EXCELCIOR: 3D printed customized hand rehabilitation device with embedded sensors

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Abstract

The primary purpose of this project was to create a device using additive manufacturing with embedded sensors, a kind of technology that has never been attempted before. The design team chose the biomedical field for attempting this technology, more importantly focusing on stroke patients. Based on the team’s background research, victims of stroke often lose some motor functions, causing disability and difficulty with Activities of Daily Living (ADL) which can range from opening a door knob, holding a pen to buttoning a shirt button and other finer dexterous movements. Repetitive finger and hand motion can help restore lost motor functions by re-wiring undamaged portions of the brain through neuroplasticity. This repetitive motion rehabilitation can be accomplished with the help of a device that assists post stroke patients during treatment and provides feedback about the patient’s condition and progress to the physician. Existing commercial stroke rehabilitation devices such as the Hocoma Armeo that is in use only offers gross movement of the hand, while a few research devices such as the MIT Manus & Rutgers Master II deal with fine dexterous movements of the fingers. Keeping the limitations of the existing and research devices in mind, the team interviewed a few experts and physical therapists. Based on their feedback the team decided on a design concept that falls in the middle in order to overcome the limitations and offers stroke patients a device that assists in rehabilitation of the hand and fingers at the same time with real-time feedback and progress. Most parts of the device were designed to be additively manufactured with customizability as the primary advantage. Since the device’s function was to interact with the human hand, biomechanics and stress analysis were crucial in optimization of the design for safety and functionality. Cost analysis helped the team decide on how the design can be split into different pieces for ease of manufacture, customizability and material selection. As embedded sensors were one of the primary objectives of the project, the type and positioning of the sensors were finalized based on what the team wanted the device to measure in order to give feedback to the user.
The Need for Project

Post stroke patients require physical therapy for their hands and limbs. Coordinated movements of the arm and hand is essential for regaining ability to do activities of daily living (ADL) and regaining fine motor controls. Every year in the United States approximately 800,000 people suffer from strokes. It is the leading cause of chronic adult disability. 20% of stroke survivors require rehabilitation 3 months post their stroke. In many cases parts of the brain that are responsible for regulating movement are damaged by stroke. However, rehabilitation can help a stroke patient regain their lost motor functions. Exercises that involve repetition of desired motions helps rewire the brain to allow other undamaged portions of the brain to perform physical movements. This process is known as brain plasticity. Rehabilitation exercises traditionally require physical contact with a therapist and various low-tech objects that resist motion to strengthen weak muscles. However, robotic systems are increasingly being used in clinical settings for assisting stroke patients. These systems offer few advantages such as precise feedback and data analysis, adaptability to various situations, and a computer interface to make the repetitive motion more interesting for the patient. Numerous studies have shown that robot-assisted rehabilitation is more effective than traditional methods of stroke rehabilitation and results in quicker and more thorough recovery.

One of the primary goals for disabled post-stroke patients is to perform activities of daily living (ADL) such as buttoning a shirt, turning a doorknob to open a door, being able to write with a pencil, and so on. Regaining the ability to engage in ADL requires rehabilitation of both gross and fine motor function. Unfortunately, this is the area that is most difficult to rehabilitate effectively with robotic technology. Two reviews of literature on robot-assisted upper extremity rehabilitation found that while robotic rehabilitation is significantly more effective than traditional rehabilitation in helping patients regain gross motor function, it is not statistically superior in assisting with recovery of ADL. The concept of robotic rehabilitation is sound and proven, and theoretically the benefits should extend to fine motor rehabilitation as well. The fact that they do not, likely indicates an opportunity to create new technology with an eye towards ADL rehabilitation.

The Design Project Objectives and Requirements

Create a device that is customized to the user using additive manufacturing with embedded sensors that is designed to assist post stroke patients with flexion and extension of their fingers and improve their cognitive skills at the same time.

Design Objectives

The innovation brought with this project is to create a hand/wrist device using additive manufacturing and embedded sensors with customizability as the advantage. Fine motor rehabilitation is too complicated and variable to design a simple universal effective system, which is why it is not included in existing commercial systems. The variation in grasps, hand anatomy, and in patient impairment makes a one-size-fits-all solution complex. By building a hand/wrist device using additive manufacturing, it can be customized to every patient using a 3D scan of their hand anatomy and other measurable parameters. There is currently no existing research-based or commercialized system that combines gross and fine motion rehabilitation, a computer interface, and the addition of a customized component.
Design Requirements

The design requirements for the device were formulated based on the feedback received from interviewing experts and physical therapists on campus, Spaulding Rehabilitation Hospital, and In Motion Robotics. Each requirement was ranked with respect to the concepts. Among the highest ranked design requirements are: protection against hyperextension of the metacarpal phalangeal joint, finger extension & flexion, testing and improving cognitive skills of the user, ease of manufacture and customizability.

