Phalanx Rehabilitation and Replacement (PRAR)
Two Degree-of-Freedom Wearable Exoskeleton

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ABSTRACT

The human hand is an integral part of human dexterity that requires target-oriented rehabilitation with repetitive motions under constant supervision from a professional physiotherapist to avoid further damage. The introduction of robotic rehabilitation can help the task of repetitive hand motions and reduce the need for therapist dependency. This paper addresses the design and development of PRAR (Phalanx Rehabilitation and Replacement), a two degree-of-freedom single actuator exoskeleton that attaches to three phalanxes of the index finger. The actuator is controlled by a flex sensor that is worn and guided either by a therapist or the patient (on the alternate hand) which allows organic hand movement. A force sensor is additionally mounted on the distal phalanx to measure patient grip and ensure the task is safely performed. This design minimizes the number of actuators and aids in rehabilitation independence in a cost-effective manner.

INTRODUCTION

Background

Exoskeleton phalanx rehabilitation is a well-explored study and can be achieved through a multitude of mechanisms. Aside from the linkage mechanism explored in this paper, other methods include hydraulic and pneumatic actuators with fabric or silicon bases (also known as tendon method) (Yoon and Lee 2021). While the linkage method requires a rigid exoskeleton, the hydraulic and pneumatic methods can use soft exoskeletons. Many current models implement soft robotics and are paired with fuzzy controllers that do not require a mathematical model to control. This allows better flexibility and more adaptability in the controls. However, because of the lack of structure, any force exerted by the actuators cannot be distributed evenly throughout the exoskeleton and the grip becomes unstable (Yoon and Lee).

A common method is a combination of the linkage method and pneumatic actuators. Depending on the material, this amalgamation is not always considered soft robotics. Zhang et al. created a similar kinematic structure to PRAR with linear pneumatic motors thus achieving a full glove exoskeleton that aids in rehabilitation. However, their model does not include sensors and it relies on the pneumatic actuators to control the movement of the hand (Zhang et al. 2021). Cui et al. also proposed a linkage and pneumatic exoskeleton design with a different kinematic structure for the linkage however no force feedback was integrated into the system (Cui et al. 2015).

Theory

The function of PRAR focuses on patients with little to no mobility in the phalanxes. This includes patients who have had surgeries or nerve damage and require physical therapy to regain motor control. The idea is to design a mechanical structure which imitates the motion of the finger and can be easily mounted on the patient's hand. Additionally, the structure should be light enough to not impede movement and should be externally controlled.

With such a structure, the movement of the patient's finger can be facilitated when they are incapable of doing so independently. The structure can be controlled by a physical therapist if required and the controls should be simple enough for users without engineering backgrounds.

Additionally, other tools can be used in tandem with the device. For example, a ball with an arbitrary diameter can be used for the patient to curl their finger and assess grip. A ball of larger diameter would be used if the patient is commencing their recovery and cannot completely bend their finger over it. If the patient is further in the process of recovery, a ball with a smaller diameter can be used so the patient can practice a larger range of motion.

METHOD

PRAR works as an under-actuated system with a single servo-motor as an actuator. All the parts of the design were 3D printed using PLA as the built-material to provide rigidity to the design. On the other hand, a flex sensor is simply sewn on a hand-glove for the prototyping phase. All the connections are made using a normal breadboard which can be easily replaced by a PCB circuit to make the design compact by fitting it right on the top of the existing design. Enough care is taken to ensure that the ergonomics of the device is easy to wear and remove. When the device is used as a replacement, the 'controller-glove' will be worn on the other hand and its actions will be mirrored for the other one. A slight modification in the method shows that it can be worn by someone else, maybe a physiotherapist who might be helping the patient with the rehabilitation of that particular finger. The force sensor attached to the tip of our device, will measure the force applied on any object while grasping it.

User interface

This device can have two users: the physiotherapist and the patient.

1. Physiotherapist:
   The user will be able to control the exoskeleton by a separate glove, which will be worn on the hand. The glove has a flex sensor mounted on the finger which will detect the bend of the user's finger - the movement will then be mirrored on the mechanical support finger. Both the user's finger and the mechanical support finger will move in tandem with a slight delay for the patient's safety. The values of the flex sensor can be displayed by the serial monitor in the code.
2. Patient:

The user will have the mechanical support finger mounted on their hand using Velcro straps at each phalanx and around the palm and wrist. As the physiotherapist moves the glove, the mechanical support finger will mirror the movements in the patient's finger.

