A Rigid-Elastic Hybrid Finger Exoskeleton Rehabilitation System (FERS)

for Stroke Patients with Motor Impairment

Log Book

Brad Wu

7/15/2023

- Identified a few potential topics related to the finger rehabilitation, for patients with cerebral palsy, stroke, or spinal cord injury.

- Read the reference website
  - Centers for Disease Control and Prevention. Stroke statistics.

    https://www.cdc.gov/stroke/facts.htm

  - Stroke Awareness Foundation, Stroke Facts & Statistics. https://www.strokeinfo.org/stroke-facts-statistics

- Read research papers

  - Lewis A. Ingram,Annie A. Butler,Matthew A. Brodie,Stephen R. Lord, and Simon C. Gandevia(2021). Quantifying upper limb motor impairment in chronic stroke: a physiological profiling approach. *Journal of Applied Physiology, Vol. 131, No. 3*
  - J. Ngeo et al., "Control of an optimal finger exoskeleton based on continuous joint angle estimation from EMG signals," 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2013, pp. 338-341.
  - M. H. Abdelhafiz, E. G. Spaich, S. Dosen and L. N. S. Andreasen Struijk, "Bio-inspired tendon driven mechanism for simultaneous finger joints flexion using a soft hand exoskeleton," 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR), 2019, pp. 1073-1078
  - P. Heo and J. Kim, "Power-Assistive Finger Exoskeleton With a Palmar Opening at the Fingerpad," in IEEE Transactions on Biomedical Engineering, vol. 61, no. 11, pp. 2688-2697, Nov. 2014

The first paper showed that approximately 80% of people with stroke will experience some degree of motor impairment in their upper limbs. Hand/finger exoskeletons are perfect for these patients to use at home. Repeat movements can provide neuromuscular training and let the fingers gradually regain their functions. This is self-rehabilitation.

7/17/2023

- Continued reading the reference papers.
- **Hand exoskeleton systems** can often be described and distinguished by their mechanical design, the number of possible degrees of freedom, the choice of actuators, or the chosen control strategy. Among exoskeleton designs, some have rotating joints that are simple in design but do not follow the exact trajectory of a human finger. Others provide multi-finger support with a large number of degrees of freedom, but are mechanically complex, bulky, and require high power to drive all actuators simultaneously. Some designs also use pulleys and cable-driven transmission mechanisms to reduce accessible parts of the hand that may impede natural hand movements and to provide user comfort and low weight.
  One of the most important requirements in hand exoskeleton design is safety. Since the exoskeleton is in direct contact with the human limb, any malfunction will cause harm to the wearer. In addition, hand exoskeletons should be lightweight, portable, and appropriately sized to assist the wearer in activities of daily living. Exceeding the range of motion should be avoided by implementing mechanical stops into the hand exoskeleton design. Some hand exoskeletons involve controlling all five degrees of freedom of the fingers to replicate the full motion of the hand. Several other hand exoskeletons utilize under actuated mechanisms to provide mechanical solutions coupled between individual finger joints via cables and pulleys or linkages.

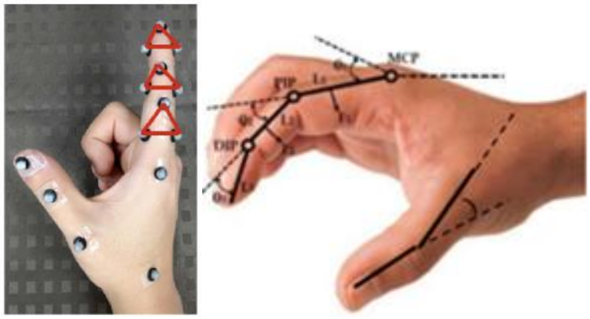
- Key features for the design – **Safety, Lightweight, Portable, and Accessible.**

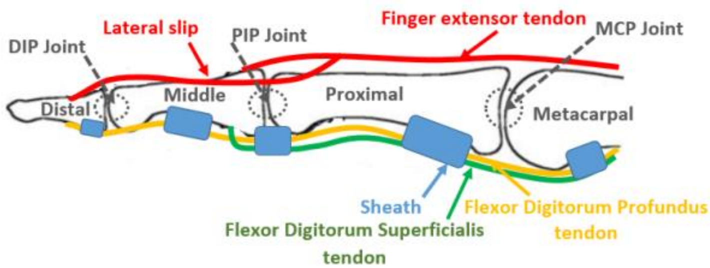
- The project is likely to include bio-engineering, 3D CAD design, mechanical engineering, and electrical engineering for user interface.

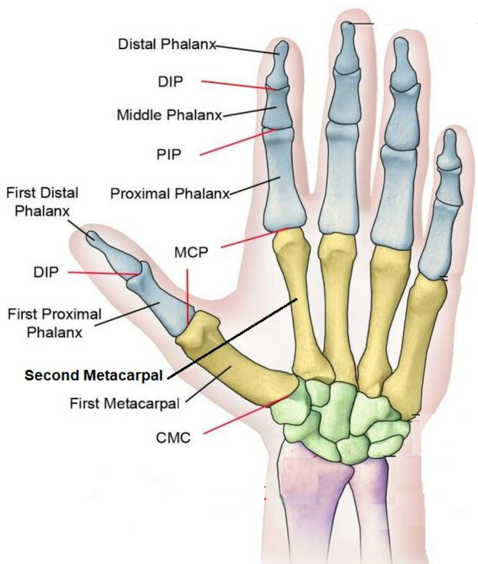
7/19/2023

Takeaways of readings –

- Anatomy of human palm and fingers --







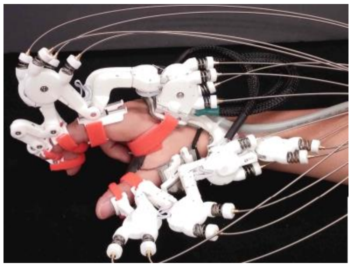
Existing exoskeleton summary

. Rigid Linkage

The rigid linkage is the traditional actuation mechanism

Advantages: Signal, current and torque are applied on fingers directly. The finger control is straightforward. Usually more DOFs and wider ROMs.

Disadvantage: Joint-axis misalignment or unexpected torque can cause pain on human joints. Also volume and weight are usually high.



b. Pneumatic

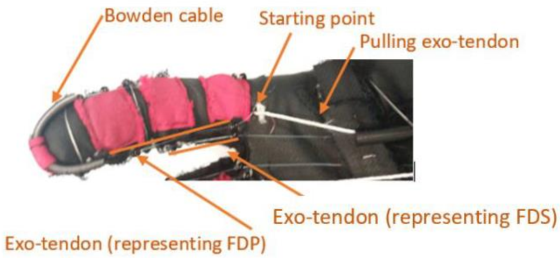
Advantages: Weight is usually light. Materials are soft.

Disadvantages: Being lack of accuracy caused by the non-linearity of soft actuators from hyperelastic materials. Control of Pneumatic pressure is too complicated.

c. Tendon-driven

Advantages: Wearable parts have light weight. Materials are soft.

Disadvantages: Being lack of high quality materials as exo-tendon. There is not enough space for sensors. Both torque and compressive force on fingers can cause pain.

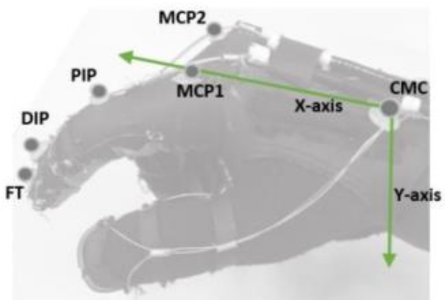


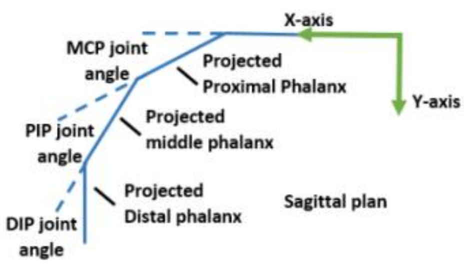
The following characters are usually used to evaluate the performance of the hand/finger exoskeleton system.

- DOF(Degree of Freedom): Extension/Flexion(F/E), Abduction/Adduction(A/A) and Opposition
- ROM (Range of Motion): Thumb F/E & AA, Other Fingers MCP/PIP/DIP joints
- Weight
- Size
- Force
- User Interface

7/20/2023

Index finger and thumb finger can achieve the majority of tasks required by hand.





To achieve the goal of lightweight, narrow down the mechanical engineering on index and thumb finger only.

SOLIDWORKS, CAD Design Software, is the best software but very expensive. Student version is available for $99 per year. Good deal!

Downloaded SOLIDWORKS and started to play when learning on Youtube.

Learning from –
https://www.youtube.com/@solidworks
https://www.solidworks.com/

7/22/2023

In a direct drive mechanism, where the actuator is located in the hand itself, there is more opportunity for finger movement. Through the direct drive mechanism, independent joint control of human fingers becomes possible, thereby realizing the grasping and manipulation of objects.

- Research status - Finger exoskeleton robot 1

literature: J. Ngeo et al., "Control of an optimal finger exoskeleton based on continuous joint angle estimation from EMG signals," 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2013, pp. 338-341, doi: 10.1109/EMBC.2013.6609506.

Disadvantages: EMG (Electromyography) data processing is needed

- Research status - Finger exoskeleton robot 2

literature:

M. H. Abdelhafiz, E. G. Spaich, S. Dosen and L. N. S. Andreasen Struijk, "Bio-inspired tendon driven mechanism for simultaneous finger joints flexion using a soft hand exoskeleton," 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR), 2019, pp. 1073-1078, doi: 10.1109/ICORR.2019.8779547.

Disadvantages: Lack of high quality material, Unexpected pain, Not enough for sensors

- Research status - Finger exoskeleton robot 3

literature:

P. Heo and J. Kim, "Power-Assistive Finger Exoskeleton With a Palmar Opening at the Fingerpad," in IEEE Transactions on Biomedical Engineering, vol. 61, no. 11, pp. 2688-2697, Nov. 2014, doi: 10.1109/TBME.2014.2325948.

Disadvantages: forearm structure is too heavy and bulky.

Summary of the pros and cons of these types of linkages.

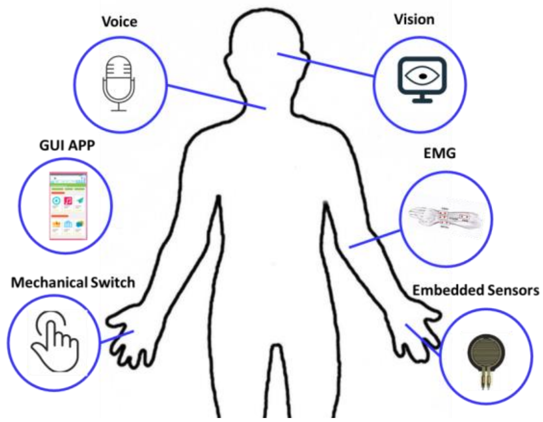
Type	Advantages	Disadvantages
Rigid Linkage	Directness and Straightforward More DOF and ROM	Large sized and heavy Unexpected pain
Pneumatic	Light weight Soft materials	Less accuracy Complicated control
	Light weight Soft materials	Lack of high quality material Unexpected pain Not enough for sensors

The goal of the project should be an effective hybrid finger rehabilitation system which combines rigid and software linkages. This new system has both advantages of Rigid Linkage device and Soft Linkage device and also resolve the gaps they miss.

The gaps are mainly in missing training on finger precision, missing training on fine motor coordination, missing training on isolated finger movement and ignored pain and injury caused by the device itself.

7/25/2023

- *Variety of User Interfaces used for hand exoskeleton system*



- Currently, only a few existing systems boast versatile user interfaces, presenting another challenge that needs addressing in the development of new systems.

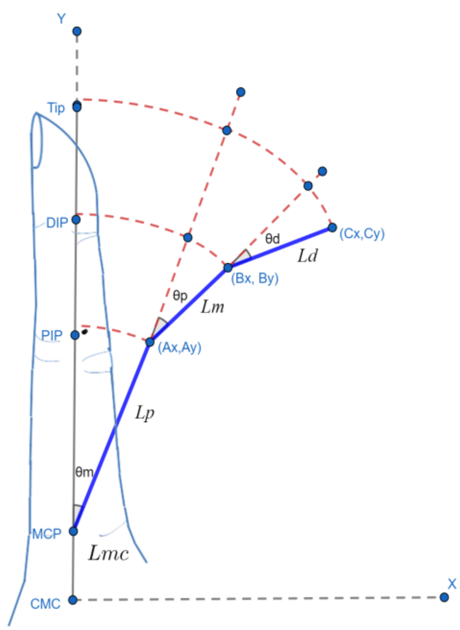
List Design Objectives –

- Accuracy.
- DOFs on the Index Finger for each phalanx, F/E DOFs on the Thumb Finger for each phalanx, Abduction/Adduction (A/A) DOFs on the Thumb, and Opposition DOF.
- Perform daily life functions.
- Lightweight and compact.
- Grasping.
- Pushpin force.
- Prevent injury and avoid pain.
- Interfaces – voice, mechanical input, machine learning computer vision method for object detection, etc.
- App with GUI App on a phone/tablet for task control.

