An Orthotic Hand-Assistive Exoskeleton for Actuated Pinch and Grasp

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Abstract — **Over 450,000 Americans suffer from debilitative disorders resulting in the loss of proper hand function. A lightweight, non-cumbrous, orthotic hand exoskeleton was designed to restore normal pinching and grasping finger motions. Three functional digit mechanisms were designed: a thumb, index, and grouped third digit, comprised of the middle, ring, and small fingers. Each phalange was enclosed by a series of cylindrical aluminum bands connected at the centers of rotation of each joint. Bowden cables were mounted beneath each digit to provide active flexion, mimicking the tendons in the hand. A spring extension mechanism maintained constant tension in the Bowden cables, and during relaxation, returned the actuated digits to a fully extended resting position. Individually controlled actuators mounted on a forearm assembly produced 15 N of tensile force in each cable. The orthotic hand exoskeleton will be integrated with a digital control system currently under development in this laboratory. The complete system was designed to restore hand functionality through the amplification of precision pinch and/or power grasp.**

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 impinges on an individual's ability to perform everyday tasks, such as picking up a pen or grasping an apple. 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 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.

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 non-cumbrous in design and incorporated cables, as opposed to bulky pistons positioned atop the dorsum of the hand. The spring extensor mechanism passively controlled the return of actuated digits.

II. EXOSKELETON CONSTRUCTION

A. Digit Mechanisms

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. 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 (green), thumb (red), and third (blue) digit mechanisms.

B. *Dorsal and Forearm Assemblies*

The digits were connected to the body of the exoskeleton via the dorsal assembly, shown in gray 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 (purple), the batteries (yellow), and the motor controllers (orange).

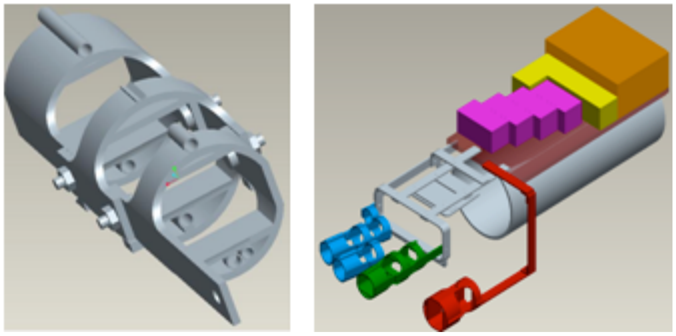

Fig. 1. (a) Band design common to digits. (b) Assembly of hand/forearm.

III. EXOSKELETON ACTUATION

A. *Active 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, one cable actuated the distal interphalangeal (DIP) and the proximal interphalangeal (PIP) joints, while the second cable actuated the metacarpophalangeal (MCP) joint, 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.

B. *Passive Extension*

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 0.5 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.

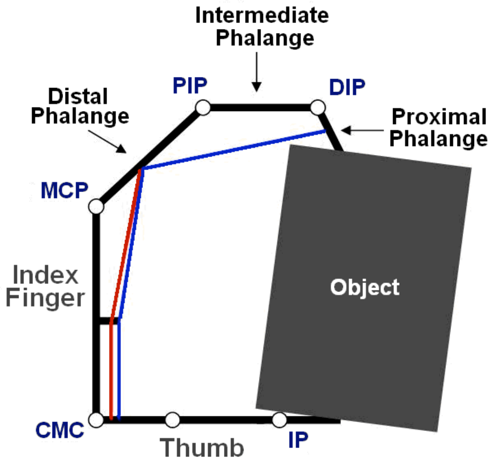

Fig. 3. The poly-articular tendon-drive mechanism in the index digit.

IV. CONCLUSION

We designed an orthotic hand exoskeleton that can dynamically amplify residual hand strength in both pinching and grasping movements. The hand-assistive exoskeleton will be integrated with a hybrid binary control system that was developed in this laboratory. The complete system will undergo quantitative and qualitative evaluation of strength and dexterity. Grasping strength will be quantified as the force-EMG relationship when producing a target force without the exoskeleton, and with the exoskeleton with and without powered actuation. 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. Qualitative assessment will include feedback from the wearer during the completion of strength and dexterity tasks. The goal of our work is to develop an assistive device for the hand that is non-cumbrous and able to restore the user's ability to perform everyday tasks.

ACKNOWLEDGMENTS

We would like to thank The College of New Jersey School of Engineering and Dean Steven Schreiner for funding support. We ware grateful for the contributions of Professor Bijan Sepahpour and Dr. Jennifer Wang to the design of the exoskeleton components.

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