Bowden cabling structures [7,8,9,10,11,12,13,14,15,16,8,10,18]. Where motion is driven by either servo motors or linear actuators. We decided to utilize a passive elastic force from the user's fingertips to wrist to aid in the user's intended motion of grasping with their hand taking inspiration from designs [19,20,21]. For this design we theorized that we could utilize a passive resistive force to aid the user in the primary high stress functions of climbing, closing the hand to support yourself. This method of actuation would avoid having cables or other components on the palmar side of the hand. Giving the climber more feeling and sensation in their hands of the surface they are gripping. This method also had the benefit of providing a more direct path to distribute the stressor forces that would normally be running through the users' pulleys and tendons. Allowing climbers to have full range of motion while gripping a rock or ledge, while still reducing force. Encouraging the climber to develop proper climbing techniques and develop their muscles to improve themselves. By relying on external actuators to aid only when the user already intends to open the hand the actuator can be sized to counteract the passive resistive force. This works to reduce the torque, power and weight requirements of the motor that will power the Bowden cable system [5]. We are not trying to force the user's hand open but to make the user feel as if the resistive forces of the band are not present when they open their hand as normal. This design is only focusing on reducing the stress on the fingers and what is necessary to counteract the force of

the bands, so the exoskeleton is not distracting to the user. The design stays under the weight parameters of our design requirements and meets our requirements in all other areas.

C. Detailed Design

We chose to use resistance bands for the elastic force and a cable running along the dorsal side of the hand to a motor mounted at the base of the wrist. To achieve the closing and opening of the fingers, respectively, in order to support muscular pulleys and flexor muscles in the human fingers. Resistance bands are held in position with the help of 3D printed wrist plates on the gloves as shown in Fig. 1. This keeps the resistance bands in place and when the user is wearing the exoskeleton the bands are kept in consistent tension. With the aid of cables, we were able to perform the opposite action, opening the fingers by attaching one end of the cables to the same point at the fingertips as the resistance band. The cables are then guided down the dorsal side of the fingers to a splitter which joins all the finger cables into one cable connected to the motor.

To start the design process, we needed to pick a resistance band to use before picking other components. We tested 5 different thickness of bands. To test the bands, we cut them into strips 177.8mm Long and 12.7mm wide. Then using a force gauge, we stretched the bands to different lengths, while recording the force required to stretch them. Our results showed the bands behaved linear regardless of thickness. Which meant we could pick a band based on the force and not worry about the force curve of the band. We decided to go with a 0.45mm thick band. Which generates the most amount of force while not overpowering the design of the exoskeleton. Next, we measured the force change of the band based on width. Repeating setup from the previous test. We cut strips 177mm long with different widths. We decided to go with a band of 12.7mm as it offered the maximum amount of force without distortion in the curve. We are using the section of the curve in Fig. 2 from width 9.51mm to 14.265mm as our prototype needs behavior of the bands under this curve. There is no measurable force below 100% elongation. The band with a length of 152.4mm and a width of 12.7mm acts more uniform than other lengths. We believe this is due to warping in the band.



Figure 1. Side view of CAE (resistance bands are held in place by bending around the fingertip, and secured at the wrist with a screwed down plate)

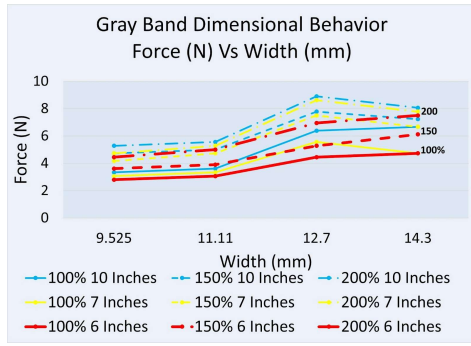


Figure 2. Width vs Force (3 different widths were tested to measure the force required to stretch them to the same length.)

