Designing a powered 3D exoskeleton for the rehabilitation of the hand.

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Abstract:

This paper describes the implementation of a motorized 3D printed orthosis for the rehabilitation of the hands for patients suffering with long term disability caused by brain injuries.
The first portion of this research paper will be focusing on identifying the sources of neuromuscular diseases on the median, ulnar and radial nerves which are the primary nerves in the hand that control movement [4]. Following this, the second part of the research paper will include a design analysis of pre-existing rehabilitating exoskeletons in order to find key elements and useful additions to add to the final product being designed in this project. Finally, prototypes will be created, tested and analyzed until a final functional product that fulfills the aim and purpose of this project is created.

Introduction:

The hands are an extremely vital part of the human body and help facilitate even the most basic daily activities. However, despite the importance of this limb, it is extremely susceptible to immobility; primarily due to trauma near the cranium resulting in hand paralysis[13]. More often patients live with this disability because rehabilitation is expensive and not everybody has access to the most innovative technology for rehabilitation[18]. Developing a cost-efficient device to help aid the rehabilitation of the hand would allow many to benefit from it. The aim of this device is to assist the hand with motion and movement that would've been compromised due to the damaged nervous system which came from the brain trauma.The adaptation of a 3D printed device provides a great value by serving as a temporary product that patients with hand immobility can utilize whilst they continue to gather the funds for professional medical treatment.

Neuromuscular diseases are commonly caused by stroke or trauma to the head in the frontal lobe within the brain [2]. Other causes of neuromuscular diseases include spinal cord injuries or brachial plexus injuries [15].A study done by the center of disease control and prevention in 2020 showed that every year more than 795,000 people in the United States have a stroke [6].
A stroke is a brain attack caused by a disruption of the blood flow in some areas of the brain causing the cells in that area to die. The damage of the brain cells due to a stroke or other brain injuries breaks the transmission of nerve signals from the brain to the muscles resulting in non responsive muscles , per consequence a loss of function for the affected body part [13]. Stroke is a leading cause of serious long-term disability and it reduces mobility in more than half of stroke survivors age 65 and over [6]. Spinal cord injury is a lesion within the spinal cord that results in the disruption of nerve fiber bundles that convey ascending sensory and descending motor information. A Spinal cord injury at the cervical level results in tetraplegia, responsible for the loss of hand and upper limb function with impairment or loss of motor and/or sensory function [16]. More often than not, the body part that is the most commonly impacted by these diseases are the hands[13] But with the understanding of the relationship between the nervous, skeletal and muscular system and the biomechanics of the human gait, prosthetic devices and assistive devices have been designed to improve the functionality of the body parts suffering from a disability [19].

Several devices have been designed to help with the rehabilitation and after a stroke such rex-bionic, hybrid assistive limbs(HAL) and many others. These devices play an important role in the process of rehabilitation. Most of those exoskeleton devices are operated in 3 ways for different purposes. Joystick control, posture control and electromyographic control. Joystick control consists of having a joystick which controls the entire limb, this could be used to help the person eat or drink while using a joystick. The posture control is used to help someone who has lost their ability to stand straight, the exoskeletons are used as bones which correct the posture in different desired positions and lastly the electromyographic control consists of having multiple electromyogram pads attached to the person. When the patient flexes a muscle, the pads detect the difference and use that to provide different movements to the exoskeleton attached to the patient. The hybrid assistive limb(HAL) exoskeleton is a machine which is designed as having two braces with multiple degrees of freedom for the knees, the hips and the ankles. The device is hoisted up with a machine, this is done so that the patient and the machine do not collapse during the session. While on a treadmill the patient will walk normally while having the machine on. The result is that the patient is able to regain the muscle strength within the legs and is also able to build muscles which will allow them to walk without having any motor or posture problems [20].

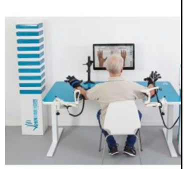
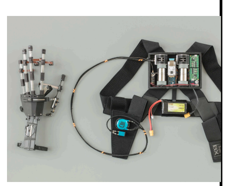
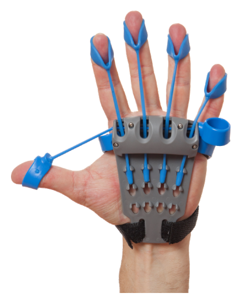
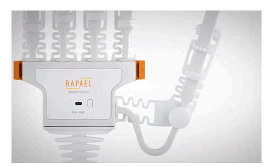
Even with the presence of many devices that have been created for assisting in the rehabilitation, few of these devices are accessible to most individuals due to costs and those that are easily accessible don't provide the same efficacy. This research project has been focused on the development process of a powered exoskeleton that can be 3D printed to help facilitate movement and accessibility.

