The Exoskeleton Glove for Control of Paralyzed Hands

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Abstract

We describe the design of a prosthetic device for patients who have suffered loss of muscular control of the hand. We describe some preliminary design considerations with emphasis on the sensing and actuation systems. The prototype achieves several movements of the fingers of the hand. The design was closely based on the natural human hand to ensure effectiveness and comfort. The Exoskeleton is worn as a tight glove and the joints are flexed by cables and motors. We also describe some preliminary tests.

1 Introduction

Victims of nerve or muscle damage in the hand or lower arm have few options for restoring use of the limbs. Functional Neuromuscular Stimulation (FNS) aims at stimulating the muscles from external sources, but the technique is confined to a few laboratory tests. Our approach was based on the relative success of prostheses for replacing functions of the arm in amputees. We have therefore attempted to create an externally powered device which can actuate the fingers and allow patients to accomplish more delicate and precise manipulations.

A few similar devices exist in different forms. Exos Inc. has developed the Dexterous Hand Master [3]. It has been used in conjunction with the Utah/MIT Dexterous Hand. It consists of an external 'shell' worn on the hand which measures the angles of the finger joints and relays the information to the mechanical hand. Another similar product is the VPL Dataglove [4] developed primarily for gesture recognition. It consists of an elastic glove which monitors the movements of the user's hands through specially treated optical fibres attached to the top of the hand. However, none of these products address the issue of external actuation. Perhaps the device that resembles our approach the most (and which we found out about after we had completed most of our work), is the JPL glove controller [5]. This controller also senses human hand inputs through four-bar linkages and pulleys that backdrive the human finger joints. Four modular finger drive pacakges are included (each with four actuators to drive each finger). Flex cables transmit motion and power from the drive package to the glove.

The primary purpose of our project was to construct a mechanical device which could externally actuate a person's fingers. Since precise manipulation is one of the goals, it was necessary to design a system which could be used in conjunction with a feedback controller. The primary motions considered were:

1. Flexion and extension of the fingers.
2. Flexion and extension of the thumb.

Eventually, extensions to the control of the roll, pitch and yaw motions of the wrist and hand can be designed. The control of the finger and thumb motions allows the hand to perform 'pinching' motions. The finger is modeled as a simple three degree-of-freedom linkage. The side-to-side motion of the finger and hand was not considered since it is not necessary for many tasks. The thumb has four degrees of freedom enabling it to oppose the fingers.

The primary design constraints were as follows:

1. Ability to accomodate natural motions of the hand. The mechanics of the human hand must be accounted for. For any joint, the shape of the bones causes the center of rotation to change during the rotation. The exoskeleton must allow this to occur without unduly stressing the joints.
2. Ability to mount sensors and actuation systems.
3. Low weight.
4. Comfort to the user. Since the user will wear it on the hand, it must not be too heavy, bulky or uncomfortable in any other way.

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2 Design Methodology

Since our primary objective is to restore natural motions of the hand, human anatomy forms the basis of our design. The methods used for actuation were designed to mimic natural motions as much as possible. The final design was considered in terms of its 'controllability', the combination of movements and the placement of components.

The anatomy of the human hand was closely studied [2]. The tendons are the primary actuators for the fingers. The digital flexor tendons of the fingers lie on the palmar side of the hand, within the flexor tendon sheath. Along this sheath, there are two areas of thickening which act as pulleys, enabling the tendon to flex the finger. A ligament at the first joint (the carpometacarpal joint, CMC) acts as another pulley. By passing the tendon through two pulleys, the human body naturally actuates the CMC joint and the interphalangeal joint, IP, at the same time.

Extension of the fingers is accomplished by a *co-joined tendinous structure* consisting of an intrinsic and an extrinsic portion [2]. The extrinsic extensor mechanism consists of several tendons connected to the top of each bone in the finger, blending together at the back of the hand. The intrinsic extensor mechanism is more intricate, consisting of many tendons attached to muscles within the hand. Several tendons wrap around the finger and through a pulley system, combining work from the muscles located on the back of the hand and on the palm. These two extensor mechanisms work together to enable several complicated movements of the finger.