8/10/2023

Finger Kinematic Model Position Analysis

Position Analysis is conducted to determine the position of all links in the exoskeleton. This analysis employs a geometric method. The Index finger kinematic model can be illustrated below using GeoGebra. In this model, Lmc, Lp, Lm, and Ld represent the lengths of the links for the Index (Second) Metacarpal, Index Proximal Phalanx, Index Middle Phalanx, and Index Distal Phalanx, respectively. Additionally, ϴm, ϴp, and ϴd denote the rotating angles of the joints on the Index MCP, PIP, and DIP. The position coordinates of the Index PIP joint, Index DIP joint, and fingertip after the movements are represented by (Ax, Ay), (Bx, By), and (Cx, Cy), respectively.



The positions of the Index PIP joint, Index DIP joint, and fingertip can be determined in equation (1). Microsoft Word is good at entering equations.

$$Ax = Lp \sin \theta m$$

$$Ay = Lp\ cos\ \theta m + Lmc$$

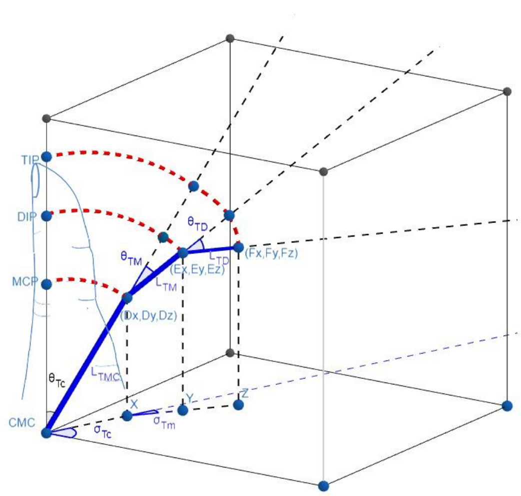
$$Bx = Lp\ sin\theta m + Lm\ sin(\theta m + \theta p)$$

$$By = Lp \cos \theta m + Lm \cos(\theta m + \theta p) + Lmc$$

$$Cx = Lp\ sin\theta m + Lm\ sin(\theta m + \theta p) + Ld\ sin(\theta m + \theta p + \theta d)$$

$$Cy = Lp \cos \theta m + Lm \cos(\theta m + \theta p) + Ld\ \cos(\theta m + \theta p + \theta d) + Lmc \qquad (1)$$

The thumb finger kinematic model can be illustrated in a similar way. In this model, Ltmc, Ltm, and Ltd represent the lengths of the links for the First Metacarpal, First Proximal Phalanx, and First Distal Phalanx, respectively. Additionally, Ɵtc, Ɵtm, and Ɵtd denote the rotating angles of the joints on Thumb CMC, Thumb MCP, and Thumb DIP. ϭtc represents the shifting angle of the First Metacarpal plane from the initial plane, and ϭtm represents the shifting angle of the First Proximal Phalanx/First Distal Phalanx plane from the First Metacarpal plane. The position coordinates of the Thumb MCP joint, DIP joint, and fingertip after the movements are represented by (Dx, Dy), (Ex, Ey), and (Fx, Fy), respectively.



The positions of the Thumb MCP joint, DIP joint and fingertip are determined in equation (2).

$$Dx = L_{\text{Tmc}} \sin\theta_{\text{TC}} \cos \sigma_{\text{TC}}$$

$$Dy = L_{\text{Tmc}} \cos\theta_{\text{TC}}$$

$$Dz = L_{\text{Tmc}} \sin\theta_{\text{TC}} \sin \sigma_{\text{TC}}$$

$$Ex = L_{\text{Tmc}} \sin\theta_{\text{TC}} \cos \sigma_{\text{TC}} + L_{\text{Tm}} \sin(\theta_{\text{TC}} + \theta_{\text{TM}}) \cos(\sigma_{\text{TC}} + \sigma_{\text{TM}})$$

$$Ey = L_{\text{Tmc}} \cos\theta_{\text{TC}} + L_{\text{Tm}} \cos(\theta_{\text{TC}} + \theta_{\text{TM}})$$

$$Ez = L_{\text{Tmc}} \sin\theta_{\text{TC}} \sin \sigma_{\text{TC}} + L_{\text{Tm}} \sin(\theta_{\text{TC}} + \theta_{\text{TM}}) \sin(\sigma_{\text{TC}} + \sigma_{\text{TM}})$$

$$\begin{aligned} Fx &= L_{\text{Tmc}} \sin\theta_{\text{TC}} \cos \sigma_{\text{TC}} \\ &+ L_{\text{Tm}} \sin(\theta_{\text{TC}} + \theta_{\text{TM}}) \cos(\sigma_{\text{TC}} + \sigma_{\text{TM}}) + L_{\text{TD}} \sin(\theta_{\text{TC}} + \theta_{\text{TM}} + \theta_{\text{TD}}) \cos(\sigma_{\text{TC}} + \sigma_{\text{TM}}) \end{aligned}$$

$$Fy = L_{\text{Tmc}} \cos\theta_{\text{TC}} + L_{\text{Tm}} \cos(\theta_{\text{TC}} + \theta_{\text{TM}}) + L_{\text{TD}} \cos(\theta_{\text{TC}} + \theta_{\text{TM}} + \theta_{\text{TD}})$$

$$\begin{aligned} Fz &= L_{\text{Tmc}} \sin\theta_{\text{TC}} \sin \sigma_{\text{TC}} + \\ & L_{\text{Tm}} \sin(\theta_{\text{TC}} + \theta_{\text{TM}}) \sin(\sigma_{\text{TC}} + \sigma_{\text{TM}}) + L_{\text{TD}} \sin(\theta_{\text{TC}} + \theta_{\text{TM}} + \theta_{\text{TD}}) \sin(\sigma_{\text{TC}} + \sigma_{\text{TM}}) \end{aligned} \quad (2)$$

Inverse Kinematics

Inverse kinematics is employed to determine the orientation and angles of each linkage based on the positions. It is commonly known that solving inverse kinematics can be challenging, particularly when open kinematic chains may have multiple solutions. Utilizing the finger kinematic model from the previous section 3.1.2, the simplified inverse kinematics equations can be determined as in equation (3) and (4).

Index finger inverse kinematics:

$$\theta m = \arctan\left(\frac{Ax}{Ay - Lmc}\right)$$

$$\theta p = \arctan\left(\frac{Bx - Ax}{By - Ay}\right) - \arctan\left(\frac{Ax}{Ay - Lmc}\right)$$

$$\theta d = \arctan\left(\frac{Cx - Bx}{Cy - By}\right) - \arctan\left(\frac{Bx - Ax}{By - Ay}\right) \quad (3)$$

Thumb finger inverse kinematics:

$$\sigma_{\mathrm{TC}} = \arctan(\frac{Dz}{Dx})$$

$$\theta_{\mathrm{TC}} = \arctan(\frac{\sqrt{Dx^2 + Dz^2}}{Dy})$$

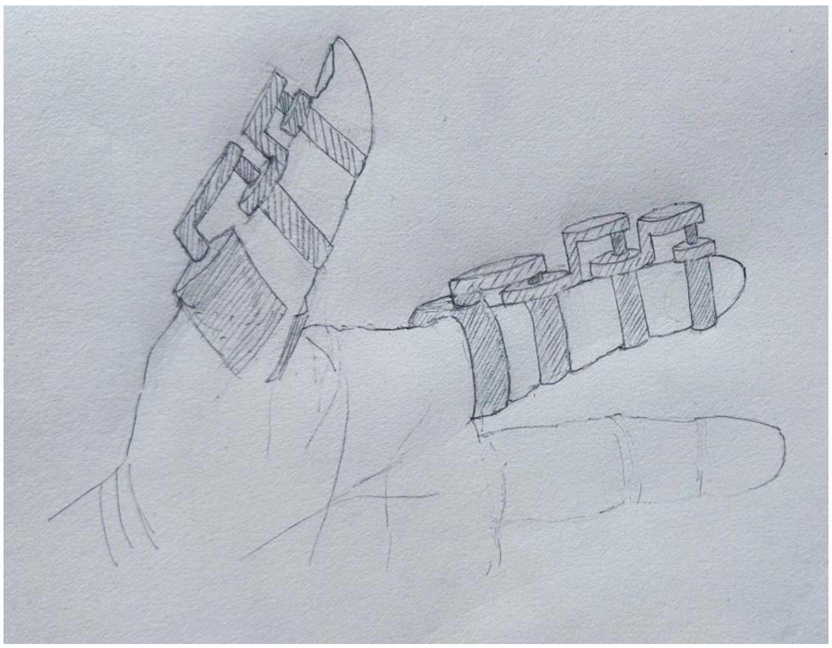
$$\sigma_{\mathrm{TM}} = \arctan\left(\frac{Ez - Dz}{Ex - Dx}\right) - \arctan(\frac{Dz}{Dx})$$

$$\theta_{\mathrm{Tm}} = \arctan(\frac{\sqrt{(Ex - Dx)^2 + (Ez - Dz)^2}}{Ey - Dy}) - \arctan(\frac{\sqrt{Dx^2 + Dz^2}}{Dy})$$

$$\theta_{\mathrm{Td}} = \arctan(\frac{\sqrt{(Fx - Ex)^2 + (Fz - Ez)^2}}{Fy - Ey}) - \arctan(\frac{\sqrt{(Ex - Dx)^2 + (Ez - Dz)^2}}{Ey - Dy}) \qquad (4)$$

8/15/2023

Before developing the finger exoskeleton structure using SolidWorks, a preliminary design sketch of two 3-bar/4-bar segmented compact linkages is drawn below. A fundamental design principle dictates that the bases of all linkages and the finger rings should be aligned straight.



The following materials have been prepared.

- 3-D printer. Not all 3-D printers can print flexible materials. Luckily I am able to borrow a K-1 Speedy printer which can print both PLA and TPU materials.
- A few rolls of PLA filaments came with the printer. No need to purchase. □
- TPU transparent filament was purchased from Amazon. $20.49

8/16/2023

In order for the exoskeleton to be accurate, the design needs to be based on a patient's specific finger and hand size. Measured my own hand as reference and the finger parameters. Also measure the movement range of my finger joints as human movement ranges.

Link/Phalanx	Palm-Finger	Joint	Length(mm)	Movement Range(degree)
LMC	Palm	CMC-MCP	71.7	N/A
Lp	Index	MCP-PIP	48.1	70
Lm	Index	PIP-DIP	25.7	90
Ld	Index	DIP-Tip	21.8	15
Ltmc	Palm	CMC-MCP	61.3	30
Ltm	Thumb	MCP-DIP	33.6	35
Ltd	Thumb	DIP-Tip	29.6	70

9/04/2023

This week, a few linkages and motor holders were designed and printed.

The linkages and motor holders play a pivotal role in the basic structure of the finger exoskeleton. The following are fundamental design principles for this group of parts:

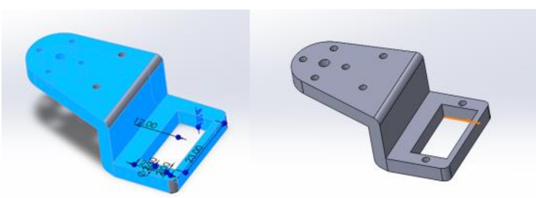
a) Establish serial linkages between joints for coordinated movements.

b) Ensure stable and secure mounting of all motors for structural integrity.

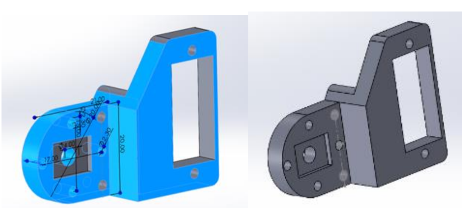
c) Incorporate a Z-shape design to enhance the overall streamlined structure, optimizing efficiency and performance.

These design principles ensure the effective functioning of the finger exoskeleton.

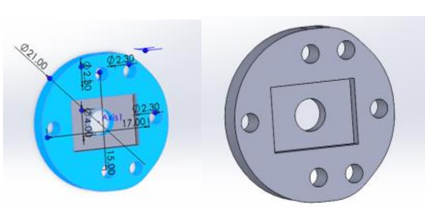
Linkage on Index finger between MCP and PIP



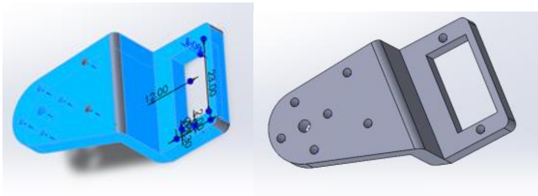
Linkage on Index finger between PIP and DIP



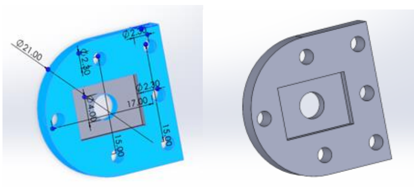
Linkage on Index finger between DIP and tip of the finger



Linkage on Thumb finger between MCP and DIP



Linkage on Thumb between DIP and tip of the finger



9/8/2023

A few finger rings were designed and printed.