With the growth of open-source, 3D printing has allowed for much more attainable and customizable options for prosthetic and assistive devices. The question that arises is how can 3D be effectively used to create rehabilitation devices that perfectly suit the individual using it. With 3D printing, manufacturing costs can be significantly reduced, while still maintaining the majority of material properties used in traditional manufacturing techniques. This technology can be associated with the understanding of biomechanics to provide solutions for disabled people that are very customizable with reduced costs.

Using a 3D powered exoskeleton can not only aid with the motion and movements of the hand such as pinching and grasping but is also effective in amplifying the strength which can be beneficial for completing the norm everyday tasks [3]. Additionally, A study conducted by AIP Conference proceedings [1] details how the usage of exoskeletons for rehabilitation is favorable for not just the physical health of patients but also their emotional health. This is due to the fact that patients can live a close to normal life independently rather than having to commit to going to a rehabilitation center which often has negative emotional connotations attached to it. This emphasizes the usefulness of developing an exoskeleton to help with rehabilitation and can help illustrate the benefits of further scientific development in this area of technology and rehabilitation.

The table below describes some of the devices that have been implemented for the rehabilitation of the hands with their advantages and disadvantages.

Table 1.1 Hand Rehabilitation Exoskeletons

	GLOREHA SINFONIA. [9][10]	Relab Tenoexo[11]	Xtensor[8]	Raphael [17]
Description	A computer-based glove. Supports upper limb rehabilitation.	Actuated hand exoskeleton, include a hand module, a Myo armband for electromyography and data collection, a backpack containing the actuators and computer board.	Xtensor is a wearable device that can be used to perform flexion and extension of the hand.	Neofect Smart Glove is a high-tech rehab device that measures movements of the forearm, wrist, and digits with accelerometer and bending sensors.
Developer	Idrogenet Srl	ETH Zurich Rehabilitation Engineering Labs	ClinicallyFit	Neofect
Images	  	 	 	 
Advantages	Helps patients perform activities easily by following a 3D	Wearable, Can be used independently at home, provides a user interface through a smartphone,	Can be accessed easily due to low cost, increases muscle and tendon strength in the hand.	This device is with great advantages, it comes with training programs that makes it easy to perform the rehabilitation of the hand. Those

	simulation on a computer screen; Stimulates the neuromuscula r pathway of the hand.	allow the patient to perform tasks easily with the myoelectric sensor and allow patient to use a control board to adjust the options		activities are for example games that require the performance of some movements that are challenging to the patient, in this way the rehabilitation becomes engaging.
Disadvantages	Device is connected to a station and can only be accessed at a rehabilitation center that has it.	Requires wearing a backpack which contains the actuator and computer board	The device can only be used by individuals with some control of their hand and no assistance from an external motor.	Expensive thus not accessible to everyone.

Materials and Methods:

Overall, the primary method utilized in order to develop the final product was biomimicry, as we utilized a variety of software and hardware in order to simulate the connective tissue present in the hand. The three crucial components in this product include the 3D printed exoskeleton, which houses all of the other pieces of hardware, the myoware EMG and electronics which allow the exoskeleton to function and move, and the mainboard and power supply, which store the code and power the stepper motor. The predominant reason behind 3D printing the framework of the product was to make it inexpensive and more accessible to the general public. A study done between 2001 and 2005 showed that “Average cost for outpatient stroke rehabilitation services and medications the first year post inpatient rehabilitation discharge was $17,081. The corresponding average yearly cost of medication was $5,392, while the average cost of yearly rehabilitation service utilization was $11,689.”[18] Personal 3-D printers and Commercial 3-D printing services are becoming more commonplace and accessible, allowing for a plethora of affordable prosthetics. On the other hand, the myoware EMG electronics essentially acts as the muscles of the hand as it works by sensing the electrical activity within the forearm during muscle contractions. The contraction is then processed via the code in the microcontroller, signalling the stepper motor to pull the fishing line, thus assisting the flexion of the finger(s).

The software works to connect all of the electronics together and create a chain of commands that dictate how the product functions. Firstly, the signal path begins when the forearm muscles contract, the EMG sensors are able to pick up the electrical signal via the electrode pads. Following this, the signal is amplified by the myoware muscle sensor and then perceived as an analog signal by the Arduino; next the analog pin 0 in the Arduino processes this signal and compares it to a signal range as specified within the code (present within the mainboard). Based on the range percentage, the output signal is sent to the stepper motor which then turns the appropriate amount based on the signal in order to mimic a regular hand's ability to partially or completely contract its fingers depending on the action being conducted.

