ACTUATED THUMB EXOSKELETON WITH VARIABLE AXES OF ROTATION FOR STROKE REHABILITATION

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Abstract

Chronic hand impairment is very common amongst stroke survivors. More specifically, movement of the thumb is highly restricted causing a major decrease in the functionality of the entire hand. The non-orthogonal, non-intersecting joint axes of the thumb and the many actuating muscles involved make it very difficult to understand the thumb, let alone provide techniques for rehabilitation. Thus, an exoskeleton that incorporates the 5 anatomical Degrees of Freedom (DOF) of the thumb, both for actuation and measuring, was created in order to better understand motor control of the thumb, both in neurologically intact individuals and in stroke survivors. A mounting bracket was developed to affix the exoskeleton to a forearm brace. The exoskeleton was then tested to determine if it restricted movement. The movement space of the thumb was tracked both with the thumb connected to the exoskeleton and for the free thumb using a Digital Motion Analysis System (DMAS). Neurologically intact subjects were able to cover an average of 72% of their normal thumb working space while wearing the exoskeleton. Most of the restriction occurred in the upper region of the workspace. Thus, the device seems to allow considerable freedom of movement of the thumb, particularly in the region of the workspace used for everyday tasks. Subjects remarked that thumb movement felt quite natural. Further research using this exoskeleton can be done to better understand the impairments that occur in the thumb and thus provide better insight into rehabilitation methods. For example, the use of a system including motors and flexible shafts to drive the joints of the exoskeleton which in turn drives the joints of the thumb might provide a successful mode of rehabilitation.

Introduction

Diabetes is known to affect millions of individuals all over the world. In the United States alone, 20.8 million people suffer from diabetes[1]. The elevated levels of blood glucose in the body that result can cause other health issues as well. For example, diabetics have 4 times a greater risk of experiencing a stroke than the rest of the population due to a higher blood pressure and higher cholesterol[1]. One very common side effect that dramatically impacts the quality of life is chronic, or long-term, hand impairment[1]. Motor movement of the thumb, which is especially important in many activities of daily living, is particularly affected.

When functioning properly, the thumb provides opposition, or resistance, to each of the fingers of the hand. This enables precise grasping and pinching movements that are crucial for interacting with objects. The thumb is unique for its ability to move independently from the other digits. Certain movements of a particular finger depend on the position of the others. The thumb is also special for its large representation in both the motor cortex and sensory cortex of the brain[2]. A significant amount of area within the portion of the brain that deals with movement and sensation is devoted to the thumb. It can also generate the largest force out of all the digits and is involved with over 50% of hand function[3].

Impairments caused by stroke or other neurological injuries significantly decreases the amount of work capable by the hand. However, the thumb is quite difficult to understand for multiple reasons. It contains many actuating muscles, or muscles that cause its operation[4]. Also, the many axes by which the various parts of the thumb rotate are not perpendicular, or orthogonal, to each other[5]. Furthermore, these axes do not intersect making it all the more complex. The lack of full knowledge in the many actuating muscles and non-orthogonal, non-intersecting rotational axes, make it very difficult to develop modes of rehabilitation. There are a number of robotic devices that have been developed to facilitate hand rehabilitation[1]. However, most fail to incorporate all the DOF of the thumb or have a difficult time manipulating them[6-8].

Thus, there is a need for a device that can precisely measure the joint angles and torques of the thumb, independently control each of its DOF, and align anatomically with the rotational axes of the thumb. Such a device would[l] greatly improve the understanding of thumb impairments and lead to better rehabilitation for the future.

We have developed a prototype for a device that can independently actuate each of the 5 DOF of the thumb

[Wang, Jones, et al.]. This paper describes the design and development of a fixture to mount the exoskeleton to a forearm brace while providing 5 DOF for aligning the exoskeleton with the thumb. This adjustability permits fitting the exoskeleton to individuals with varying hand sizes and axes of rotation[9]. Mechanical motion, or kinematic, analyses were performed with the complete system to determine movement restrictions imposed by the exoskeleton.