Additionally, an object of a certain diameter can be used for the patient to curl their finger to test their grip. If the force applied on the ball is greater than the allowed safe value established by the therapist, the force sensor mounted on the distal phalanx of the mechanical support finger will detect it and prevent any further strain by returning the actuator to the initial position. The values of the force sensor can be displayed by the serial monitor in the code as well.

The glove that controls the mechanical support finger can be modified such that the patient can control the support finger with their opposite hand if they are only injured on one hand. This allows the possibility for independent use if the patient is at the end of their recovery period. The physiotherapist and patient will be able to access the emergency stop push-button should any emergency arise.

Electronic Circuit

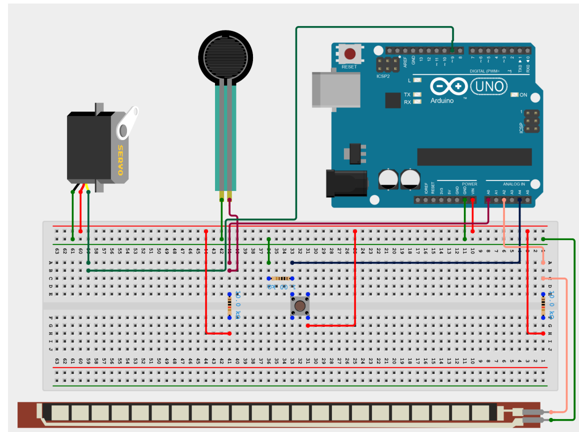

Fig 1: Full circuit diagram including the servo motor (left), force sensor (center), Arduino microcontroller (right), and flex sensor (bottom)

Microcontroller

The microcontroller used for this project is an Arduino UNO. In the interest of prototyping, the Arduino UNO was selected over other controllers because of speed and it's closed nature. Each time a program is run on BASIC Stamp, it behaves procedurally and re-interprets it. This limits the speed with which we can execute commands. For this project, reading real time data and sending appropriate output to a display either on an LCD or mobile via bluetooth based on this was taken into consideration. The Arduino is more intuitive in integrating these options for future implementations and can perform the task faster, with minimal delay between input and output.

The Arduino also provides better options for writing new commands and creating libraries which is valuable in the prototyping stage. In future iterations of the model, a smaller more simplified controller can be used to reduce cost and streamline the design.

Sensors

1. Flex sensor

As explained in the previous section, the PRAR support structure should mirror an actual finger bending. Thus, a sensor which accurately measures the movement of the phalanges is needed. The flex sensor provides an adequate measurement for this task.

A flex sensor behaves like a variable resistor where the resistance increases with the angle at which it is bent. By mounting this sensor on the finger of the operating glove, we can measure the degree at which the finger of the operator is bent and send the input to the Arduino.

In the circuit, the flex sensor is connected in a voltage divider circuit with a 10KΩ resistor. As the flex sensor bends, its resistance increases and the voltage across it also increases. The voltage across the flex sensor is connected to the analog input port of the Arduino, with resistance in series to safeguard the input pin.

2. Force Sensor

The force sensor is concealed in the Velcro band of the distal phalanx of the mechanical support finger and should sense the force applied on the object at the point of contact. It acts as a safety mechanism if the force applied by the wearer on the object goes beyond an arbitrary safe value established by the physiotherapist.

A force sensor, like flex sensor, is a variable resistor where its resistance decreases when force applied on it increases. Like the flex sensor, the force sensor is connected in a voltage divider circuit with a 10KΩ resistor. As the force applied on it increases, it’s resistance decreases and thus, the voltage across it also decreases. The voltage across the force sensor is given to the analog input port of the Arduino, with resistance in series to safeguard the input pin.

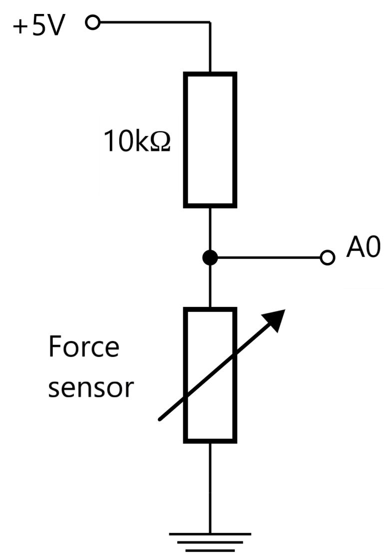

Fig 2: Force sensor integrated in the voltage divider circuit

3. Push-button:-

The push-button acts as an emergency stop to the mechanism. In case the device malfunctions and applies excess force or performs irregular movement, the wearer should be safe and unharmed.