Bone Structure

The head of many of the finger and thumb bones have an "ovoid surface in a sagittal plane" and a trapezoid shape in the cross-sectional plane (see Figure 2). As the finger flexes, the ovoid surface serves as a cam, causing the axis of rotation to translate during rotation. Also, the cross section of the joint forces the finger to rotate out of the primary plane of rotation.

3 Actuation System

The base upon which the system is mounted consists of bands around the fingers between the joints (see Figure 1). The bands fit snugly but must allow the flesh to expand and contract with hand motion. We experimented with two different materials for the bands- a thermoplastic that is easily moldable and is light and aluminum. For reliability, we chose aluminum.

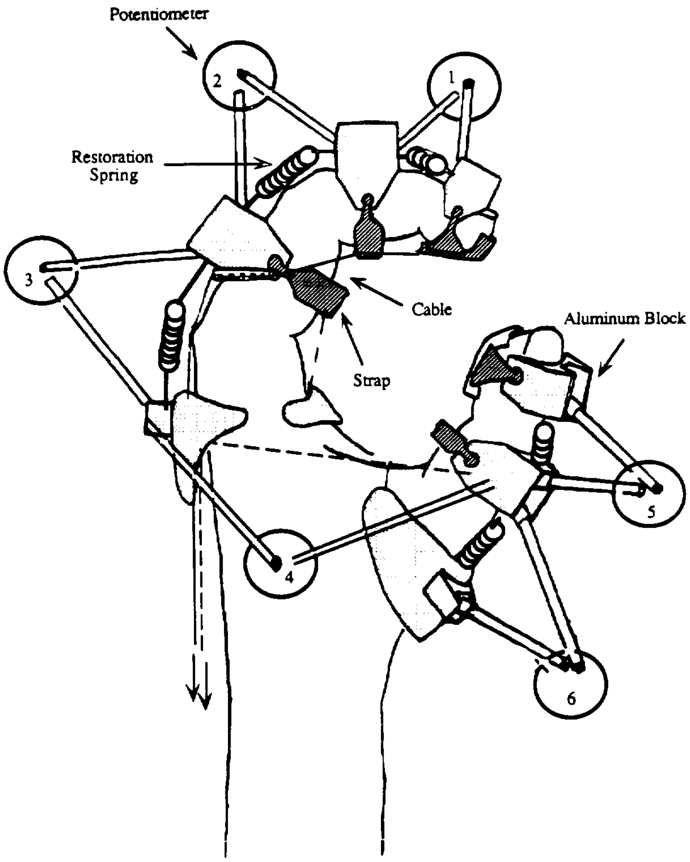

Figure 1: Final Design

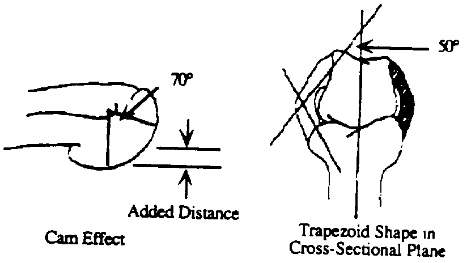

Figure 2: Bone Structure. From [2]