Finger Rings are the loops to hold the finger. Here are basic design principles for this group of parts:

a) Provide rings to securely hold each phalanx.

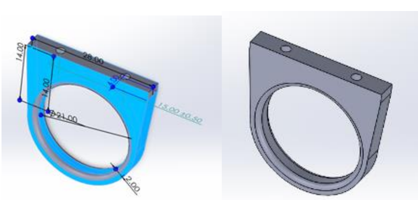
b) Ensure a balance between snugness and flexibility; neither too tight nor too loose for optimal user comfort.

c) Use soft and flexible materials to enhance comfort during prolonged usage.

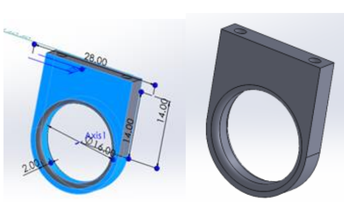
d) Opt for a half-circle shape (wide base) instead of a balloon shape to stabilize the rings on the linkages.

e) Ensure stable attachment of the rings to the linkages for reliable performance.

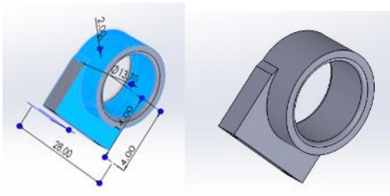
Ring on Index Finger Proximal Phalanx



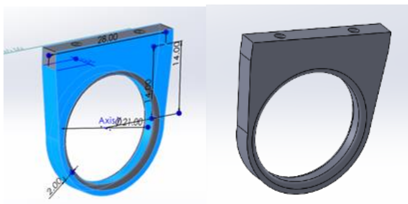
Ring on Index Finger Middle Phalanx



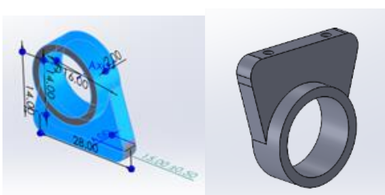
Ring on Index Finger Distal Phalanx



Ring on Thumb Finger First Proximal Phalanx



Ring on Thumb Finger Distal Phalanx



9/14/2023

A few other linkages parts on Metacarpals and Others were designed and printed.

Here are the basic design principles for this group of parts:

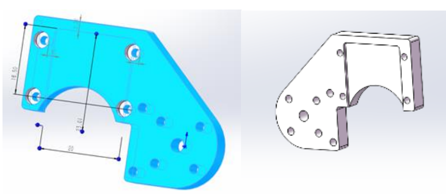
a) Provide linkages on metacarpals to connect to the MCP joints.

b) Securely hold the First Metacarpal (Thumb) and Second Metacarpal (Index).

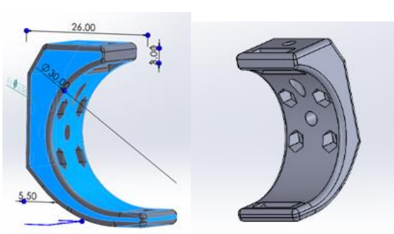
c) Ensure stable mounting of all motors to maintain structural integrity.

d) Incorporate features to tighten the belts, enhancing the overall stability of the structure on the palm.

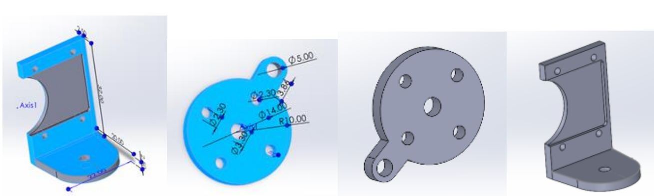
Linkage on the First and Second Metacarpal to connect MCPs



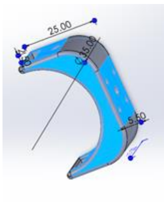
The holder with special shape on the Second Metacarpal

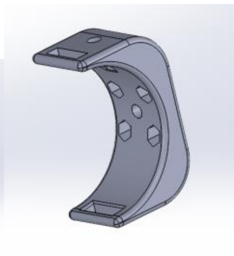


The motor holders hold the motor to push Thumb Abduction and Adduction.



The holder with special shape on the First Metacarpal of Thumb





_9/20/2023_

Modular Integration

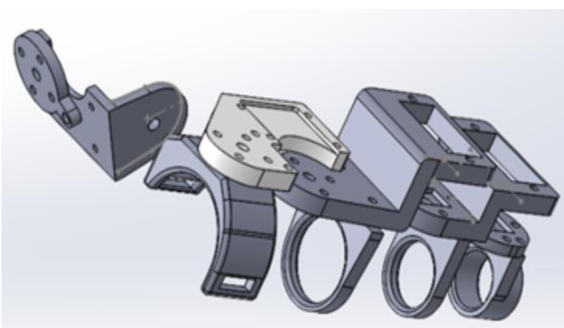
Here are the integration design principles:

a) Ensure that the bases of all linkages are aligned straight, and all finger rings are also aligned straight.

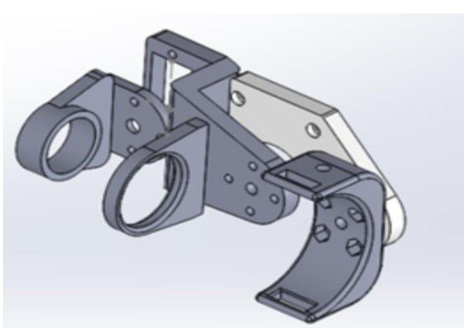
b) Ensure that the holders of the First Metacarpal and Second Metacarpal fit the shape of the palm.

c) Before placing motors, ensure that all linkages can rotate freely without touching other parts.

Index Finger Linkages Integration



Thumb Finger Linkages Integration



9/22/2023

Steering Linkage between Index Finger and Thumb

A Metal Steering Servo Link 70-90mm Adjustable Turnbuckles Camber Linkage is employed to connect the Index Finger integration structure with the Thumb integration structure.

Metal Steering Servo Link. Purchased from Amazon $10.89.

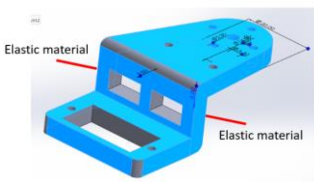
M2 and M3 screw assortment packages were also purchased from Amazon for $9.99 each.

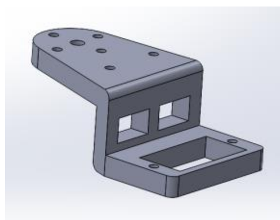
9/30/2023

Elastic Design of Force Relieving Connector and Rings

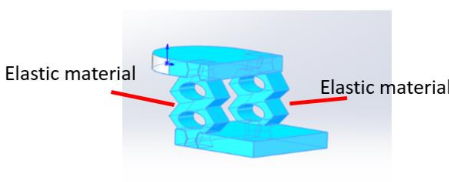
One critical design principle of the finger exoskeleton is to avoid excessive force and pressure on the patient, which can potentially cause accidental pain or injury. Special Elastic Force Relieving Connectors and Rings are designed for this purpose.

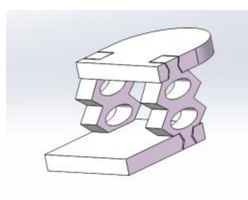
Special Force Relieve Connector Z-part made by flexible material



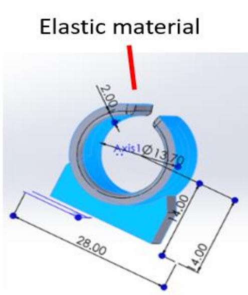


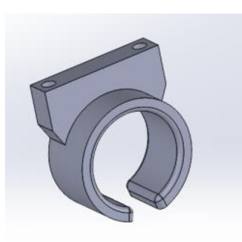
Another Design of Special Force Relieve Connector Z-part made with flexible material





Special Rings with open notch structure, made with flexible material





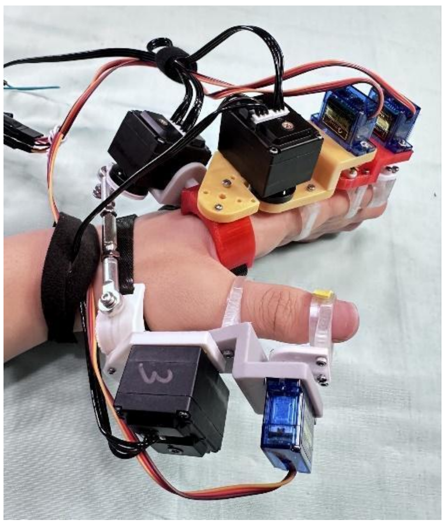
10/15/2023

Integration with motors

Six servo motors are installed and integrated with the exoskeleton structure.

- 3x HX-06L Bus Servo motors
  Spec: HX-06, 240º, 6kg/cm@7V, 0.18s/60º
  These motors have high power to drive metacarpals.
  Purchased from Amazon $15.99 each.

- 3x SG90 Micro Servo motors
  Spec: SG90, 180º, 17.5oz/in@4.8V, 0.09s/60º
  These motors have low power to drive finger upper sections.
  Purchased from Amazon $7.99 for 4.



10/17/2023

Measured the size and other parameters of the finger exoskeleton

Total weight(including 6 motors)	289g
Total Index Finger Dimension	122.3mm x 77.6mm x 73.4mm
Total Thumb Dimension	85.2mm x 47.2mm x 72.1mm
Length of Index connecting linkages	37.8mm, 31.9mm,22.9mm
Length of Thumb connecting linkages	41.8mm, 31.6mm
Free Rotating Flexion angles(without motors) on Index Finger	110º(MCP-PIP),95º(PIP-DIP),180º(DIP-tip)
Free Rotating Flexion angles(without motors) on Thumb	110º(MCP-DIP),120º(DIP-tip)
Free Rotating A/A angles(without motors)	360º
Materials	PLA, TPU, steel, rubber
Manufacturing	3D printing

The weight is only 289g. Light weight and compact size!

10/21/23

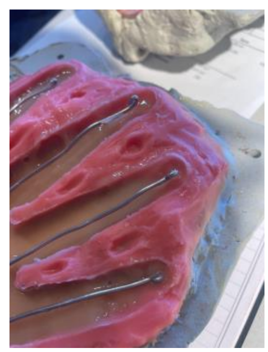
Flexible Silicone Hand with silicone and wire

A prosthetic flexible silicon hand is made to perform the testing. The materials include Ecoflex 00-30 silicone and wires.







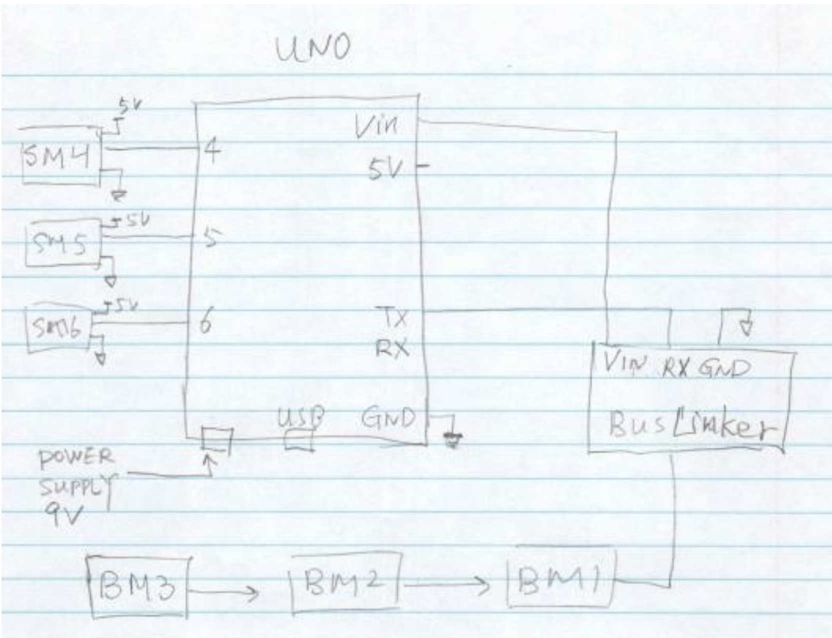





10/25/2023

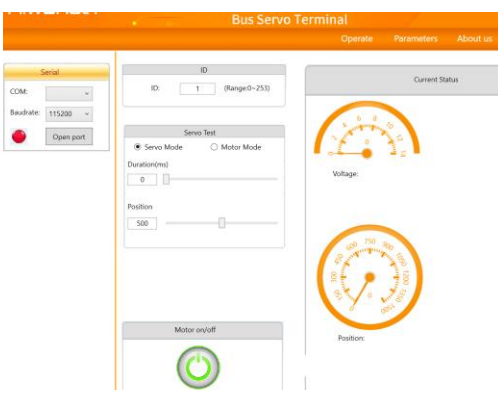
Connect Exoskeleton to MCU board. Use my existing Arduino UNO board (no need to purchase) and Arduino IDE as software platform.