It is connected with a pull down resistor of 1KΩ and a resistor of 1KΩ in series with A4 pin to safeguard the input pin. When the button is pressed, the mechanism comes to a halt and returns the actuator to the default position so the wearer can safely remove their finger, with assistance.

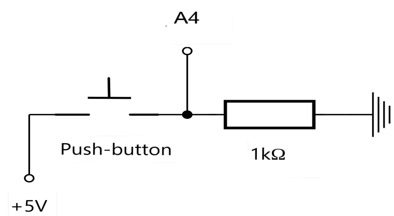

Fig 3: Pull-down resistor circuit for the push-button

Actuators

The project uses only one servo motor as the actuator. The servo motor is attached to the mechanical support finger mechanism through a link. The mechanical finger moves according to the rotation of the servo motor and has a certain unique position at each servo motor angle.

The servo motor takes 5V input and a control input from one of the digital pins in the Arduino. The output given to the servo motor depends on the values received from flex sensor, force sensor and the push-button state as a function condition.

Mechanical and Mathematical Design

The underactuated mechanism is based on a linkage mechanism. Four-bar linkage is one of the simplest mechanisms among all the other mechanisms. A four-bar linkage has three moving links and one fixed link along with four pin joints. These linkages can perform rotating, oscillating or reciprocating motion. A four-bar mechanism follows Grashof's law - "The sum of the shortest and the longest links cannot be greater than the sum of the remaining links if there is to be continuous relative rotation between two members."

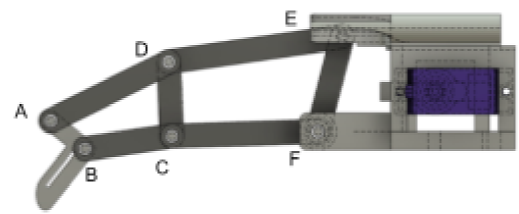

Fig 4: Side View

$$AB + AD = BD$$
$$DC + BC = BD$$

In the equations above the vector BD will be equal for both the loops. Therefore we can equate both the equations above as follows -

$$AB + AD = DC + BC$$

Similarly will be the case for the 4-bar linkage mechanism DECF. The close loop analysis using Euler's equation -

$$\text{angle}(DAB) = \Theta_1$$
$$\text{angle}(ABC) = \Theta_2$$
$$\text{angle}(BCD) = \Theta_3$$
$$\text{angle}(CDA) = \Theta_4$$
$$ABe^{i\Theta 1}+BCe^{i\Theta 2}+CDe^{i\Theta 3}+DAe^{i\Theta 4}=0$$

The above equation is called loop closure equation. The same can be interpreted for 4 bar linkage CDEF from fig 4.

The design has two four-bar linkages; one at the lower end of the finger and the second at the middle attached to the lower one. The proposed finger mechanism is similar to that of a human finger with three phalanges and three joints. The mechanism has two four-bar linkages as shown in Fig 4 (proximal phalanx and middle phalanx) proximal linkage CDEF being a four-bar linkage has 1 DOF which is the same as the middle linkage ABCD. The ratio of the lengths of the finger links is inspired from the human finger joints link ratio.

The figures presented below show the sequence of motion of the PRAR mechanism.