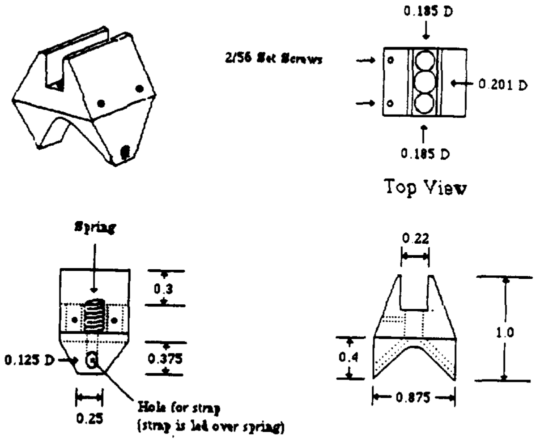

Figure 3: Aluminum block design

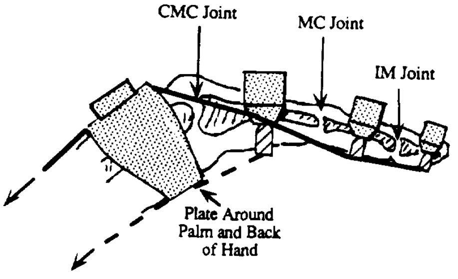

Figure 4: Finger Flexion

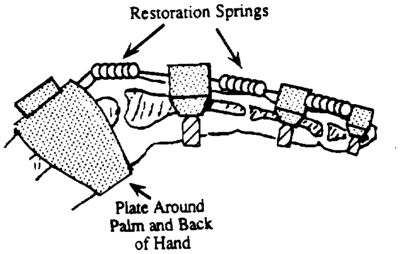

Figure 5: Finger Extension

To ensure a snug fit, we affixed aluminum V-blocks to the finger [3]. A plastic strap is led over a spring in the block (see Figure 3), allowing the shape to change as the finger bends and accomodating different finger sizes.

In order to provide mounts in those areas, 1/8" thick aluminum plates are molded to the palm and the base of the thumb. The pieces are attached to a Lycra glove to restrict motion relative to the hand and to provide a comfortable lining. Leather is sewn into the glove in places where the aluminum should not move relative to other pieces.

Flexion

Flexion of the finger and thumb is accomplished by cables connected to motors that are mounted on the upper arm. The cables are routed in a way that imitates the natural placement of the tendons. Five cables permit several common movements of the finger and thumb. They are kept close to the hand by running them through tubing under the plates on the palm and and the back of the hand.

The index finger (see Figure 4) of the Exoskeleton has been designed such that the last two joints (the LM and MC) joint flex in unison, as they do naturally. A cable extends from the base of the fingertip under the strap of the middle band to the back of the hand. By running the cable over the back of the hand, the LM and MC joints are isolated from the CMC joint. This cable assists the extension of the CMC joint, but this effect is minimized by running the cable along side the finger. Flexion of the CMC joint is accomplished by one cable attached to the band at the base of the finger and led under the plate on the palm of the hand. The thumb movements are more complex than those of the finger, requiring several degrees of freedom to be combined into a few motions. As in the finger design, the last two joints of the thumb are flexed in unison by one cable. A second cable draws the thumb across the hand to oppose the fingers. This cable simply holds the thumb in position where other cables are able to cause a pinching or grasping task. A third cable extends from the middle band to the back of the hand, pulling the thumb close to the hand.

The cables run through Teflon coated tubing embedded in the padding under the bands around the finger and thumb. These tubes and bands act as pulleys, much like the bone growths in the human hand. Once the cables reach the plates on the palm and on the back of the hand, they must change direction, resulting in greater stresses on the tubing. In order to transmit these stresses to the plates, copper tubing is epoxied to the plates. The cables are led out of the tubing as close to the axis of rotation of the wrist as possible, reducing the effect of this actuation system on the wrist. All cables that are used in the finger and thumb may assist or inhibit the flexion or extension of another part of the hand, but these effects have been minimized in this design.

Extension of the finger is accomplished by springs so that the default position of the hand is with fingers extended, as previously described by the fundamental designs for the hand and lower arm. The use of springs to return the hand to an extended position limits the numbers of motors needed to operate the Exoskeleton and will simplify the entire structure (see Figure 5). While the finger and thumb contain many tendons which enable extension, the exoskeleton will reduce this to five cables. This design limits the number of intricate motions the hand is able to accomplish but preserves the most common and useful functions. The springs cause the system to become harder to control and require a larger motor torque, but only five motors are required to actuate the finger and thumb.

The springs are located between the aluminum blocks on the top of the fingers and hand. Each joint requires a different spring to return it to an extended position, as the springs must overcome any friction in the tubing and the natural resistance of the hand. The spring constants have been exmined during construction and testing (See test results for spring constants).

3.1 Sensing System

Several methods of monitoring the individual joint angles were considered:

1. Potentiometers

2. Hall Effect Sensor are much smaller and more accurate, but require custom designed magnets which must be exactly suited to the geometry of the problem. The magnetic field depends on the shape of the magnets and any alteration to that shape destroys their effectiveness. They are used with success in the Utah/MIT Dexterous Hand and in the Exos Dexterous Hand Master.