Methods

The thumb exoskeleton incorporates 5 active DOF that are driven by external motors and 3 passive DOF that rotate as a result of the active DOF. Together, these control and measure the 5 DOF of the thumb: flexion/extension (F/E) of the carpometacarpal (CMC), metacarpophylangeal (MCP), and interphalangeal (IP) joints, and the abduction/adduction (Ab/Ad) of the CMC and MCP joints. The joints and segments of the thumb are displayed in Figure 1.

The exoskeleton attaches to the distal, proximal, and metacarpal segments of the thumb. Two-bar hinge-like linkages are used to actuate the MCP and IP joints (Fig. 2) and accommodate the variation in thumb segment lengths. Magnetic sensors were attached to the exoskeleton in order to measure the angle of rotation produced at each active joint.

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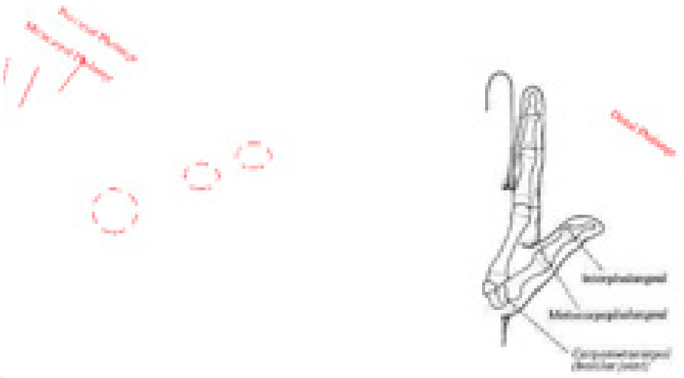

Figure 1. *Animated thumb x-ray displaying the names of the thumb joints and their locations.*

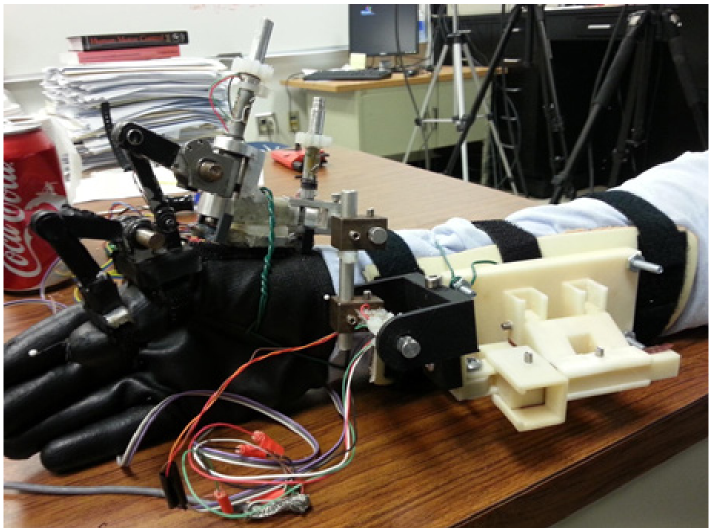

Figure 2. *Exoskeleton with arm mounting brace on subject. Two bar linkages are shown connecting at the MCP and IP joints.*

In order to properly ground the base of the thumb exoskeleton to the user, an adjustable fixture was created to connect the exoskeleton to a brace worn on the forearm. The fixture was designed in the computer software SolidWorks and a prototype was created using 3D printing. The fixture was made to permit translation and rotation of the CMC FE shaft in a total of 5 DOF such that the carpometacarpal flexor-extensor (CMC FE) axis of the exoskeleton was aligned with that of the user's thumb.

Upon completion of the fixture, the movement spaces of subject thumbs were tested both with and without the exoskeleton. The subjects was directed to move the thumb throughout its full active range of motion performing any movements desired that stretched the thumb to its maximum distances. Thumb tip movements were tracked using a digital motion analysis system (DMAS, Spica Technologies Corporation, Maui, Hawaii). Tracking trials were performed both with the exoskeleton and without the exoskeleton.