When the band at different lengths begins to warp and bend, reducing its surface area, this causes the band to look like a wave with high tension spots and low-tension spots. As the band width is increased, the force becomes progressively harder to predict based on its elongation. Fig. 3 shows the force vs elongation of the length and width of the bands we are using for the final project.

The force from the bands is not the same as the force required to straighten the fingers of the exoskeleton. If you stretch a band straight on its own, it will have 4N of force. However, due to changes in the direction of forces and the friction from the fishing line against the plastic. Drastically increases the force required to open the hand. The force is also constantly changing depending on the angle and position the finger is in at any given moment. The resistance band displays a linear behavior within a 100% elongation, as shown in Fig. 3. The slope of the curve is 0.02723N/mm, representing the stiffness (k) of the band determined using Hooke's law,

$$F_s = -kx \quad (1)$$

where, F_s = changes in applied force, k = material constant, x = is change in displacement. Assuming the initial position is the prototype's resting position Fig. 1. Also, assuming static equilibrium at initial position, force exerted by the resistance band, the force applied by the motor, and reaction to these forces at fingertip will balance each other. We used our test results to test the force exerted from the band when stretched to various lengths. We were able to create charts to help us pick out the best length, width and color of band for the project. At initial position from Fig. 4, We used the measurements for the distal (17.40mm), middle (26.33mm), and proximal (44.63mm) average phalangeal lengths of an adult human [22]. We calculated the angle formed by the proximal phalanx and the X-axis, to be 32° [3]. For our calculations we used these variables: F_1 is force on the fingertips from the resistance band, F_2 is opposite force on the fingertips from the cable, α is the angle between F_2 and the horizontal axis, β is angle between F_1 and the vertical axis, h is the reaction at fingertip due to hand inertia/resistance where hx and hy are X and Y components of h .

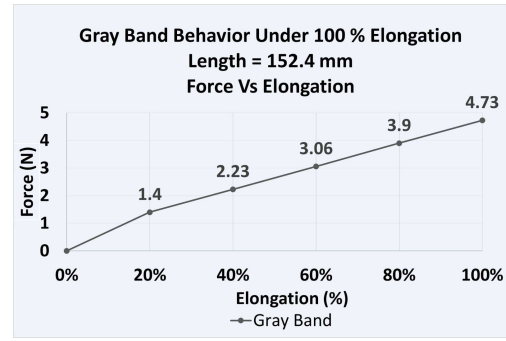


Figure 3. Gray band behavior (Gray band cut to 152.4mm long and 12.7mm wide, measuring the force required to stretch to different percentages of elongation.)

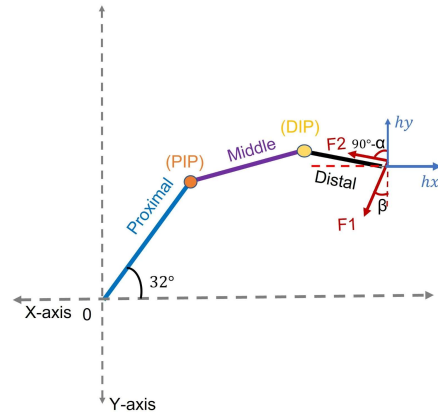


Figure 4. Free Body Diagram of finger phalanges with forces acting on the fingertips.

The force values change depending upon the values of angle α . Due to relatively very small length of the distal phalanx to the resistance band's length, we assume its movement does not change the value of angle β significantly and we measured the angle $\beta = 15^\circ$ and we obtained the following result considering static equilibrium.

$$F_x = 0, F_y = 0 \quad (2)$$

As we are considering static equilibrium as an initial condition, the situation should satisfy the conditions from (2). We are considering two cases of static equilibrium; the first case is when no opposite external force is applied on the fingertip to overpower the force exerted by resistance bands. The second condition is with the external force acting on the fingertip where F_2 is an external force applied by a motor.

