A Pressure Controlled, Hand-Assistive Exoskeleton for Actuated Pinch and Grasp

Donald J. Bucci, Michele Rotella, Sana Fathima, Erik Hage, Cory Hofmann, and Katherine Reuther

***Abstract*—A combined 450,000 American suffer from debilitative disorders that result in a loss of strength and dexterity within the skeletal muscles that control hand motion. An assistive exoskeleton was designed for the human hand that utilized residual strength to influence synergistic control, resulting in the restoration of both pinching and grasping functionality. Additionally, the device was implemented using feedback mechanisms to account for grasping strength modulation and hyperextension prevention. Preliminary testing utilizing forearm EMG data showed a reduction in pinching/grasping effort to 85-90% with respect to nominal force production in each subject.**

***Index Terms*—Dexterous Manipulators, Handicapped Aids, Minimum Effort Control, Control System Human Factors**

I. INTRODUCTION

A combined 450,000 Americans suffer from debilitative disorders, such as multiple sclerosis and muscular dystrophy [1], resulting in the loss of muscle strength and dexterity in the hand. The degeneration of hand function therein impinges on an individual's ability to perform everyday tasks, such as picking up and/or grasping an object. As a solution, a variety of hand exoskeletons have been developed to amplify the remaining muscle control in the hand, but most are limited to actuating either a pinching or grasping movement.

A. *Previous Designs*

A tendon-drive mechanism incorporating three laterally mounted cables was utilized to produce flexion of the three index finger joints in the five-fingered assistive hand designed at the University of Tsukuba [2]. Although this device amplified grasping force, pinching and other synchronous finger movement occurred without amplification. A pneumatic piston driven cable system was responsible for actuating a pinching movement in the lightweight exoskeleton designed at Carnegie Mellon University [3]. In this device, the index finger actively flexed and extended at the three finger joints, complementing a fixed thumb, while a spring mechanism enabled passive index extension.

Currently there are two predominating controller methodologies: binary and variable. The majority of binary control algorithms operate such that all system outputs exist between two states, usually an 'ON' state and an 'OFF' state. The controller reads the input signal, checks it against a predefined threshold, and sets the output state accordingly. A binary control algorithm that was utilized in the development of another hand exoskeleton was found to allow for faster object interactions through increased system response times, but at a cost of a decrease in control precision. This was readily noticeable in cases of pinching more delicate objects [3].

Variable control designs relate system output signals proportionally and linearly to input control signals. Saturation of the output occurs if the input signal falls outside of a predefined range. In contrast with binary control, variable control systems exhibit a relatively greater level of control precision for more delicate objects; however this was contrasted with a slower response time when compared to other binary algorithms.

B. *Design Objective*

Our objective was to design an orthotic hand exoskeleton that dynamically amplified the user's residual hand strength in both pinching and grasping movements. The tendon-drive mechanism was to be non-cumbrous in design and to incorporate cables, as opposed to bulky pistons positioned atop the dorsum of the hand. Furthermore, we strove to design a digital control system with the benefits of binary and variable control architectures. Our design was to utilize feedback from force resistors and angle sensors to modulate motor control thereby effectively modeling the natural control of the human hand.

II. MECHANICAL DESIGN

A. *Digit Mechanism*

The exoskeleton of each digit featured a common cylindrical aluminum band design, enclosing the phalanges, Fig. 1a. The thin bands were sized larger than the finger to improve comfort and accommodate internal sensors and cushioning. Integrated cable guide channels were located on the dorsal surface for the spring system, and within the band for the tendon system. Extensions from the bands connected the subunits and created points of rotation that coincided with the centers of rotation of the natural joints.

Manuscript received April 20th, 2009. This work was supported in part by The College of New Jersey, School of Engineering. D. J. Bucci is with The College of New Jersey, Ewing, NJ 08628 USA (phone: 856-361-3931; e-mail: don.bucci@gmail.com). M. Rotella is also with The College of New Jersey, Ewing, NJ, 08628 USA (email: rotella4@gmail.com). All other authors may be contacted through the two shown above. **Our IEEE Student branch counselor is Dr. Allen Katz with the Department of Electrical and Computer Engineering, The College of New Jersey, Ewing, NJ, 08628 (e-mail: a.katz@ieee.org).**

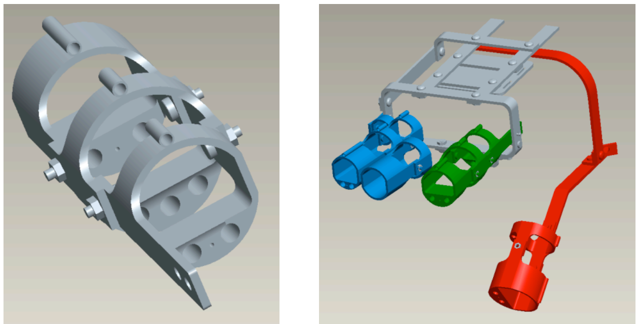

Fig. 1. (a) Linkage design common to digits. (b) Assembly of hand.