Here is the circuit diagram.



BM1, BM2, BM3 are HX06L Bus Motors. SM4, SM5 and SM6 are SG90 Micro motors.

Use Bus Servo Terminal to setup Bus motor ID.



Develop Arduino code to drive each motor.

```
#include <Servo.h>

#define GET_LOW_BYTE(A) (uint8_t)((A))
#define GET_HIGH_BYTE(A) (uint8_t)((A) >> 8)
#define BYTE_TO_HW(A, B) ((((uint16_t)(A)) << 8) | (uint8_t)(B))

//
#define LOBOT_SERVO_FRAME_HEADER         0x55
#define LOBOT_SERVO_MOVE_TIME_WRITE      1

#define ID1   1
#define ID2   2
#define ID3   3
Servo servo4;
Servo servo5;
Servo servo6;

void setup() {
  // put your setup code here, to run once:
  Serial.begin(115200);
  delay(1000);

  servo4.attach(4);
  servo5.attach(5);
  servo6.attach(6);

  Serial.println("Initial positions: ");
    motorsRotations(0,0,0,0,0,0); //initial positions

void motorsRotations(int pos1, int pos2,int pos3,int pos4,int pos5,int pos6){

  LobotSerialServoMove(Serial, ID1, ini1+pos1, 500);
  delay(20);
  LobotSerialServoMove(Serial, ID2,ini2+pos2, 500);//default 500
  delay(20);
  servo5.write(ini5+pos5); // default 0
   delay(20);
  servo4.write(ini4+pos4); // default 90
  delay(20);
  LobotSerialServoMove(Serial, ID3, ini3+pos3, 500);//default 500
  delay(20);
  servo6.write(ini6+pos6); // default 90
  delay(200);
}
```

Arduino code is able to control each motor to rotate!!!

10/29/2023

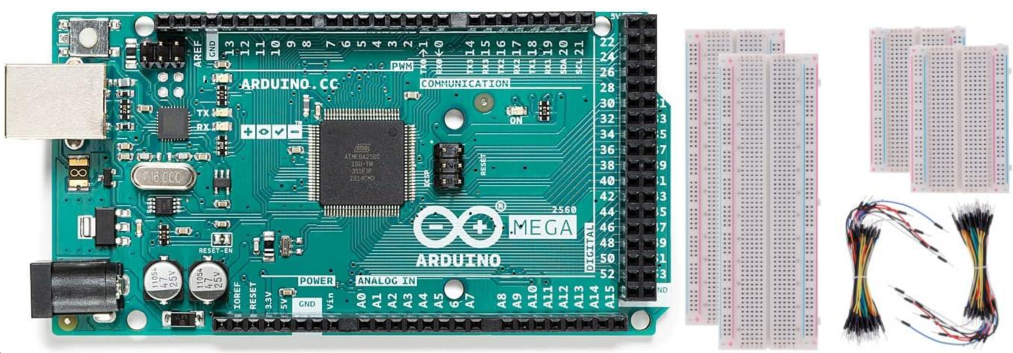
Started User Interface Design

Consider the following User Interface.

- Mechanical Switch
- AI Voice Recognition Control
- Computer Vision Control with Machine Learning
- Phone GUI App
- Embedded Sensors

When these user interfaces are added. UNO board won't have enough ports. Arduino MEGA 2560 is needed. Purchased from Ebay $17.99.

Changed board from UNO to MEGA 2560. All motor connections have no port number change. A breadboard is used. Purchased breadboard and jump wires from Amazon $11.99



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11/05/2023

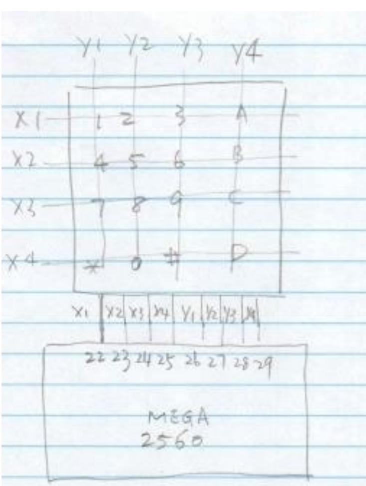
Mechanical Switch

A Mechanical Switch is employed by patients to input command numbers for running pre-programmed protocols. This method is particularly beneficial when the patient possesses a functional hand for self-treatment or when assisted by a therapist.

In this project, a 4-row by 4-column keypad serves as the mechanical switch, allowing the patient to enter commands and communicate effectively with the system.

Purchased from Amazon $8.99.

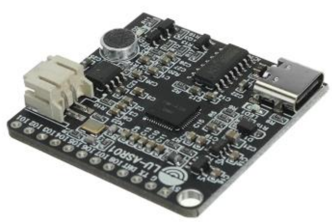
Here is the circuit diagram to connect the mechanical switch to MEGA2560 and code.




```
#include <Keypad.h>

const int ROW_NUM = 4; //four rows
const int COLUMN_NUM = 4; //three columns

char keys[ROW_NUM][COLUMN_NUM] = {
  {'1','2','3', 'A'},
  {'4','5','6', 'B'},
  {'7','8','9', 'C'},
  {'*','0','#', 'D'}
};

byte pin_rows[ROW_NUM] = {26, 27, 28, 29}; //connect to the row pinouts of the keypad
byte pin_column[COLUMN_NUM] = {22, 23, 24, 25}; //connect to the column pinouts of the keypad

Keypad keypad = Keypad( makeKeymap(keys), pin_rows, pin_column, ROW_NUM, COLUMN_NUM );

void setup(){
  Serial.begin(115200);
}

void loop(){
  char key = keypad.getKey();

  if (key){
    Serial.println(key);
```

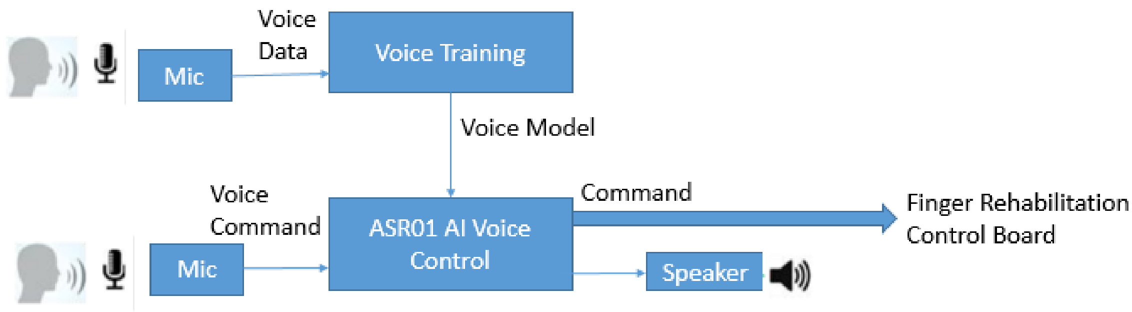
11/07/2023

AI Voice Recognition Control is implemented for patients with impaired hands who utilize voice commands to interact with the system during treatment. Pre-programmed treatment protocols and communication processes are established based on voice commands. The AI Voice Control system collects and trains the patient's voices to detect and recognize valid commands, enhancing the overall user experience.



- MCU – TW-ASR ONE (aka TWen ASR ONE) microcontroller with 4MB flash, 512KB RAM, and a BNPU for voice processing; package: QFN48L (6x6x0.85mm)
- Audio I/O
  - Built-in microphone
  - 2-pin speaker header plus 3W power amplifier for 4Ω/3W speaker
- Voice recognition
  - Up to 10 meters wake-up range
  - 98% ultra-high recognition rate
  - Customizable to 5 wake-up words and 200 recognition words
- USB – 1x USB Type-C port for power and programming via CH340C USB to TTL chip
- Expansion – 12x through holes with 8x GPIOs, of which 6 can be used as PWM, one serial Tx, one DHT11/DS18B20 temperature sensor interface
- Dimensions – About 3.7 x 3.7 cm
- Weight – 35g

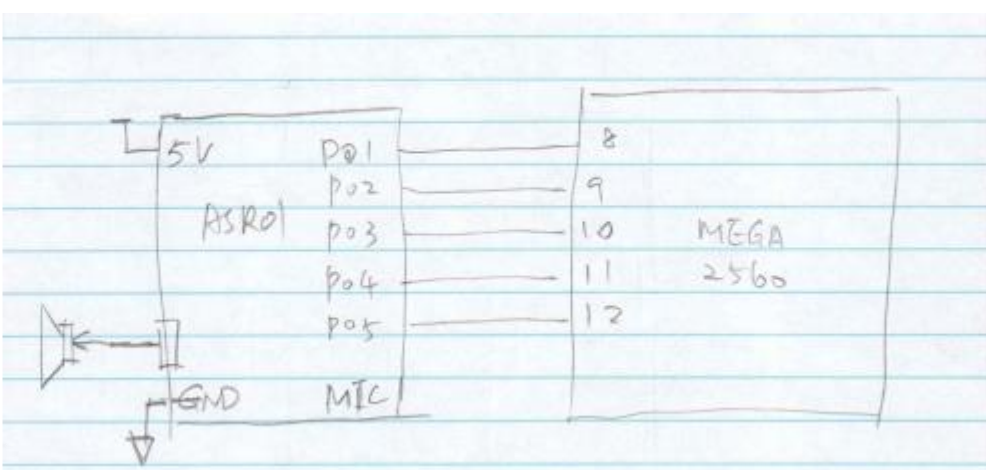
Here is AI Voice Recognition Control Flow



The ASR01 AI Voice Control Board is chosen as the AI Voice control solution. The control flow for voice recognition is designed using Blocky software. The voice training data and the voice recognition control flow are compiled into the Voice Model on the ASR01 control board. A patient issues a vocal command to the Voice AI. The Voice AI responds vocally and conveys the same command to the Finger Rehabilitation control board, directing the finger exoskeleton motors for the commanded movement.

Purchased ASR01 module from Amazon $17.23.

Here is the circuit diagram to connect ASR01 to MEGA2560



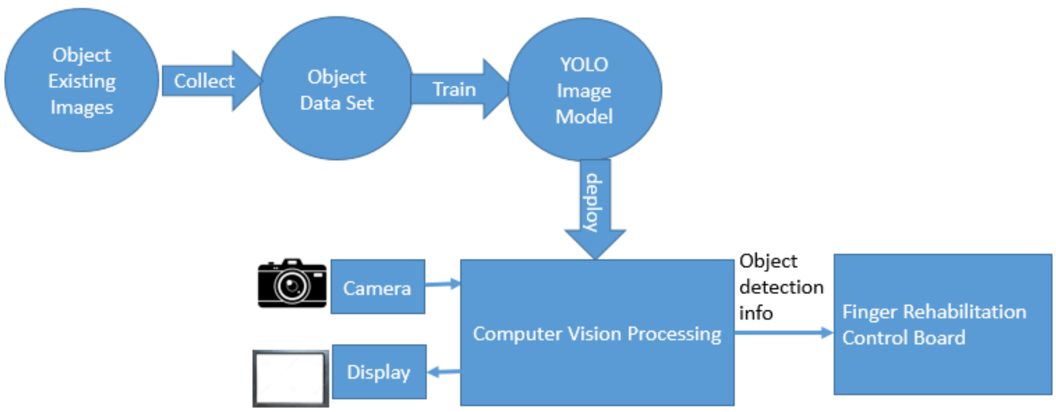
```
int DigPin8= 8;
int DigPin9= 9;
int DigPin10= 10;
int DigPin11= 11;
int DigPin12= 12;
```

```
pinMode(DigPin8, INPUT);
pinMode(DigPin9, INPUT);
pinMode(DigPin10, INPUT);
pinMode(DigPin11, INPUT);
pinMode(DigPin12, INPUT);
```

11/17/23

Computer Vision Control with Machine Learning is implemented for object detection and preliminary autonomous grasping. When a command is given to grasp an object, the finger exoskeleton requires precise timing to drive the actuator for the grasp operation. This operation is executed only when the object is detected and properly positioned.