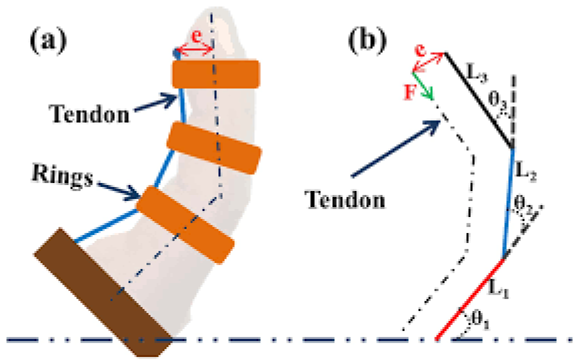


Fig1.1 Biomimicry of the biomechanics of the flexion of the fingers.

Results and Discussion:

The design phase for this project involved multiple redesigns to achieve the function desired in our initial concept. The redesigns mainly consisted of essential ergonomic changes, allowing the product to successfully achieve all the goals and purposes. Originally, the design of the product placed the orthosis on the dorsal side of the hand, with sections hinging over the joints of the fingers. The original design was difficult to manufacture and assemble, having multiple hinged sections for each finger. Furthermore, it wasn't based on the human physiology of the hand, which resulted in it being extremely inefficient in performing flexion of the fingers.

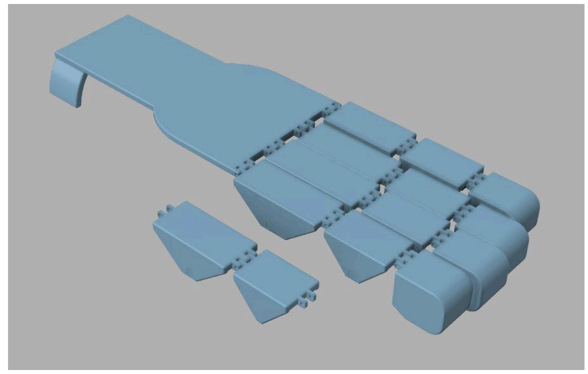


Fig1.2 Design n°1

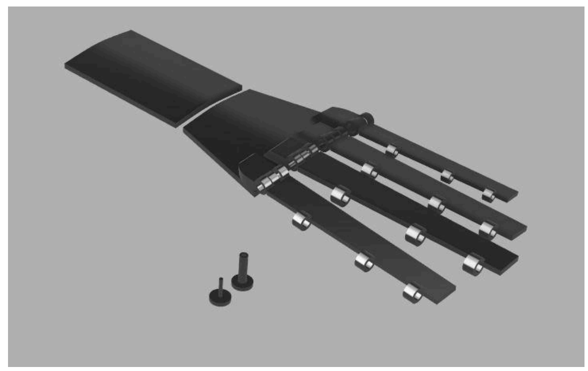


Fig 1.3 Design n°2

The most recent iteration of the design moves the main part of the orthosis to the palm of the hand, where it mimics the action of the flexor tendons. This substantial change allows the orthosis to work in tandem with the tendons already present in the wearer. The flexor tendons are represented by high-strength fishing lines, which run parallel to the tendons in the palm. At the distal end of the fishing line, a semi-flexible ring is attached to the middle phalange of each finger, providing the anchor point for the string to move the fingers. The 4 strings run through the main body of the orthosis device, where the other end is attached to the stepper motor. The EMG sensor is attached to the opposite forearm, and actuates the stepper motor through closing the hand. Through this implementation, the current design achieves its intended purpose of serving as a rehabilitation device, by performing bilateral movement of the hand.

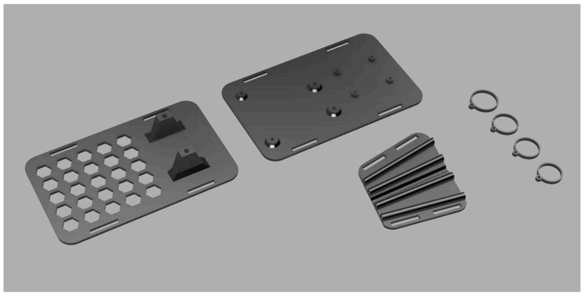


Fig 1.4 Final Design

The strengths of our product are in its ergonomic and accommodating design, with the use of modular and readily-available components. The components are manufactured with 3-D printing, meaning that they can be made with a variety of material properties, colors, and finishes. The shape and sizes of the various components were designed to allow for as much movement as possible with the orthosis attached. The nature of 3-D printing allows for the parts to be scaled and edited to the user's preferences, effectively making the current design a one-size-fits-most. Total filament costs for all of the pieces are the least expensive component of the project, with the prototype costing less than $2.50 in filament. The rest of the materials used are relatively inexpensive and modular, with a variety of substitutes being acceptable with little to no modifications. For example, any model of Arduino microcontroller with analog pins can be used for this project, including cheaper clones or smaller units such as the Arduino nano. Fastening straps of various sizes can be used to secure the pieces, with other alternatives such as string or shoelaces being a possibility. The openings of the orthosis device can accommodate fishing line up to 2 mm in diameter, allowing for whatever size is most available to the individual.