In all digits, the distal and proximal band connections fit within the intermediate band, eliminating bulk between the fingers. To articulate pinch and grasp movements, our design included three functional digits: the thumb, index finger, and a grouping of the middle, ring, and small fingers. The exoskeleton assembly, Fig. 1b, highlights the index, thumb, and third digit mechanisms.

The digits were connected to the body of the exoskeleton via a dorsal assembly, shown in Fig. 1b. This component of the exoskeleton secured the device to the hand via adjustable Velcro™ straps. The aluminum framework supported the underside of the hand, while the palmar surface was free to interact with the environment. Fig. 1b displays the locations for hardware mounting on a forearm assembly, reducing bulk on the hand: the motors, the batteries, and the motor controllers.

B. *Actuated Flexion*

At rest, the index and third digit are fully extended at 0°, in plane with the flat palm, and the thumb is oriented at a right angle to remaining digits, as shown in Fig. 1b.

Bowden cables were mounted to the distal and proximal links of the index finger, the distal link of the third digit, and proximal link of the thumb. For the index finger, a single cable actuated the distal interphalangeal (DIP) and the proximal interphalangeal (PIP) joints, Fig. 3. This system coupled the rotation of the DIP and PIP joints, which naturally occurs in the hand. In the third digit, a single cable flexed the DIP, PIP, and MCP joints. In the thumb, the carpometacarpal (CMC) and interphalangeal (IP) joints were actuated in a plane parallel to the palm. In our design, the thumb contributed to force production, as opposed to remaining fixed as seen in previous designs [2].

Each band of the index and thumb digits incorporated a platform, Fig. 1a, that isolated the cables and reduced contact stress on the digit. To create an evenly distributed tensile force on the third digit, the cable was connected via an external linkage between the middle and ring fingers. The actuators can produce a 15 N force in each cable, maximally achieving a force of 8 N normal to each fingertip. With a stroke length of 20 mm and a stroke speed of 20 mm/s, the actuators allowed for the performance of most tasks in real time. The cables pulled from beneath the phalanges, better mimicking the behavior of human tendons. The system utilized two cables, as opposed to three [2], allowing for a more realistic design for the desired task.

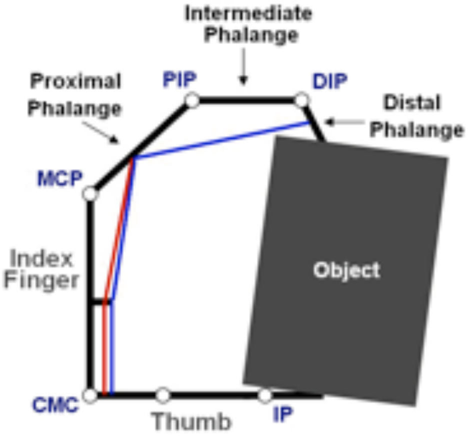

Fig. 2. The poly-articular tendon-drive mechanism in the index digit.

C. *Passive Extension Mechanism*

A spring extensor mechanism returned the actuated digits to their original resting position, mimicking the behavior of the complex extensor network in the dorsum of the hand [4]. The displacement of the finger extended the spring, producing a force that opposed the active flexion. This provided the ability of the digits to return to their initial rest position after actuation ceases. The springs were attached to an aluminum plate mounted to the dorsal hand assembly and, using galvanized steel cable, were routed via pulleys to the distal bands of the index and third digits. While the spring extension mechanism of the thumb was similar to that of the index and third digit, its spring was mounted on the bar connecting the thumb to the dorsal assembly, Fig.1b.

To maintain constant tension in the Bowden cable system, a spring with a constant of approximately 0.3 N/mm was used to retract the digits to a resting state after deactivation of the motors. Hyperextension of the MCP joints, where joints are extended beyond their planar resting position due to spring failure, was prevented via mechanical stoppers at each joint. In our design, the springs were mounted on the forearm assembly, away from the joints to eliminate bulk around the fingers and to improve the range of motion.

The final mechanical design is shown below in Fig 3 and incorporated all of the above proposed design concepts.