3. Optical Encoders are suited for the purpose of angle measurement, but are large and tend to have resolution problems They need gearing for better resolution.

4. Accelerometers-require more hardware to interpret information.

5. Conductive Rubber -is still in developmental stages, but may become an option in the future.

6. Optical Fiber (used in the VPL Dataglove)-expensive and difficult to interpret. Its readings are subject to sliding where stretching occurs.

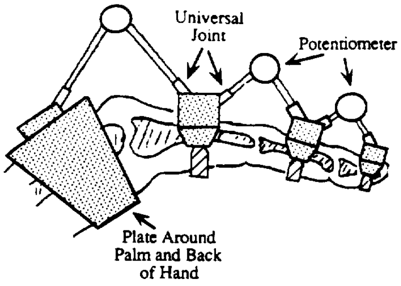

Figure 6: Joint Sensing Structure

7. Cable tension sensors. These require the actuation cables to be active, and give an estimate of the location of the finger from tension in the cables. The relationship between the tension in the cables and the location of the fingers may also be inexact and difficult to determine.

Potentiometers are easy to use and seem to be suited to the needs of this project. However, they are inaccurate at times and are not designed for long-term use. The potentiometers that were used in this project are manufactured by Clarostat and are small, light, inexpensive, and easy to apply to this application.

The initial design for the sensing device consisted of bearings and potentiometers on the side of the finger. This method, however, does not permit any inconsistencies in the rotation of the joint. If potentiometers are located next to the joints, the actuation of the finger will fight against the natural motion of the joint. Also, if the design for the index finger is extended to the other fingers, there must not be any large hardware on the sides which might interfere with the fingers rubbing against each other. The final design of the sensing system determines the position of the finger and thumb tips by measuring the angles between rods attached to aluminum blocks. The rods are coupled to the blocks through small universal joints, enabling the finger to bend out of the plane of rotation. As discussed previously, the finger has evolved in such a way that the axis of rotation changes with rotation and the Exoskeleton must allow this to occur. The aluminum block limits the rotation of the universal joint in one direction because only minimal movement out of the plane of rotation is required.

Individual Motions

Motion	Force (N)
Finger CMC Joint	3.92
Finger MC and IM Joints	8.82
Lateral Motion of Thumb	7.84
Thumb CMC Joint	6.86
Thumb MC and IM Joints	5.39

Combined Motions

Motion	Force (N)
Thumb - CMC Joint already activated - Then activate IM Joint	5.39
Thumb - MC and IM Joints already activated - Then activate CMC Joint	5.88

$$K(X - L) = m\,g$$

Spring	L (cm)	X (cm)	m (g)	K (N/cm)
1	0.476	0.794	200	6.167
2	0.714	1.349	200	4.000
3	1.349	1.920	200	3.435
4	0.794	1.588	200	2.469
5	1.191	1.920	200	2.687
6	0.952	1.429	200	4.109

Table 1: Spring constants

The relationship of the angle of the sensing finger's joint and the finger's joint is difficult to determine, and an exact comparison may not be possible because the position of the joint changes in relation to the skin as the finger flexes. However the position of the finger may be determined by calibration and by knowledge of the range of motion. The controller which interprets the sensing system will need to be calibrated for different users and each time the Exoskeleton is worn.

4 Tests

The hand used in these tests was a healthy one, and the accuracy of the results will be affected by the natural responses to external stimulus. These tests serve only as rough estimates of the success of this project and as a basis for improvements. They are only the first step in determining the characteristics of the Exoskeleton.

Spring Constants

Spring constants are shown in Table 1.

Forces Required to Actuate Joints

The purpose of this test is to provide an indication of the tension in the cables and the minimum force required to move the joints to their fully flexed position. The results may be used to determine the necessary motor torque requirements and to evaluate the DC motor.

Range of Motion

The hand was relaxed during testing, and the signal from individual potentiometers determined the resting position of the hand. To minimize variations due to gravity, the resting position of the hand was with palm down for all joints that are affected by cable on the back of the hand. Any joint that is actuated by palmar cables, the resting position was with palm up. Each cable was then connected to the motor, and the joint was actuated. The final value of the potentiometer determined the change in angle of the joint.