Computer Vision Control with Machine Learning Flow

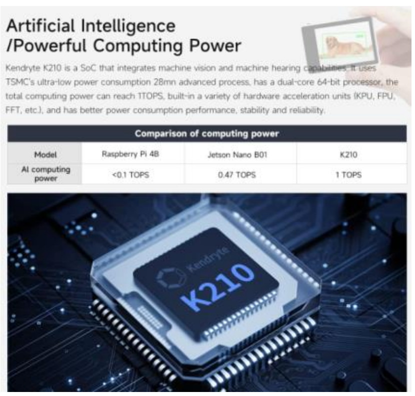


The YOLO (You Only Look Once) Machine Learning Algorithm is employed in the Computer Vision method. YOLO, known as a one-stage CNN algorithm, excels in fast and unified real-time object detection, making it an ideal choice for the finger rehabilitation detection task that demands rapid categorization and location determination.

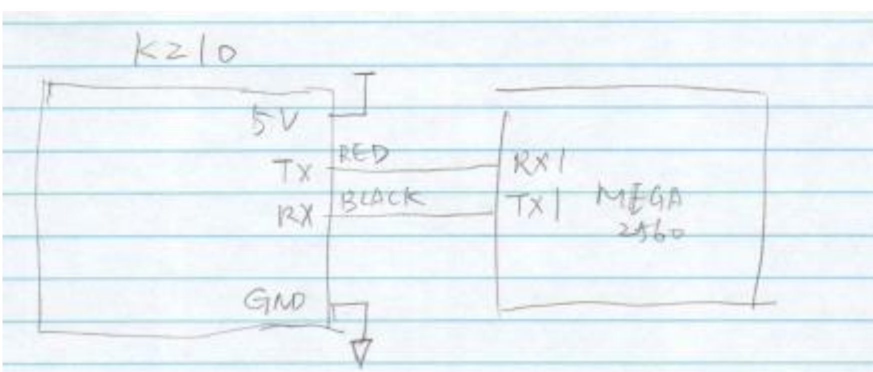
The K210 Control Board is equipped with an integrated camera and display screen, executing the computer vision task with machine learning. Utilizing the Canaan Developer Platform, existing images are curated into object datasets, which are subsequently trained using the YOLO one-stage CNN algorithm to create the YOLO image model. Once deployed on the K210 control board, this model efficiently detects objects from images captured by the camera, with the detection block prominently displayed on the screen.

Another pivotal strategy involves determining the optimal timing for executing the grasp operation. A specialized method, reliant on the size of the object captured by Computer Vision and the distance, has been devised to identify the correct moment. Upon object detection, the coordinate positions of the detection block are transmitted to the Finger Rehabilitation Control Central Board. The central board assesses the distance between the finger exoskeleton and the object, utilizing the size of the detected object. If the distance suggests that the finger exoskeleton is in close proximity to the object, the grasping operation is promptly executed.

Purchased K210 kit including the camera and display screen from Amazon $48.99.



Circuit diagram K210 to MEGA2560.



related code:

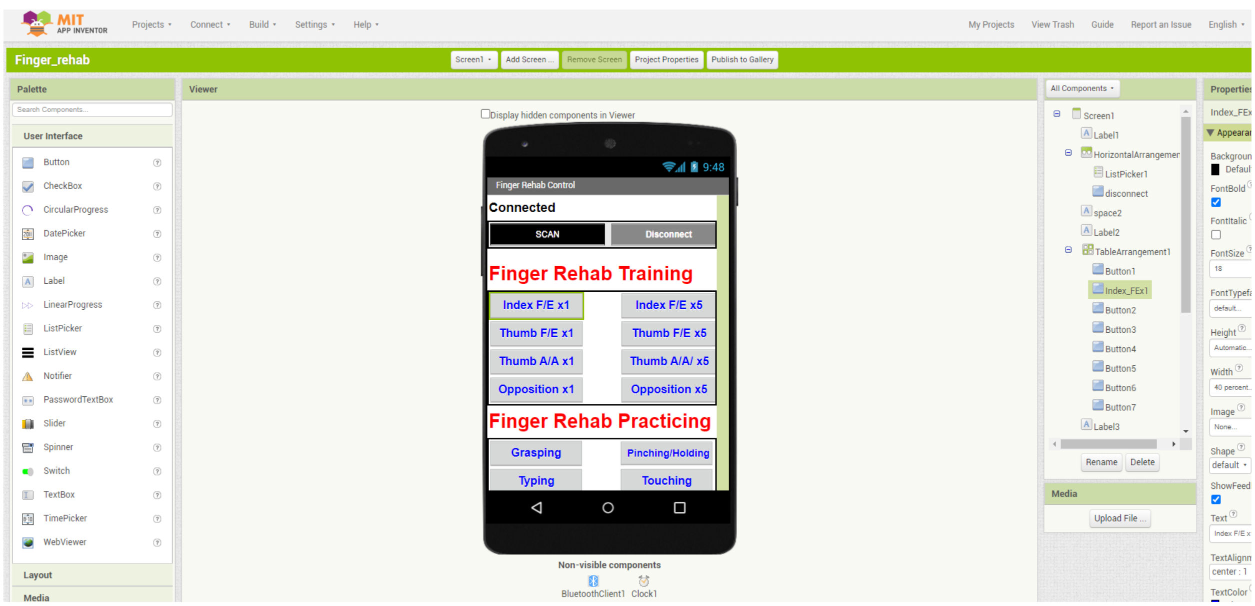
```
import sensor, image, time, lcd, gc, cmath
from maix import KPU
from fpioa_manager import fm
fm.register(8,fm.fpioa.UART1_TX, force=True)
fm.register(6,fm.fpioa.UART1_RX, force=True)
from machine import UART
uart_A = UART(UART.UART1,115200, 8,1,0,timeout=1000,read_buf_len=4096)
```

```
if len(dect) > 0:
        for l in dect :
                uart_A.write(str(l[0])+","+str(l[1])+","+str(l[2])+","+str(l[3])+"/"+"\n")
                a = img.draw_rectangle(l[0],l[1],l[2],l[3],color=(0,255,0))
                info = "%s %.3f" % (labels[l[4]], l[5])
                a = img.draw_string(l[0],l[1],info,color=(255,0,0),scale=2.0)
                print(info)
                del info
```

11/25/23

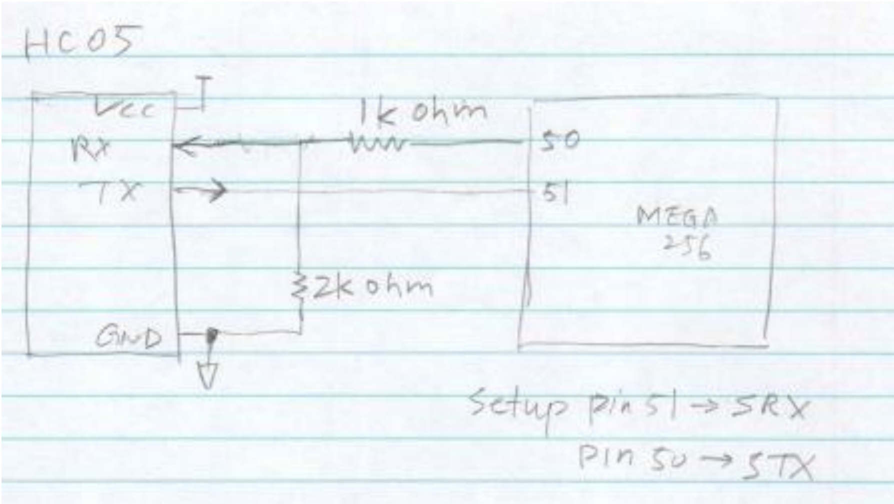
A user-friendly GUI App is developed for patients to easily manage training and practice sessions via their phones or tablets. The system's acquired data are transferred to the GUI for monitoring or further processing. Wireless transmission between the control board and the phone/tablet is facilitated through Bluetooth technology.

The MIT App Inventor serves as the development platform for this app. When the patient activates the control button on the app, it sends commands to the Rehabilitation System through Bluetooth. Additionally, data from the Rehabilitation System are transmitted to the app via Bluetooth.



==Bluetooth HC05 is purchased from Amazon $15.99 for two.==

Bluetooth HC05 connection to MEGA2560



Related code:

```
#include <SoftwareSerial.h>

#define ledPin 52
SoftwareSerial BTserial(51, 50); // SRX | STX
// Connect the HC-05 TX to Arduino pin 51(as SRX).
// Connect the HC-05 RX to Arduino pin 50 (as STX) through a voltage divider.

void setup()
{
 Serial.begin(9600);
 BTserial.begin(9600);
 pinMode(ledPin, OUTPUT);
 digitalWrite(ledPin, LOW);

}

void loop()
{
 if (BTserial.available())
 {
   byte x = BTserial.read();
   Serial.write(x);
   Serial.print(" ");
   digitalWrite(ledPin, HIGH);
 }
```

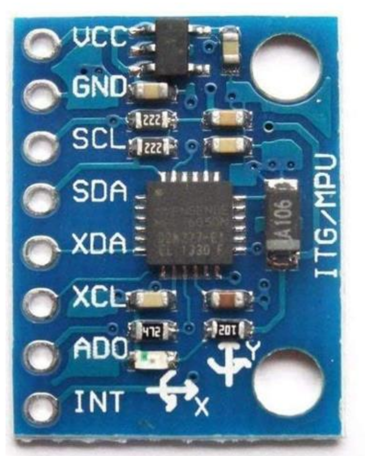
11/29/23

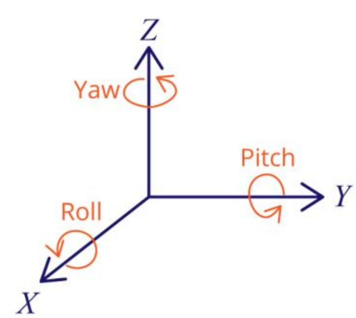
Embedded Sensors

Two embedded sensor types are incorporated: FSR force sensors and IMU sensors. FSR force sensors are strategically positioned on the fingertips and phalanxes, offering pressure force data to the central control board. Meanwhile, IMU (Inertial Measurement Unit) sensors are placed on the finger in close proximity to the target object, measuring its acceleration. The collected data is then relayed to the control board for further processing.

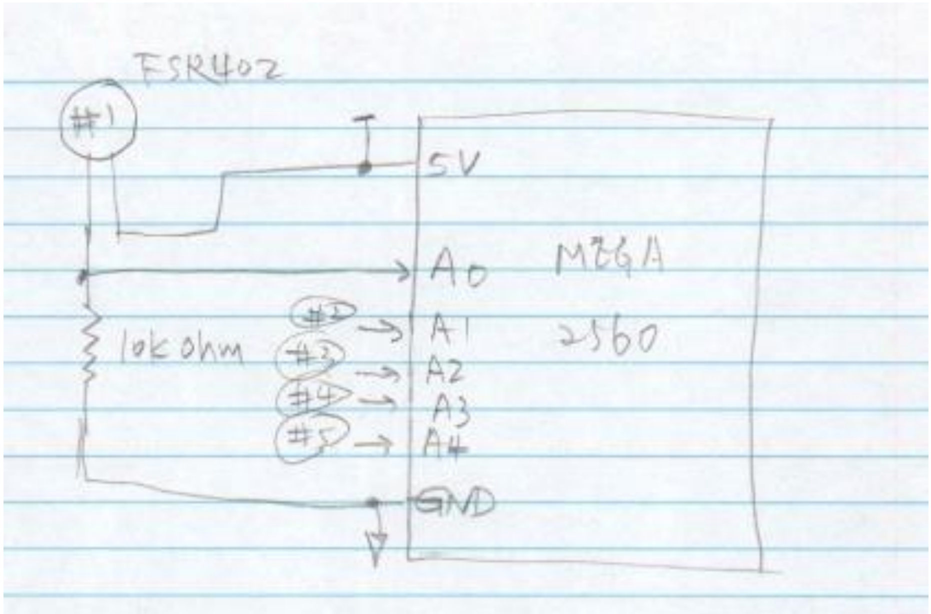
Purchased FSR402 sensor $14.99 each from Amazon.

Purchased IMU sensor MPU 6050 $9.99 from Amazon.