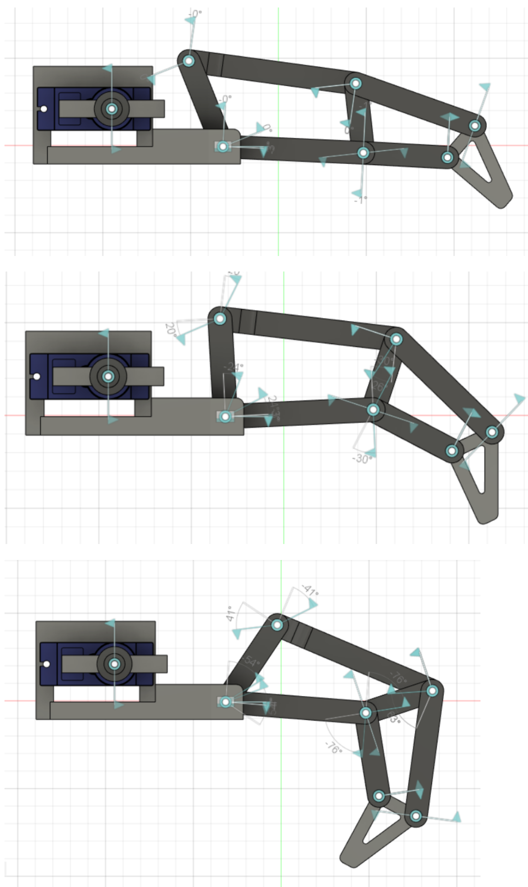

Fig 5 : Sequence of motion from default position to full curl extension

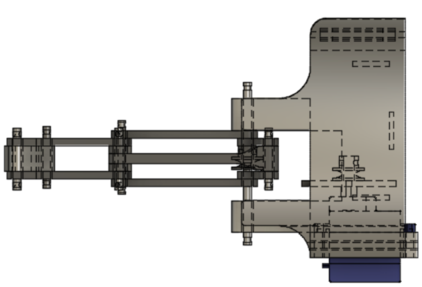

Fig 6: Top View

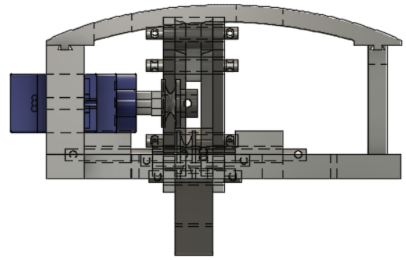

Fig 7: Back View

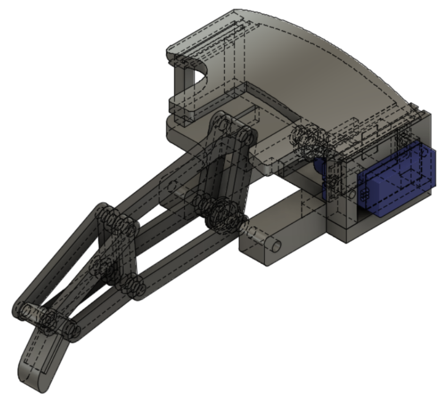

Fig 8: Isometric View

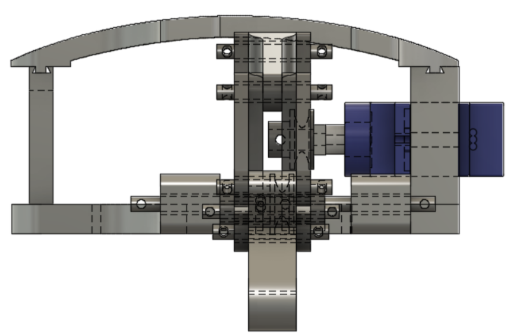

Fig 9: Front View

Data Analysis

PRAR uses two sensors viz. a force sensor and a flex sensor. A force sensor responds to the applied force, as well as converts the value to a measurable quantity. Most force sensors are created with the use of force-sensing resistors. Such sensors consist of electrodes and sensing film. Force-sensing resistors are based on contact resistance. These contain a conductive polymer film, which changes its resistance in a predictable way once force is applied on the surface. The analog reading from the force sensor is mapped to the readable values and a threshold of 600 is defined, beyond which if the value exceeds, the finger will retract. The threshold value can be determined by the therapist as well for a particular patient.

On the other hand, a flex sensor uses carbon on a strip of plastic to act like a variable resistor. The resistance changes by flexing the component. The sensor bends in one direction: the more it bends, the higher the resistance gets. The range of the mapped values ranges from 0 - 1023, however, we defined the range from 0 - 800 to control the rotation of the motor in a certain range of angles and to reduce noise as the value fluctuates at extremes. The values from the flex sensor are mapped to angular positions of the servo rotor using the map function from Arduino Library.

Prototype cost

The entire prototype cost \$46.92USD for the parts listed in table 1. The cost might vary depending on the source of purchase of the material and electronic components. For example, a pair of Force sensors are available on Amazon for \$11.09USD, while it is available on Digi-key for \$13.77USD. On the other hand, the flex sensor is available on Amazon for \$8.09USD while it's available on Adafruit Industries for \$13.67USD.

Table1 : List of components used for the prototype.

	Part(s)	Quantity	Price (USD)
Sensor(s)	Flex Sensor	1	8.09
	Force Sensor	1	11.09
Actuator(s)	Servo Motor	1	3.99
Controller	Arduino UNO	1	23.00
Misc.	Velcro	5	0.75
	Button	1	–
	Resistors	3	–
Total			46.92

Cost Analysis for Mass Production

Table2 : Cost analysis for production of 100 devices.