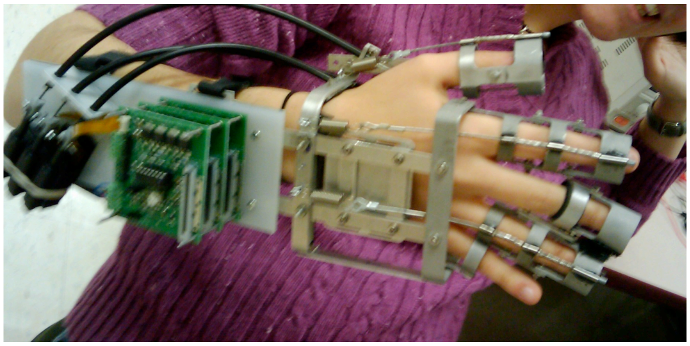

Fig. 3. Construction of final exoskeletal design, showcasing the link construction and actuation systems.

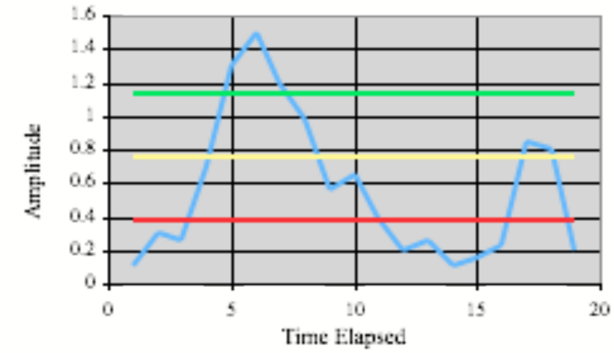

Fig 4. Graphical illustration of a two-bit binary control algorithm. The control signal is subdivided into four distinct regions by the thresholds.

III. CONTROL SYSTEM DESIGN

A. *Control Algorithm*

A binary control algorithm effectively operates as a *N+1* state controller with *N* being the number of thresholds used (in the binary case *N=1* and for variable *N=∞*). In order to improve system response time and control accuracy as compared to a simple binary controller, the state limit was set to four (*N=3*). As a result, the two-bit binary control algorithm consisted of four levels of flexion and extension control with thresholds based off the maximum value of the input signal (Fig. 4).

We attempted to mimic the natural physiology of the human hand by incorporating negative feedback from joint-angles and palmar resistance measurements. Joint angles are continuously measured by the digital control system and compared against a set of pre-defined regions. If a single joint angle existed outside of its predefined range, then all system output states would forced to zero, preventing any system output that could result in phalangeal hyperextension.

In addition, resistance measurements from the palmar side of the hand were quantified to detect the presence of an object. These resistance measurements were grouped based on their applicability to either the precision pinch or the power grasp. If a resistance measurement surpassed a pre-defined threshold, then the flexion output states would be reduced accordingly to allow for more accurate control of delicate motions.

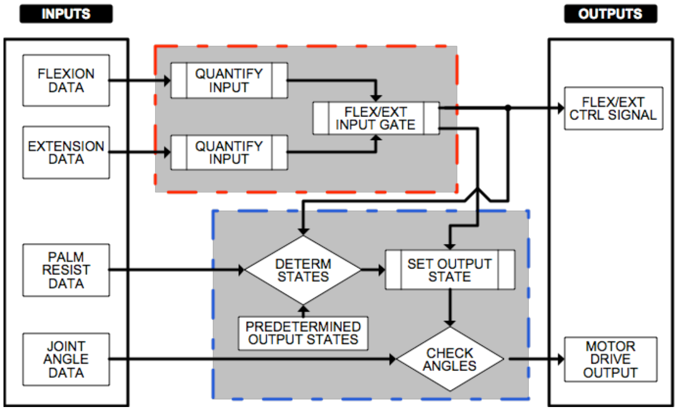

Fig. 5. Control system operational flowchart per motor driven output.

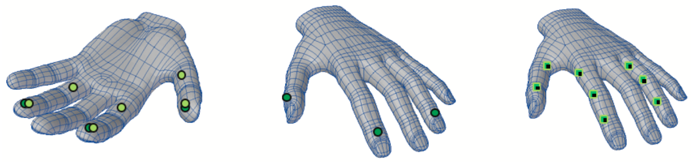

Fig. 6. Instrumentation placement of the final design. (a) Ventral side of the palm showing both palmar resistance and flexion force sensing resistors. (b) Dorsal side of the palm showing extension force sensing resistors. (c) Ventral side of the palm showing Hall sensor placements.