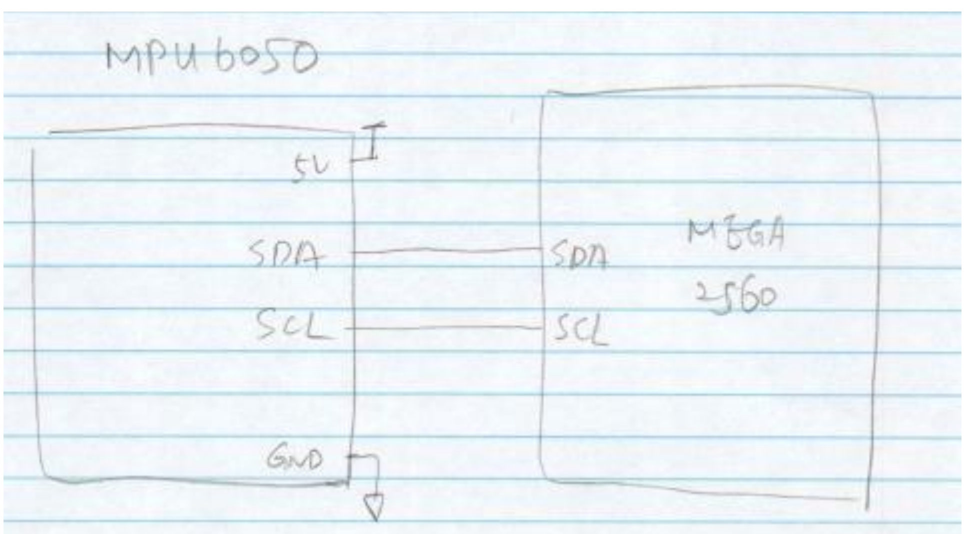
Circuit diagram FSR402 to MEGA2560




```
#define aValue1 0
#define aValue2 1023
#define forceValue1 0
#define forceValue2 20
```

```
sensor1Value = analogRead(fsr1AnalogPin);
force1Value = map(sensor1Value, aValue1, aValue2, forceValue1, forceValue2);

 Serial.print("FSR1 force (Newtons) = ");
 Serial.println(force1Value);
```

Circuit diagram MPU6050 to MEGA2560



related code

```
#include <Adafruit_MPU6050.h>
#include <Adafruit_Sensor.h>
#include <Wire.h>

Adafruit_MPU6050 mpu;
```

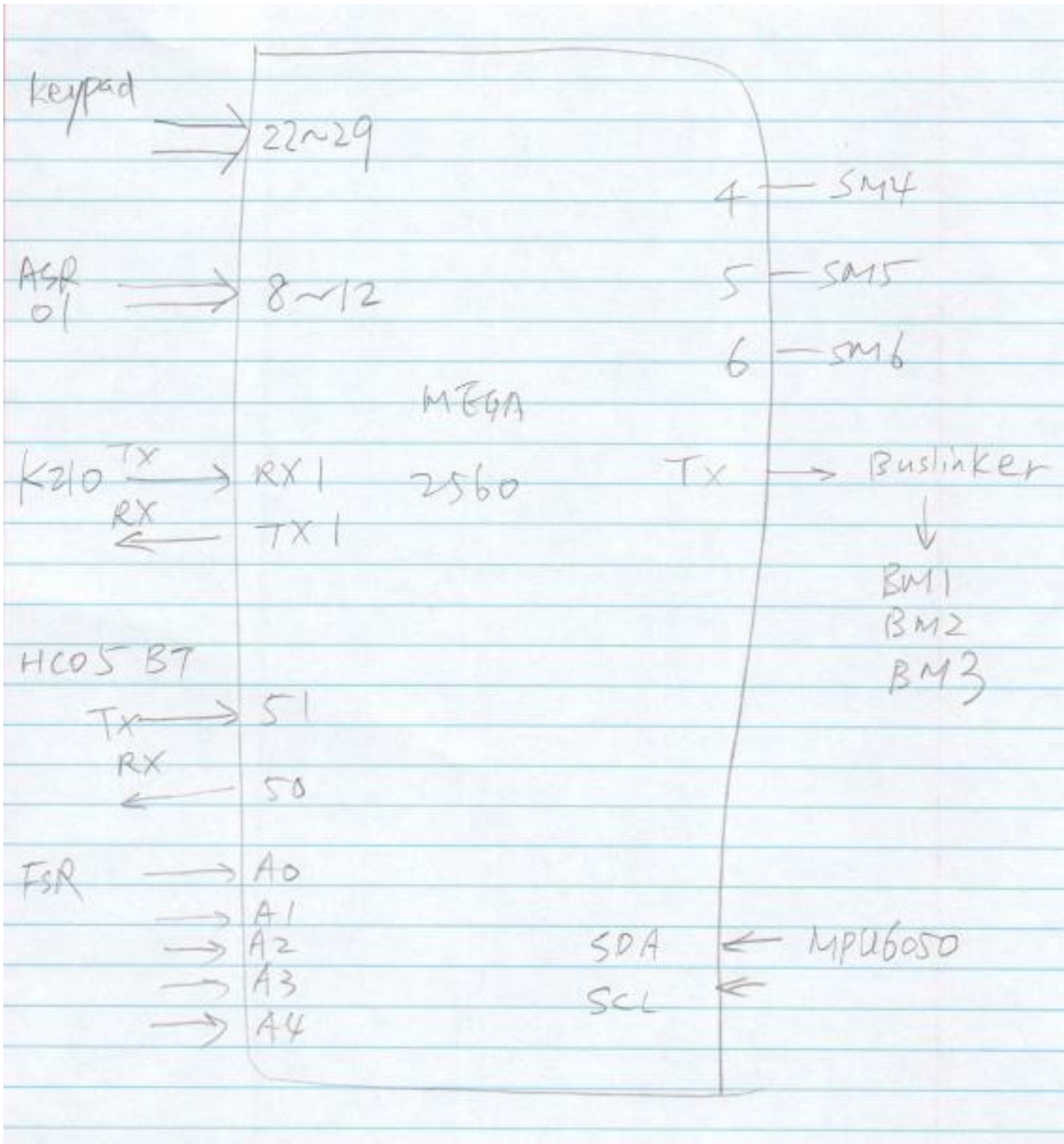
```
mpu.setAccelerometerRange(MPU6050_RANGE_8_G);
Serial.print("Accelerometer range set to: ");
switch (mpu.getAccelerometerRange()) {
case MPU6050_RANGE_2_G:
  Serial.println("+-2G");
  break;
case MPU6050_RANGE_4_G:
  Serial.println("+-4G");
  break;
case MPU6050_RANGE_8_G:
  Serial.println("+-8G");
  break;
case MPU6050_RANGE_16_G:
  Serial.println("+-16G");
  break;
}
```

```
mpu.setGyroRange(MPU6050_RANGE_500_DEG);
Serial.print("Gyro range set to: ");
switch (mpu.getGyroRange()) {
case MPU6050_RANGE_250_DEG:
  Serial.println("+- 250 deg/s");
  break;
case MPU6050_RANGE_500_DEG:
  Serial.println("+- 500 deg/s");
  break;
case MPU6050_RANGE_1000_DEG:
  Serial.println("+- 1000 deg/s");
  break;
case MPU6050_RANGE_2000_DEG:
  Serial.println("+- 2000 deg/s");
  break;
}
```

```
/* Print out the values */
Serial.print("Acceleration X: ");
Serial.print(a.acceleration.x);
Serial.print(", Y: ");
Serial.print(a.acceleration.y);
Serial.print(", Z: ");
Serial.print(a.acceleration.z);
Serial.println(" m/s^2");

Serial.print("Rotation X: ");
Serial.print(g.gyro.x);
Serial.print(", Y: ");
Serial.print(g.gyro.y);
Serial.print(", Z: ");
Serial.print(g.gyro.z);
Serial.println(" rad/s");
```

12/06/2023

So far, most system parts have been developed. The overall system connection diagram is shown below.

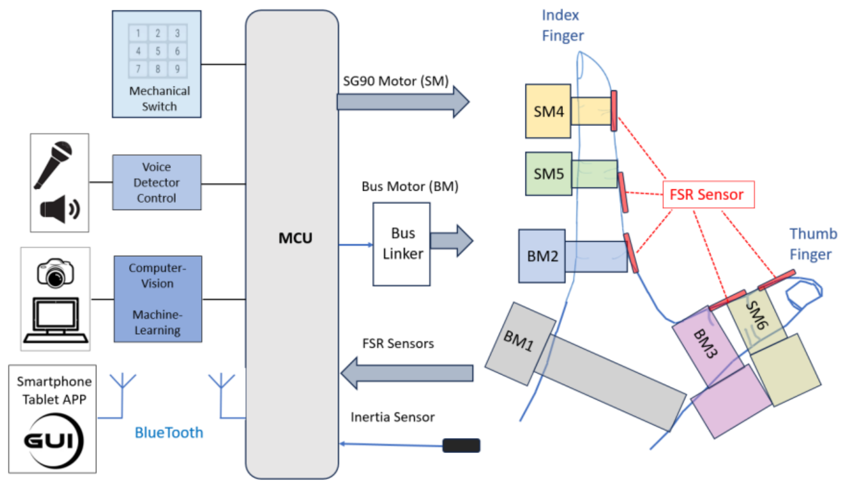


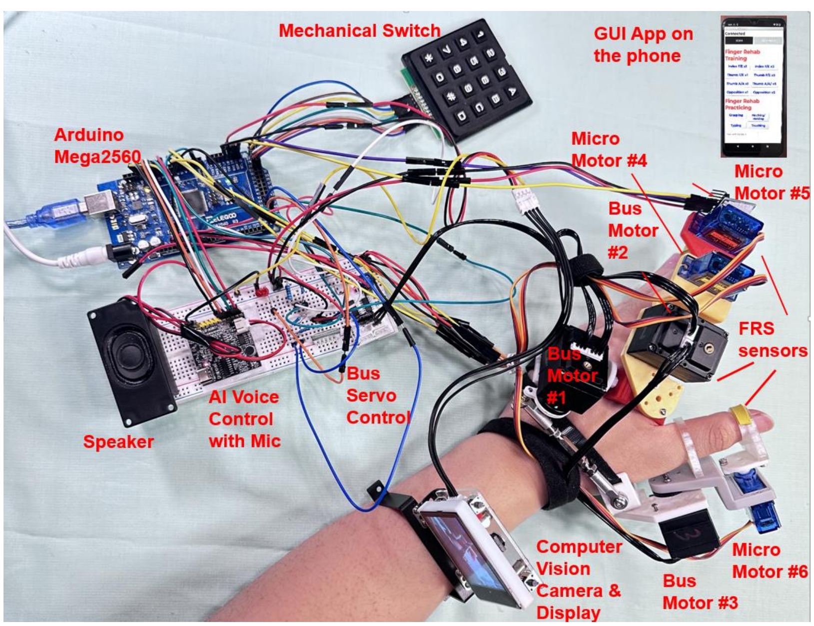
Design elements:

- Finger Exoskeleton Structure

- BM1,BM2,BM3: HX-06L Bus Servo motors and Bus linker
- SM4, SM5, SM6: SG90 Micro Servo motors
- MPU6050 Inertia sensor
- FSR force sensors
- Arduino Mega2560 and IDE
- HC05 Bluetooth
- ASR01 Voice Control Board, Mic and Speaker
- Camera Computer Vision with Machine Learning- K210 Board
- Smartphone GUI App
- Mechanical Switch- 4 R x 4C mechanical keys

Overall system diagram





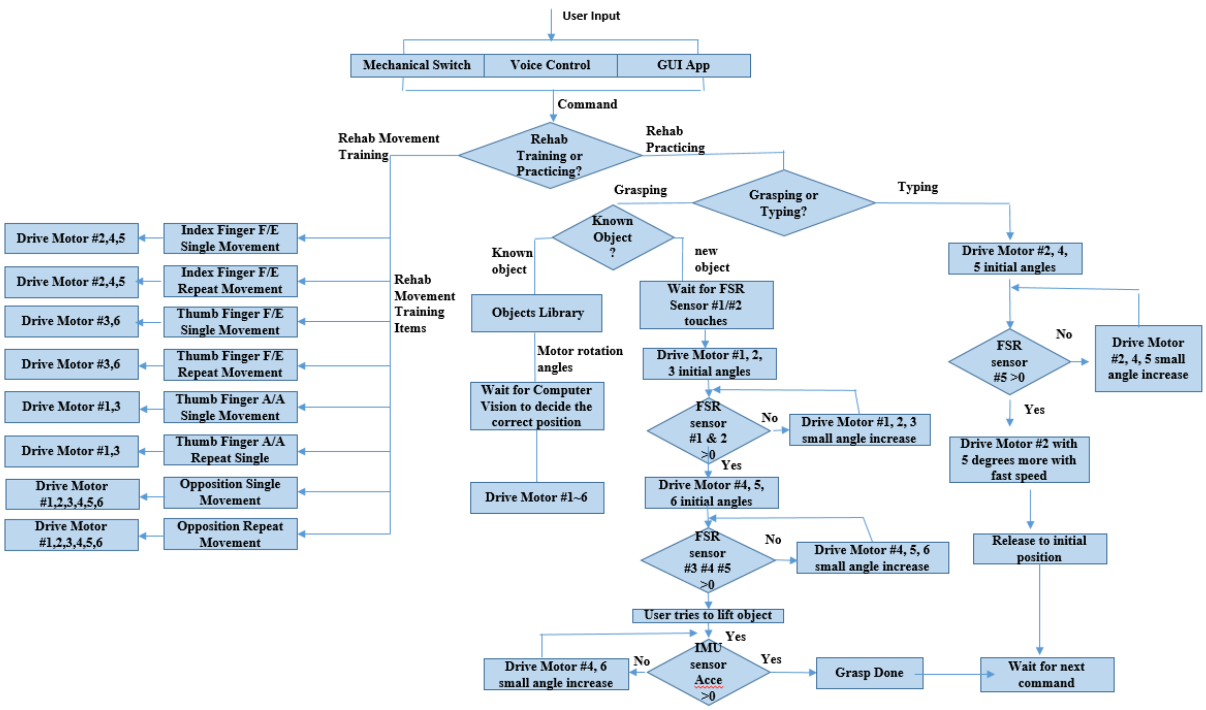
Main Components	Models/Specifications
Bus Servo Motor	HX-06, 240º, 6kg/cm@7V, 0.18s/60º
Micro Servo Motor	SG90, 180º, 17.5oz/in@4.8V, 0.09s/60º
FSR sensors	FSR402, 0.2~20N
IMU sensor	MPU 6050, Gyroscopes:± 250~2000º/sec, Acceleration: ±2~16g
Voice Control Board	ASR01 AI voice control
Mechanical Switch	4 Row x 4 column mechanical keys
Computer Vision	K210/OV7740 AI camera
Bluetooth	HC05
Arduino	Mega2560

Main Development Tools	Purpose
SolidWorks	Software for design and collaboration of finger exoskeleton parts
Arduino IDE	Software for design and testing all functions and controls on Arduino board
Blocky	Software for design AI voice control
MIT App Inventor	Software for development of GUI App
K-1 Speedy	3-D Printer

12/09/2023

Control Process Design

The Control Process is developed. It is the central flow from the user input/commands to motor/finger movements.