Each joint was tested several times, and the glove was removed between each reading in order to determine the amount of variation inherent in donning the glove. Two different hands were tested in this manned so that the changes in finger length and hand characteristics are considered.

Power vs. Change in Angle

The purpose of this test is to determine the power requirements of the motor during rotation of individual joints. Each joint was tested three times to gain an understanding of the reproducibility.

5 Results

The DC motor works well and successfully brings joints to a flexed position. The range of motion of the hand is very good, and the combination of these motions achieves the most common and useful tasks. The thumb opposes the index and middle fingers but is unable to reach across the hand as originally desired. The range of motion can not be further quantified at this time because the properties of the healthy hand are not fully understood.

Gravity has a large effect on the resting position of the hand, causing a maximum variation of 0.47 volts in the angle measurements. For this reason, specific resting positions were measured. Although it is hard to ensure that a healthy human hand is able to relax the muscles, the angles return to within 0.01 volt of the resting positions.

The results are also reproducible between similar hands and when the glove is removed. The resting positions of different hands varies, but the change in angle during rotation is similar. Nonetheless, the Exoskeleton will need to be calibrated between uses and for different users.

Potentiometer 6, on the LM joint of the thumb. has the smallest range, from 0 to 0.05 volts, causing measurements to vary by a high percentage of total movement.

Power vs. Change in Angle

This test shows a relationship between power and the change in angle during rotation, but these results cannot be used to determine the characteristics of the Exoskeleton. They are only a first step in developing an understanding of its specifications, and more information on a paralyzed hand must be obtained in the next steps of the Exoskeleton project.

Each angle was tested three times in order to obtain a variety of results. The results are not completely accurate because a working human hand was tested. The involuntary reactions of the muscles to external stimulus and the inability to ensure the resting position of the fingers introduces a great possibility of error. For each of the joints, the first test produced scattered results, showing that the hand requires time to relax before more accurate tests can be performed. These curves show that the muscles in the hand assist the motor at the beginning of the motion and that the human hand may attempt to continue rotating after the Exoskeleton has brought the joint to its final position.

Usually, the second and third test results are very similar to each other, demonstrating reproducibility. The general shape of these curves depicts the mechanical response of the hand. Initially, the motor must produce enough torque to start the joints rotation, but once the joint is in motion, it is relatively easy to continue that motion until the finger has reached its maximum angle. these tests revel great consistency in the shape and values of the curves, given the unquantifiable sources of error present in the healthy human hand. Human error in relaxing the muscles appears to have the greatest affect during the latter stages of rotation. Once the joint is in motion, the readings are probably accurate, but the final reading may vary due to intrusion of the healthy muscles or to differences in the way the flesh prevents completion of the flexion. this level of accuracy may suffice because most tasks are performed before the finger reaches the fully flexed position. Potentiometer 4, between the thumb and hand attempts to measure two degrees of freedom. A single potentiometer is unable to accurately measure two degrees of freedom simultaneously, and the resulting forces on the potentiometer housing cause the connections between the housing and the structure to break.

6 Conclusions

We have presented a very preliminary design and our experience with the first prototype for an external prosthetic glove for assisting paralyzed hands. Our experience indicates that we need to refine our design to better accomodate thumb motion, reduce friction between the cables and the tubing and, in general, reduce the size of the prototype.

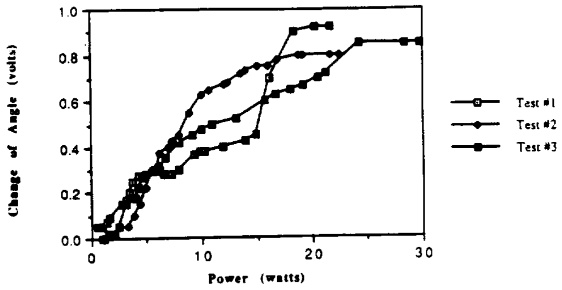

Figure 7: Power input vs. change of angle for MC joint

Acknowledgements

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