Design Concepts considered

We chose our top three concepts based on a ranking system which analyzed how well each concept met our project specifications. The team generated 9 concepts which were ranked based on a set of concrete design specifications in order to select our final design. From this ranking system our top 3 concepts were selected. The 3 concepts are as follows:

(i) Grip Cylinder

The Grip Cylinder is a device that would allow the independent motion of four fingers while in flexion or extension. Each finger would have its own separate attachment which would be spring assisted for finger extension. This design offers a solution to allow the patient’s fingers to move individually. This design also would easily integrate with the Armeo system.

(ii) LED Hand Device

The LED Hand concept is based highly on cognitive exercises which assists brain plasticity. This device allows a full range of motion and includes the thumb along with the four fingers. The design of the LED’s can be compared to a game such as Twister, which most people are familiar with, where you match the color of the LED on the fingers with that of the LED’s on the LED object.

(iii) Magnetron Concept

The Magnetron concept was inspired by high end goalie gloves for soccer which help to prevent hyperextension. To prevent MCP hyperextension, the magnetron has joints that are attached in parallel with the joints of the fingers. These block-like joints help prevent hyperextension because the fingers cannot extend beyond 180 degrees. There are springs attached on the sides to help assist in extension. There are electromagnets between the joints which would create a repulsive force which results in a moment around each joint to assist in flexion. There are also fibre optic bend sensors that run through the center of each finger link to measure the patient’s bend angle.
Recommended Design Concept

For the final design, instead of using the top ranked concept, we decided to take the best attributes from each of the top 3 concepts and combine them into 1 final design.

The Excelsior incorporates the LED finger thimbles and LED object from the LED hand, the spring assistance from the grip cylinder, and hyperextension prevention of the magnetron concept. The design is an exoskeleton in which the MCP clamp is designed to custom fit the user using a 3D scan of the hand and is firmly strapped to the hand to act as a clamp which prevents the hyperextension of the MCP joint. The Excelsior uses leaf springs running down the digits attached the finger links to assist in the extension of the digits.

After a substantial amount of research, it was found that many stroke patients lose around 50% of the force in their extensor and flexor muscles in their digits. This is a key piece of information because it means that there is a large populace that would benefit from our device. The patients would need to have some force and movement in their digits to benefit from the device so post stroke patients with severe impairment would not be able to use the Excelsior, but there are still many patients that would benefit from this device. Another issue faced by stroke patients is the range of motion they exhibit in their digits which needed to be accounted for in the Excelsior’s design so that the device can withstand maximum angles of flexion. A healthy patient exhibits on average
- 90.3° range of motion in their MCP
- 109.1° range of motion in their PIP joint.

In comparison a post stroke patient on average exhibits
- 50.4° range of motion in their MCP joint
- 64.5° range of motion in their PIP.

Using this data, our device was designed so that the neutral position of the device would be within the range of motion of most stroke patients and the device would be able to withstand the range of motion of a healthy patient.

The advantages of the Excelsior are that it is able to address so many different issues involved with stroke rehabilitation. It is spring assisted to help patients extend their digits which is often an issue with stroke patients, especially due to spasticity. The Excelsior incorporates cognitive exercise along with the physical assistance through the LED’s. Since the LED’s change color and constantly challenge the patient in different ways through the exercises of matching the LED on their finger with the LED on the exercise object, the cognitive exercise is extremely beneficial in assisting brain plasticity. A key feature of the Excelsior is that the MCP clamp is custom fit to the user. The reasoning behind this is due to the fact that every person’s MCP area is shaped so uniquely that to be able to fit the plate comfortably, prevent injury, and accurately measure parameters such as the bend angle of the digits, the MCP clamp needs to be fit to the user.
Financial Issues

The financial issues that our project faces are that we need to be able to minimize the cost due to the inherent costs of physical therapy. When designing our concept, the important factors that we took into account was that post-stroke patients already face significant rehabilitation costs ranging from $2000 to $10000. After performing a cost analysis it was determined that the full device would cost approximately $550.00 in series production which we felt was a reasonable price in comparison to the sum of the costs for stroke rehabilitation which ranges from approximately $13000 to $30000.

Recommended Improvements

Future work includes making the Excelsior entirely additively manufactured and integrating the device with the Armeo system. Our initial design exhibited the Excelsior being entirely additively manufactured besides the finger thimbles but due to time and cost constraints this was not an option for our capstone presentation. When choosing a material for the leaf spring, which connects the MCP plate to the finger link, it was modeled in comparison to the Accura 25 SLA material. By using materials with similar mechanical properties it would make transitioning the device to an entirely SLA build extremely easy.

Other future work includes integrating the Excelsior with the Armeo spring system.