B. *Hardware and Feedback*

The two-bit binary control system was implemented for the index finger, thumb, and the remaining finger group (Fig. 5) on a laptop computer using LabVIEW v8.5. The orthotic, hand-assistive exoskeleton control system contained 23 analog inputs, 4 analog outputs, and 4 digital outputs. A virtual interface displayed on the laptop computer allowed for real-time viewing of all input and output signals. The final front panel is shown in Fig. 7.

To achieve accurate measurements for flexion and extension data, force-sensing resistors (FSR) are placed on both the ventral and dorsal sides of the tips of both the index finger and thumb. FSRs are also attached similarly to the ring finger providing an overall characterization of the flexion and extension data of the middle, ring, and small finger group. To increase movement accuracy of the index finger, FSRs are attached to the ventral and dorsal sides of its proximal phalange (Fig. 6a).

To sense palmar resistance data, FSRs located on the palm were divided into two groups: precision pinch and power grasp groups. The precision pinch group consisted of 2 FSRs located on the index finger and thumb. The power grasp group included the precision pinch grouping and an additional 4 FSRs located on the middle, ring, and small finger group and lower portions of the index finger and thumb exoskeletal extensions (Fig. 6b). To measure joint angles, Hall effect sensors were attached to all finger joints on the exoskeleton (Fig. 6c).

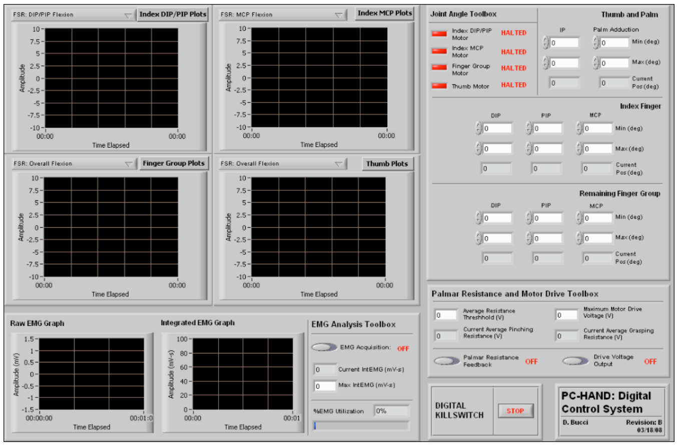

Fig. 7. Final digital controller front panel. Designed in LabVIEW v8.5

IV. PRELIMINARY DESIGN VALIDATION

A. Methods

The ability of the hand-assistive exoskeleton to assist a power grasp was quantified through the recording of the electromyography of the forearm muscles. Two separate subjects were tested: one male and one female, both approximately 21 years of age. The subjects were instructed to clench a force dynamometer with their hand while using the actuation of the exoskeleton while forearm EMG was recorded. After this, the subject was then instructed to remove the exoskeleton and produce the same amount of force. The ratio between the integrated mean-corrected EMG activity of an effort as compared to a experimentally determined nominal value is described as:

$$\%_{EMG-Utiliz} = \frac{1}{K} \cdot \left(\int_{t-T}^{t} [EMG_{Raw}(i) - mean_T(EMG)]di \right) \cdot 100 \qquad (1)$$

where T is the sample time used, EMG_{Raw} is the raw EMG data, $mean_T(EMG)$ is the mean value of EMG_{Raw} over time T, and K is the experimentally determined nominal value.

A qualitative analysis was also performed where the wearer provided feedback during the completion of lifting and grasping tasks, evaluating ease of use and comfort of the hand-assistive exoskeleton.

B. Results

Both subjects were shown to produce a clenching force that ranged between 2-3 kg with the exoskeleton. Both subjects showed a slight reduction in the EMG activity through (1). The male subject was shown to perform the same activity at 92.5% of his nominal contraction without the exoskeleton and the female was shown to produce a percentage of 86.3% accordingly. Both subjects were also able to successfully lift a total of three objects: a container of liquid cement, a roll of duct tape, and a precision screwdriver.

For each subject, a learning curve was observed that involved each user becoming acquainted with the overall sensitivity of the glove and adjusting it accordingly in the control system.

V. CONCLUSION

We designed an orthotic hand exoskeleton that can dynamically amplify residual hand strength in both pinching and grasping movements. In addition to the preliminary testing herein, the complete system will undergo extensive quantitative and qualitative evaluations of strength and dexterity. To characterize dexterity and precision control, a test subject will pinch and lift a ball of Playdoh™. The minimum force to complete the pinch/grasp and the maximum deformation of the target will be evaluated. At that point, a significant evaluation of our final design will be made and incorporated into plans for future work.

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