	Part(s)	Quantity	Price per unit (USD)	Bulk price (USD)
Sensor(s)	Flex Sensor	100	7.95	795.00
	Force Sensor	100	7.90	790.00
Actuator(s)	Servo Motor	100	3.45	345.00
Controller	Arduino UNO	100	18.40	1840.00
Misc.	Velcro	500	0.498	49.80
	Button	100	0.32	32.00
	Resistors	300	0.282	28.20
Total				3880

Safety Measures

Rehabilitation devices are tailored for assisting different sensorimotor functions and development of different schemes of assisting therapeutic training and assessment of sensorimotor performance (ability to move) of the patient. Since the device works in direct physical contact with the patient's affected body part, essential safety measures need to be taken while designing the device. While designing PRAR, safety measures were implemented by the inclusion of the feedback system.

The device is equipped with a force sensor fitted at the distal phalanx that measures the force when the contact point touches any surface. So, when the device is used for rehabilitation and the therapist controls the affected finger, the feedback system reacts when the fingertip exerts unnecessary force on any surface, the system retracts the finger to the original position irrespective of the position of the 'controller-glove', which saves the phalanges from crossing the permitted threshold while grasping objects. In addition to that, a similar procedure is adapted by the system to ensure that threshold is not crossed while grasping the objects when the device is used as replacement.

Algorithm

The flex sensor and the force sensor are the main inputs of this system with the button as an auxiliary safety feature. The button provides a manual override for the user to interrupt the procedure and provide a time delay to adjust or remove power from the system. The force sensor functions as a safety feature as well. The user can input a personalized limit value that the user cannot exceed as a condition for the program to run. If the force limit is exceeded, the servo motor will reset and provide a time delay for adjustment. The force sensor and button state are measured and updated throughout the program. The flex sensor's primary function in the procedure is to provide desired position value for the servo motor. Due to the range of the flex sensor values, it is mapped into a range of 0 to 180 for the servo motor. There is also a delay in the servo motor positioning as an additional safety feature for the patient.

Algorithm Flex sensor control with force sensor measurement

```
PROCEDURE
    Measure force sensor and Reset servo to default
    WHILE force value is under limit and the button state is not pressed
        Measure flex sensor
        Map flex sensor values into range of 180 for servo position
        Set desired servo position to the mapped flex sensor value
        FOR Current servo position to desired servo position
            IF during these increments the button is not pressed
                Measure force sensor every increment
                IF force sensor exceeds force limit
                    BREAK with no more increment
                ELSE if the button is pressed
                    Reset servo to default position
                    BREAK with no more increment
                Move servo in increments
        Measure force sensor and button state again
    REPEAT if the while loop conditions are still met ELSE exit while loop
    DELAY
REPEAT
```

CONCLUSION

As a prototype, the current model achieves two degrees-of-freedom of motion using a single actuator and successful actuator control using a flex sensor. Unlike other models, the PRAR exoskeleton can also successfully detect pressure exerted by the user with preventative safety measures to protect the user from over-exertion. However, because this model is the first prototype, there are critical improvements that should be taken into consideration for future iterations.

The connection between the actuator and the finger chassis needs to be optimized better. Ideally the exoskeleton should be capable of achieving full range of motion in the finger. Due to the current design, the joint does not reach the full range to grip smaller objects (< 5cm diameter) because of the connection. Moreover, the current mechanical design is not universal for all hand sizes. The model must be scaled individually per patient. An integration of adjustable lengths for the finger joint should be explored in future prototypes. Soft robotics could be a potential solution to the size issue as well as the precision for smaller pieces that 3D printing lacks. Additional force sensors should be implemented at multiple points of contact to ensure that the force distribution of the patient's grip using the exoskeleton is balanced and safe. This data should also be collected to analyze the progress of the patient's recovery.

At this stage, the exoskeleton can move independently without a user however the primary focus of the current prototype is rehabilitation. Further optimization must be explored before implementing the model as a phalanx replacement.

The integration of robotics in physical rehabilitation therapy opens the opportunity to eliminate constant supervision from a specialized therapist. The mechanical design detailed in the previous section along with the algorithm allows a user to complete repetitive motions that are needed in physical therapy with constraints that prevent patient over-exertion without external intervention. The PRAR exoskeleton model successfully demonstrates implementation of mechatronics in robotic phalanx rehabilitation with a minimized number of actuators and sensors for a simple and cost-efficient design.

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