Case 1: Without application of force from motor ($F_2 = 0$);

$$hx = F_1 \sin(\beta) \quad (3)$$

$$hy = F_1 \cos(\beta) \quad (4)$$

Equation (3) and (4) represent horizontal and vertical force components of force h . These are minimum requirements for the force components of h with no application of external force.

Case 2: With application of force from motor ($F2 \neq 0$), to maintain the equilibrium; the fingertip will resist this additional force due to the inertia of the human hand and finger.

$$h_x = F2 \cos(\alpha) + F1 \sin(\beta) \quad (5)$$

$$h_y = F2 \sin(\alpha) + F1 \cos(\beta) \quad (6)$$

$$F2 = (h_x - F1 \sin(\beta)) / \cos(\alpha) \quad (7)$$

The x and y components of force h can be calculated using (5) and (6) respectively. We can use these equations to calculate the force applied by the motor in (7) is $F2$. We are considering two distal phalanx positions with angles of 0° and 45° . The force values will change depending upon values of angle α and angle β . The distal phalanx has very small length with respect to the length of the band so the change in the angle β with the fingertip's movement is very negligible and its measured as $\beta = 15^\circ$. We can get two cases with (6) by changing the values of the angle α .

Case A: We are considering fingertips in the horizontal position to get the force $F2$ i.e., when $\alpha = 0^\circ$, $\cos \alpha = 1$; therefore, $F2$ is minimum

Case B: We are considering an intermediate position of α between 0° and 90° (considering intermediate climbing position of finger) i.e., when $\alpha = 45^\circ$.

$$F2 = 1.41 * (h_x - F1 \sin(\beta)) \quad (8)$$

To check developed stresses in the fingertip, horizontal force component of h should be at least more than the minimum value which we calculated in (3).

$$h_x \geq 2 * F1 \sin(\beta) \quad (9)$$

We have taken horizontal force component $F1$ twice the horizontal component of force h which can be represented by (9). We can say, the relation of force $F2$ from (8) will be

$$F2 \geq 1.41 * F1 \sin(\beta) \quad (10)$$

Considering factor of safety as 2 we get the design force for force $F2$ which we calculated in (10) will be.

$$F2 = 2.82 F1 \sin(\beta) \quad (11)$$

Equation (11) represents the relation between design value of force $F2$ and horizontal component of force $F1$ with a factor

of 2.82. Earlier from (1) and Hooke's law we calculated value of material constant $k = 0.02723 \text{ N/mm}$; so force $F1$ due to band at initial position to maintaining stretch of 25.4mm will be

$$F1 = -kx = 0.7 \text{ N} \quad (12)$$

After putting values of $F1$ from (12) and $\beta = 15^\circ$ in (10) we get,

$$F2 = 1.9 \text{ N} \quad (13)$$

From (13), the force required to extend one finger against the resistance band can be rounded up to 2N, with the other fingers requiring less effort because we calculated this using the middle finger as a reference. We determined roughly 8N is needed to lift four fingers. To select the motor, we had to consider the weight, operating voltage, lead times, and torque. The initial motor options included Linear actuators, dc brushless motors, and dc servo motors. Due to the long lead times of those motors, we went with the Zoskay 35kg High Torque coreless servo motor for prototyping. This is a 5-7.4V dc servo motor weighing 60g. It falls within our voltage range and is still within weight and torque requirements. Decided to use an Urogenex 7.4V Li-ion 2000mAh battery to power each exoskeleton. According to our poll data, the length for a rock wall climb was 10 min. Given an approximation of the user opening and closing their hand to climb every 15s. We estimated the motor to draw 2A (combination of actuating current and holding current). We estimate a 2000mah battery will power the system for one hour or 4 full climbs.