To further improve this product, more iterations can be done to further improve the current features. A future iteration can implement an additional line to connect the thumb, allowing for all of the flexor tendons to be assisted by the orthosis device. Additional time could be spent refining the stepper motor component of the orthosis, with faster motors or gearing being used to increase the speed of the device. Further understanding of the EMG sensor will lead to more accurate and consistent readings, increasing the reliability of the device. Although costs are significantly lower than other available options, reducing the amount of electronic components would help to further increase accessibility. Given the current state of microcontroller availability, reducing or eliminating electronics would ensure that the majority of potential users can effectively replicate the orthosis. A purely mechanical design would fit this criteria, however it may be a challenge to accommodate all potential users.

Ultimately, our design serves as an open-source solution, to aid in the rehabilitation of individuals with nerve damage to the hand. Our design, materials, and instructions will be posted to 3-D printing file-sharing sites, allowing for others to use, modify and improve the design to suit their needs.

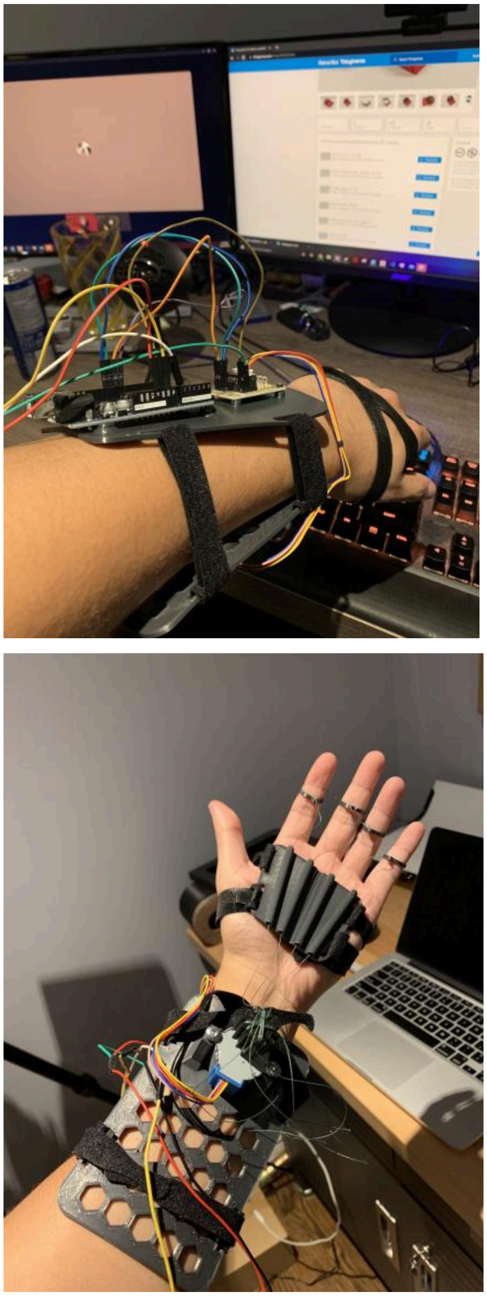


Image of finished product.

Conclusion:

With the increasing frequency in which neuromuscular diseases and traumatic brain injuries occur, the innovation and development of new non-conventional treatments that are readily accessible to the general public is crucial. The data and facts previously mentioned within this report, such as the 795 thousand reported cases of strokes by the CDC within the US alone further accentuates this statement. Thus, the purpose of this project was to develop a cheap yet effective alternative to existing hand rehabilitation exoskeletons.

Conclusively speaking, after numerous iterations of the original design, the goal of this project was successfully met as a functional product that aids with the rehabilitation of the hand was created. Despite the final product by no means being perfect due to issues such as the thumb not being present and the inconsistencies in the EMG sensor readings, this product was extremely successful in utilizing an ergonomic design in order to improve its functionality. Moreover, this product is easily adaptable due to the nature of 3D printing which allows for the dimensions of the design to be modified in order to fit anyone's hand no matter how big, small or even deformed it is. Additionally, the product is innovative as it improves upon all of the drawbacks of pre-existing products similar to it. GLOREHA SINFONIA, Relab Tenoexo, Xtensor and Raphael are all hand rehabilitation devices that are currently present in the market, however, all of them are either ineffective in allowing the user to carry on with their day to day life with additional hand mobility support or are either too expensive and thus inaccessible or are immobile to the point where it's impractical to use. On the contrary, our product is relatively cheap, provides extensive support and at the minimum, is practical to use on a daily basis. Lastly, the fact that the CAD design file is being uploaded to printables allows the product to be more accessible and subject to improvements by anyone. Overall, the benefits of this product greatly outweigh the complications of it and its implementation into modern day healthcare systems would likely have a positive impact on society.

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