The coordinates of the thumb tip in 3D space were imported into the computer program MATLAB, which was then used to compare the movement spaces both with and without the exoskeleton. Using the rotational angle measurements found from the sensors, the location of the thumb tip can be calculated. Then, the location with respect to time found from the DMAS can be compared to that found from the sensors in order to assess accuracy and for future experiments with rehabilitation.

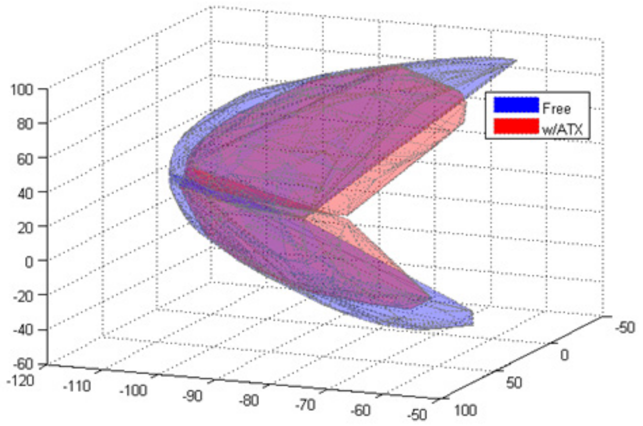

Figure 3. *Movement area in 3D space of the thumb with the exoskeleton (red) and without the exoskeleton (blue), measured in an XYZ-coordinate plane.*

Results

The fixture permitted accommodation for varying hand sizes without failure during the kinematic testing. Various subjects stated that thumb movement during testing felt natural after resizing. Using the DMAS, we obtained the workspaces of the thumb with and without the exoskeleton. Comparison of the two revealed that the exoskeleton permitted considerable freedom of movement. Figure 3 shows data obtained from a subject's thumb working space in a 3D representation. The graph displays 3D space as an XYZ-coordinate plane system. The area in blue indicates the region of space covered by the thumb without the exoskeleton, and the area in red shows the space with the exoskeleton. Only at the extremes of thumb joint rotation did the exoskeleton restrict thumb movement. For example, the exoskeleton limited thumb IP hyperextension, thereby reducing access at the very top of the workspace, and slightly limited IP hyperflexion, thereby limiting movement at the bottom of the workspace (Fig. 3).

Overall, subjects were able to access 72% of the free thumb workspace while wearing the exoskeleton. Further analysis showed that 83% of lower coverage was achieved.

Discussion

In accommodating all 5 DOF of the thumb, we were able to decrease restrictions from other devised exoskeletons being used on the thumb. Thus, subjects have very high coverage of the thumb working space. The increased comfort and ease of movement experienced by users suggests that using non-orthogonal axes of rotation in the exoskeleton is better for movement. This can become very useful in future research. Further modifications of the exoskeleton may give even more ease of movement. For example, the restriction apparent in the upper region of the thumb working space occurs due to the collision of the exoskeleton linkages of the MCP and IP joints when performing a 'Thumbs Up' motion. Redesigning this mechanism, or use of a different mechanism may help resolve the issue and thus provide maximum coverage of the thumb working space. The limitations of the lower working space may be caused due a slight lack comfort in the exoskeleton. This may have made it difficult to move the thumb. Also, tendencies to proceed carefully while using the device may have caused subjects to not use full forces.

Conclusion

These results along with further research can increase the understanding of various chronic hand impairments. In achieving a space that is close to the maximum thumb working space, researchers can hope that subjects will one day reach their original maximum thumb working space. Further development of the motor and flexible shaft system may facilitate this restoration and provide even more information about the potential for rehabilitation. Ramifications for stroke survivors may include the ability to restore close-to-normal hand function by allowing the thumb working space to increase over time. With practice using the exoskeleton, there is hope for the restoration for full, if not, partial thumb movement.

Acknowledgements

This work was supported by the Research Experiences for Undergraduates program in Diabetes at the Illinois Institute of Technology (National Science Foundation Grant No: EEC- 1157041).

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