To control the movement of the motor a switch or a sensor is needed. Safety for the climber was the priority in designing the hardware to control the Exoskeleton. It was important to make sure the input controls wouldn't move the exoskeleton unintentionally. The other factor to consider for safety was panic moments [23]. When a person is panicking or scrambling to do things quickly, they will often forget how to operate or control a system as the brain is not thinking clearly. Unless it's something they have trained to do for a considerable amount of time to engrave the behavior to memory. To accommodate both requirements we decided to use 2 EMG (electromyography) sensors. We chose to use Mayoware's AT-04-001 as it was all in one system with no additional hardware required [24]. One of the reasons we picked these EMG sensors is due to the sensors being independent circuits where the boards have built in amplifiers and rectified sensors making them easy to test and get working fast. As we were testing the exoskeleton, we found this worked against us. Due to the Flexion and Extension muscles being smaller muscles more tightly packed compared to the wrist muscles. We found that these signals were very small. The signals could still be detected and used to control the Exoskeleton but would also mean it would pick up more false readings. Even touching the muscle near the sensor is enough to give a false reading. This interference is extremely

hard to filter out and still has the Exoskeleton working quickly and reliably. Our current solution around these problems is to have the user apply force against the motor for a short duration creating larger amplitude to trigger the motor to give slack allowing the resistance bands to close the hand. We applied the same idea for opening the hand in the opposite direction. In the future we think that by employing more EMG sensors such as a full forearm sensor bracelet with 5 or more EMG sensors equally spaced around the forearm, could completely solve this problem. By increasing the number of sensors around the arm when there is noise if more than one sensor reads it it can be filtered out as noise. This solution may also help us get away from having to use electro pads for contact and instead employ non adhesive metal plates due to the noise cancellation. Another option is to build an algorithm and a custom of the rectifier from scratch which are specifically designed to measure the muscles for finger extension and flexion.

For controlling the exoskeleton, we decided to use an Arduino Uno microcontroller. This board is a bit large at 3600mm² for a retail exoskeleton. Future models could use a Nano Arduino 810mm² or a similar sized microcontroller. We used an Arduino Uno for the initial prototyping. Due to the voltage regulator on the Uno, we had more freedom for testing varying power supplies, which is absent in Nano Arduino boards. Both controllers are programmed using the Arduino IDE software. With very little change required in the program to switch the board later. For the prototyping we 3D printed all the parts in Polylactic Acid (PLA) filament. We calculated the structural integrity of the part covering fingertips, and the cable splitter, to make sure PLA is a suitable choice and parts would be strong enough. To calculate the elements of our design accurately, we used Hypermesh by Altair to run a stress analysis on the fingertip design and the cable splitter to help in the designing of the parts. The force exerted from a band is measured by stretching it to 100%, 150% and 200% of a length. F1 is acting on the frontal section of the fingertip with magnitude of 0.7N from (12) and the rear section is under the force F2 with a magnitude of 1.9N from (13). As it's shown in Fig. 5. The fingertips work by having the resistance band run up and through the front cutout. The extension cable runs through the guide hole located on the top of the part and wraps around the middle anchor to secure. Side holes are used to sew the part to the glove.

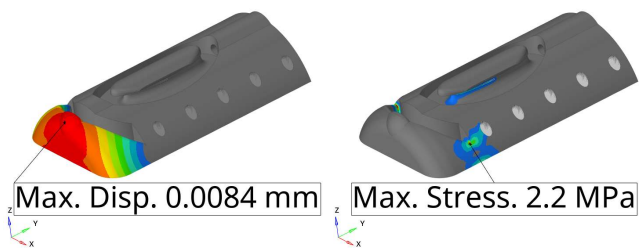


Figure 5. Fingertips force analysis (Left image is a displacement distribution. The right image is stress concentration. Red represents the maximum value for local displacement/stress. Gray represents no displacement/stress in that area.)