12/15/2023

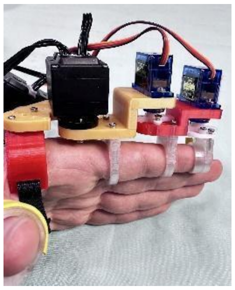
Rehabilitation Training and DOF/ROM Experiments

Index Finger Flexion/Extension Movement Training

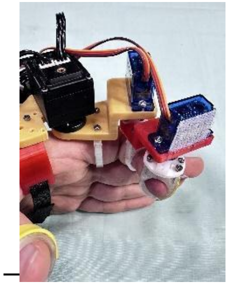
Standard tests:

1. Move Index F/E single
2. Move Index finger F/E repeat

Index Finger's initial position photo



Index Finger's F/E position after movement photo



Test Results:

Index finger is able to perform Flexion/Extension (F/E) successfully.

Thumb Finger Flexion/Extension Movement

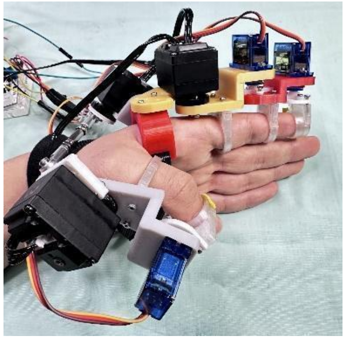
Standard tests:

1. Move Thumb F/E single

2. Move Thumb F/E repeat

Thumb's initial position photo

Thumb's F/E position after movement photo



Test Results:

Thumb finger is able to perform Flexion/Extension (F/E) successfully.

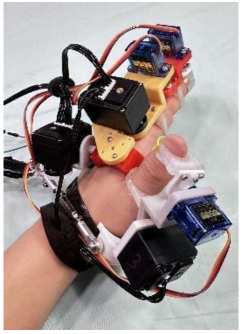
Thumb Abduction/Adduction Movement Training

Standard tests:

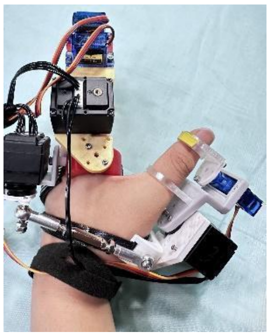
1. Move Thumb A/A single

2. Move Thumb A/A repeat

Thumb’s initial position photo



Thumb’s A/A position after movement photo



Test Results:

Thumb finger is able to perform Abduction/Adduction(A/A) successfully.

Opposition Movement Training

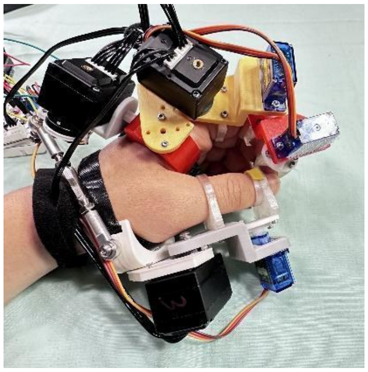
Standard tests:

1. Index Finger tip touch Thumb tip single
2. Index Finger tip touch Thumb tip repeat

Test Results:

Thumb finger and Thumb are able to perform Opposition successfully.

Opposition Movement photo



12/18/2023

DOF (Degree of Freedom) and ROM (Range of Movement) Tests

Standard Tests:

1. DOF/ROM tests. All 7 DOFs are tested with ROM recorded.
2. Actuator response time tests.

DOF (Degree of Freedom), Range of Motion (ROM) and Actuator Response Time Test Results

DOF(Degree of Freedom)	ROM(Range of Motion)	ROM Results	Reference Human ROM	Average Actuator Completion Time
#1 Index Finger MCP Extension/Flexion(F/E)	Index Finger MCP-PIP	Max 73º	70º	1.4s
#2 Index Finger PIP Extension/Flexion(F/E)	Index Finger PIP-DIP	Max 95º	90º	1.1s
#3 Index Finger DIP Extension/Flexion(F/E)	Index Finger DIP-Tip	Max 20º	15º	0.9s
#4 Thumb MCP Extension/Flexion(F/E)	Thumb MCP-DIP	Max 42º	35º	1.4s
#5 Thumb DIP Extension/Flexion(F/E)	Thumb DIP-Tip	Max 70º	70º	1.1s
#6 Thumb Abduction/Adduction(A/A)	Thumb CMC-MCP	Max 31º	30º	1.8s
#7 Opposition	Index Finger-Thumb	Touch firmly	Touch	1.9s

Test Results: From the test result, for each DOF test, ROM maximum rotating angle is larger than human reference ROM angle. That indicates this exoskeleton is able to perform the wide range of ROM and meet the design objective.

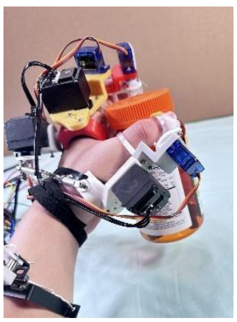
12/21/2023

Finger Practicing Functional Testing Experiment

Grasping test

Test: Grasp water bottle and cup. Hold and lift the bottle/cup.

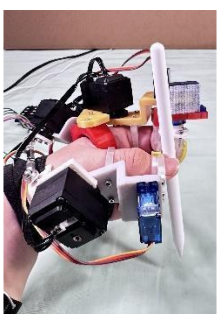
Test Results: The exoskeleton successfully grasps the water bottle and lifts it up.



Pinching and Pen-Holding

Test result: Pinch and hold a pen.

Pinch and hold a pen

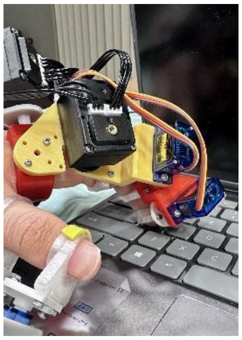


Test Result: The exoskeleton successfully pinches and holds a pen.

Typing

Test result: Typing on a keyboard.

Typing on keyboard



Test Result: The exoskeleton adeptly executes the typing task, accurately engaging the intended keys on the keyboard.

Touching Touchscreen

Test: Touch the phone's touchscreen

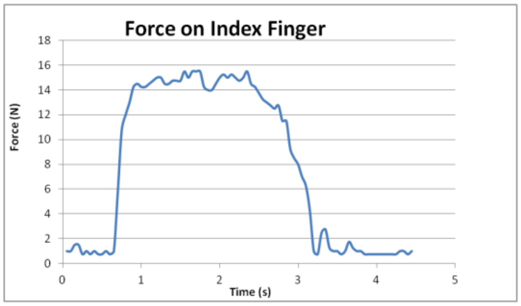
Test Result: The exoskeleton successfully touches the phone's screen and clicks the button on the screen.

12/28/23

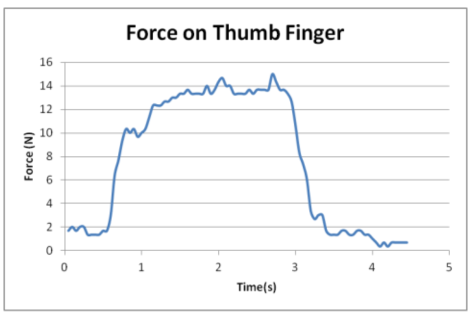
Grasping Force Experiments

The Grasping Force Experiments perform a grasping test and record the force sensor data vs Time on Thumb and Index Finger.

Index finger Force vs Time



Thumb finger Force vs Time



weight of the object ~150g

Test Result: The forces exerted on both the index finger and thumb surpass 10N when handling a 150g object, which aligns with the intended design objective.

Reference paper: V. Nazari, M. Pouladian, Y. Zheng and M. Alam(2021), A Compact and Lightweight Rehabilitative Exoskeleton to Restore Grasping Functions for People with Hand Paralysis, *Sensors (Basel). 2021 Oct 18;21(20):6900.*

1/3/2024

Started Elastic Part Force Relieving Tests

Extra force is exerted on the elastic parts to gauge the extent of twist or stretch at the edges of these components.

Non-elastic part was broken when extra force was applied on the edge.

Below are tests on elastic parts.

Z-part normal

Z-part is twisted by a force to the left

Z-part is twisted by a force to the right

Elastic Ring at normal position

Elastic Ring is stretched

Test Results: The Elastic Z-part exhibited torsion of over 10º on both sides without breakage, confirming its elastic capabilities. Similarly, the Elastic Ring demonstrated stretch ability without fracture. These tests validate the elastic components' ability to alleviate additional force, affirming that the hybrid material system aligns with the intended design objectives and expectations.

<u>1/6/2024</u>

User Interface Tests

Expected Action for Mechanical Switch, AI Voice Control and GUI App Control	Command Number
Index Finger F/E Single	1
Index Finger F/E Repeat	2
Thumb F/E Single	3
Thumb F/E Repeat	4
Thumb A/A Single	5
Thumb A/A Repeat	6
Opposition Single	7
Opposition Repeat	8
Grasping	9
Typing	A
Pinching	B
Touching	C

Mechanical Switch control tests

Test Description: The user enters a command number on the mechanical keypad and verifies if the system executed the expected action as intended.

Test Results: The system responds to the command number entered and all actions are accomplished as expected for each commend number #1~C.

Voice Detection Control

Test Description: Voice commands are trained and programmed into the AI Voice control board. The user vocalizes the command, assessing whether the system executes the expected action

Test Results: The system responds to the voice command and all actions are accomplished as expected for each command.

Computer Vision Control with Machine Learning

Utilizing Computer Vision with Machine Learning, this test involves a YOLO model trained with 32 images of cups loaded into the K210 control board. The board, equipped with a camera/display, is fixed on the wrist near the finger exoskeleton. A cup is placed on the table, and the finger exoskeleton is slowly moved towards it. The steps include checking if Computer Vision detects the cup and displays a detection block (Step 1), assessing the distance range of the detection (Step 2), verifying if the coordinates of the detection block are transmitted to the Arduino control board (Step 3), and ensuring that, when the finger exoskeleton nearly touches the cup, the calculated distance triggers motor movement as per the control process flow (Step 4).

Test Results:

Step 1. Computer Vision detects the object and shows the detection block on the display.

Step 2. The distance range of detection is 7~14 cm.

Step 3. The coordinate of the screen detection block is successfully sent to the Arduino control board.

Step 4. The distance from the camera to the base of the thumb is around 10 cm. When the calculated distance is 10 cm, the motors BM4, BM5 and BM6 starts to rotate.

In summary, the test is successful to achieve the preliminary autonomous grasp.

GUI App Control Test

Test Description: The test is to use GUI App on a smartphone to control the system expected actions .

Step 1. Run Bluetooth terminal app on the smartphone to send and receive characters with Arduino.

Step 2. Press buttons on the GUI app to issue control commands and check whether the system takes the action as expected.

Test Result:

Step 1: The terminal app on the phone is able to transmit and receive character with Arduino via Bluetooth successfully.

Step 2. The system responds to the GUI command and all actions are accomplished as expected for each command.