In Fig. 5 the results for maximum displacement of 0.0084mm and maximum stress value of 2.174MPa. We conclude that this component will withstand application of minimal force values. We calculated the maximum stress and displacement by multiplying the original minimum force data by a factor of 22.760. The maximum displacement observed was 0.1902mm and a maximum stress of 49.456MPa before the Part would fail. These values are adequate for operating under the full range of forces, stresses, and displacements found in our real-world prototype.

III. SYSTEM INTEGRATION AND TESTING

There are muscles for finger flexion and finger extension. The muscles are in the forearm. The extensor muscle group is on the dorsal side of the forearm. The extensor muscle group is located on the same side as the antecubital fossa (elbow pit). Following our top priority of safety first our microcontroller algorithm is checking both EMG sensors, with XOR logic. The motor will move when only 1 sensor is high, if both are high the motor will not actuate. The exact value measured from the muscle is unpredictable, so a high reading is set with a broad. To avoid the motor from actuating from a false high. We implemented a 2 stage, time delay style if statement. if the sensor values are within the high range, the program will wait for 20ms. This will happen 2 more times. If the sensor is still high after the third if statement, then the motor will move either closing the hand or opening the hand based on which sensor is high. To make sure the motor is unobstructed. We added a hall effect current. sensor to the motor. During normal operation the servo will draw 1A peak, anything above this would mean.

The motor is obstructed or is being acted on by an external force. In the event the motor's current draw is above 1A, the motor will stop receiving new commands which will stop it from moving for 200ms. In addition to stopping the motor an error will be counted. If the motor faults more than 3 times the motor will be sent to its home position (rotated toward the fingers). The motor will not receive new commands for 100s giving the climber time to figure out what the problem is and fix it. After the time is up the Program will reset the counter and go back to normal operation. Fig. 6 is a photo of our CAE version 1 prototype.



Figure 7. Strain gauge rig for lab testing

To test the overall force reduction on the user by the exoskeleton we had a tester place their elbow on a table, so the arm is supported and isn't adding any weight to the exoskeleton as shown in Fig. 7. We then set up a strain gauge, so it was level with the base of the fingers (where the fingers attach to the hand). The tester then relaxes their hand letting the resistance bands act upon the strain gauge. We Performed this test with 2 users 5 times each. From this test we found that the exoskeleton had an average force of 18N aiding the grasping motion. This is enough force to reduce the users weight affecting the fingers by 1827g.

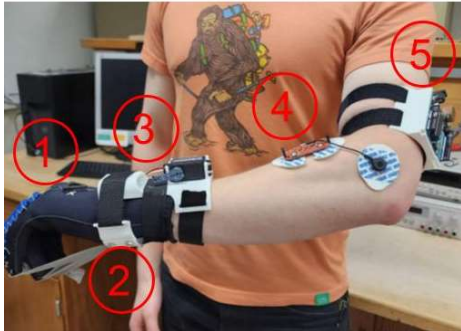


Figure 6. CAE Prototype (1: Glove with finger tips and cable guides, 2: resistance bands clamp, 3: motor mount and cable splitter guard, 4: EMG sensor on flexor muscles, 5: microcontroller and battery mount)

IV. CONCLUSION

In this project we successfully designed, devised and fabricated a proof-of-concept exoskeleton, which can operate in a lab environment for testing. The device consists of a neoprene glove with attached custom fabricated fingertips, cable guides, motor mount, controller and battery case, EMG sensors, and control algorithm. All components are strapped to the user by Velcro straps or sown directly into the glove. The test results came short of our goal of achieving 20-40N of force reduction. The project succeeded though at showing the promise this concept can achieve from refinement. To make this device both efficient and practical in the future, it is recommended to switch to high torque and speed BLDC motors to reduce the weight while still being able to open the hand. For production, it is recommended switching to higher strength plastics and material if necessary. Materials such as nylon infused plastic, or carbon fiber can be explored as options to allow for a reduction in size and weight. Using an Arduino nano or custom circuit in place of the Uno is another consideration that could reduce the size of this product.

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