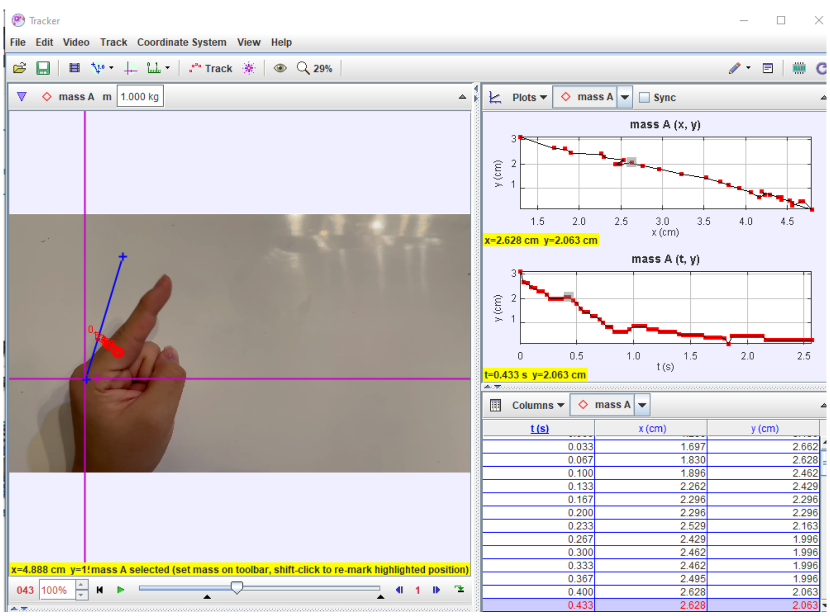
1/15/2024

Fingers Trajectory Experiments were performed.

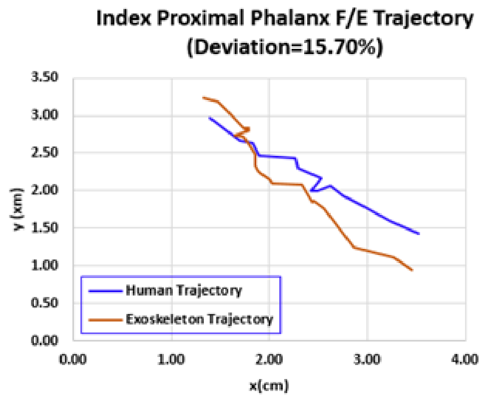
To record the finger trajectory and compare the trajectory of exoskeleton with human can to tell how close the exoskeleton

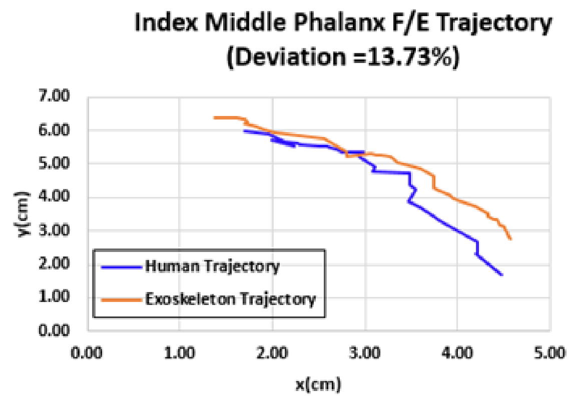
Test setup: Put a red mark on the finger's specific point including Index Finger Proximal Phalanx, Middle Phalanx, and Distal Phalanx, Thumb Proximal Phalanx, and Distal Phalanx. Let the finger do F/E and A/A movement. Take videos on the finger movements. Then use tool Tracker to analyze the trajectory and draw the diagram.

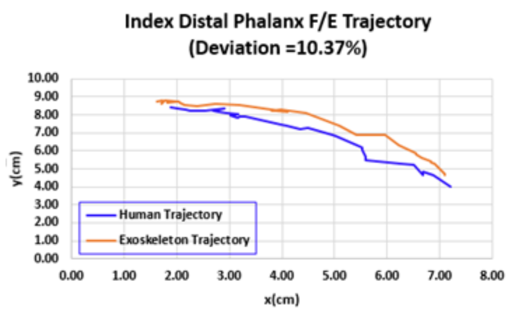
Do the same movement on human finger and exoskeleton finger and compare the trajectory(x-y) data on the same coordinate. Then calculate the error(difference) between two trajectories.

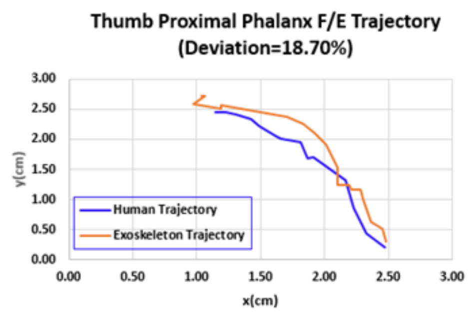


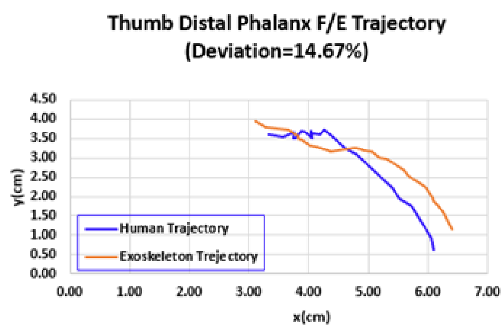
Below are test results.

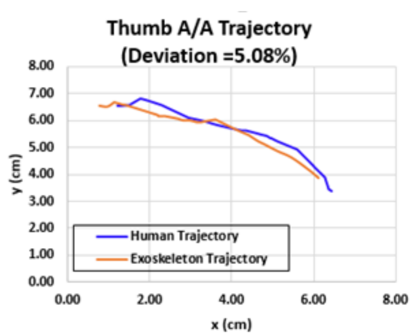

Index Proximal Phalanx F/E Trajectory
(Deviation=15.70%)
y (xm)
x(cm)
Human Trajectory
Exoskeleton Trajectory


Index Middle Phalanx F/E Trajectory
(Deviation =13.73%)
y(cm)
x(cm)
Human Trajectory
Exoskeleton Trajectory


Index Distal Phalanx F/E Trajectory
(Deviation =10.37%)
y(cm)
x(cm)
Human Trajectory
Exoskeleton Trajectory


Thumb Proximal Phalanx F/E Trajectory
(Deviation=18.70%)
y(cm)
x(cm)
Human Trajectory
Exoskeleton Trajectory


Thumb Distal Phalanx F/E Trajectory
(Deviation=14.67%)
y(cm)
x(cm)
Human Trajectory
Exoskeleton Trejectory

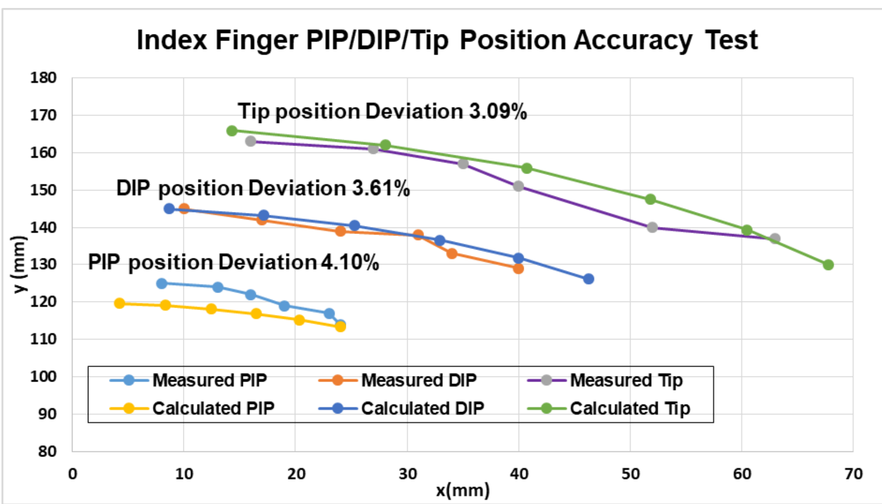

Thumb A/A Trajectory
(Deviation =5.08%)
y (cm)
x (cm)
Human Trajectory
Exoskeleton Trajectory

1/20/2024

Position Accuracy Tests were performed.

Position accuracy tests are to compare the kinematic theory position with the actual exoskeleton position. The result can tell how accurate the exoskeleton's position.

LMC	71.7							
Lp	48.1							
LM	25.7							
LD	21.8							
calculated								
θm	θp	θd	Ax	Ay	Bx	By	Cx	Cy
5	5	5	4.1921912	119.617	8.654949	144.9265	14.2972	165.9837
10	10	10	8.3524773	119.0693	17.1424	143.2194	28.0424	162.0987
15	15	15	12.449196	118.161	25.2992	140.4179	40.71412	155.8328
20	20	20	16.451169	116.8992	32.97081	136.5866	51.85016	147.4866
25	25	20	20.327938	115.2934	40.01528	131.813	60.50058	139.2691
30	30	20	24.05	113.3558	46.30685	126.2058	67.77566	129.9914
Measured								
θm	θp	θd	Ax	Ay	Bx	By	Cx	Cy
5	5	5	8	125	10	145	16	163
10	10	10	13	124	17	142	27	161
15	15	15	16	122	24	139	35	157
20	20	20	19	119	31	138	40	151
25	25	20	23	117	34	133	52	140
30	30	20	24	114	40	129	63	137



1/26/2024

Repeatability and Accuracy tests were performed.

Test Description

1. Establish an opposition movement by rotating all motors to specific angles, ensuring a gap between the Index finger tip and Thumb tip when the motion halts.

2. Validate the completion of the movement for each repetition.

3. Measure and record the distance between the Index finger tip and Thumb tip for every iteration.

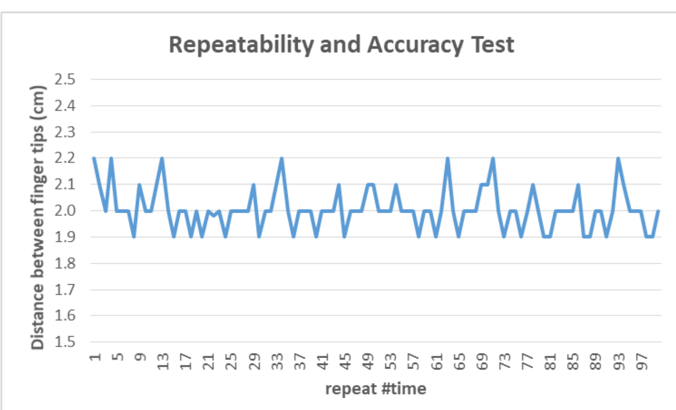
4. Reset the motors to their initial positions.

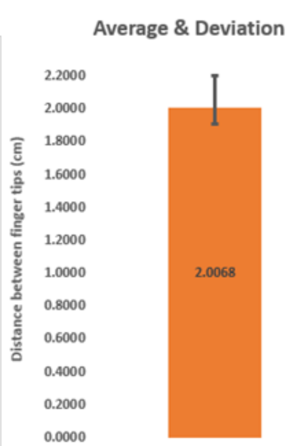
5. Repeat steps #1 to #4 for a total of 100 cycles.

Test Results:

1. All movements are successfully completed in all 100 iterations, achieving a 100% repeatability rate.

2. The distance measurements for each repetition are shown in the figure..





The average distance is 2.0068 cm. Use the following formulas to calculate standard deviation is 0.0795 (3.96%)

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N}}$$

3/17/2024

Information from www.quanthub.com about correlation heatmap,

A correlation heatmap is a graphical tool that displays the correlation between multiple variables as a color-coded matrix. It's like a color chart that shows us how closely related different variables are.

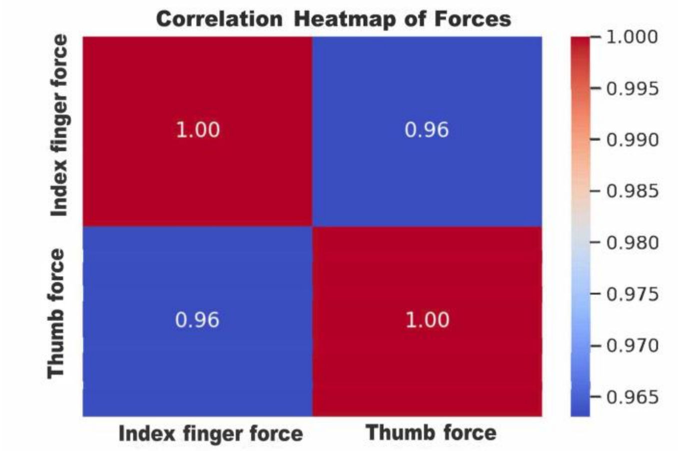
In a correlation heatmap, each variable is represented by a row and a column, and the cells show the correlation between them. The color of each cell represents the strength and direction of the correlation, with darker colors indicating stronger correlations.

For example, if we're studying the relationship between the type of food we eat and our health, a correlation heatmap might show how closely related different types of food are to different health outcomes, such as heart disease or diabetes.

We have data of forces from two fingers when grasping the object, we can try to create a correlation Heatmap of Forces to show the correlation of two fingers.

Use python code to create seaborn correlation heatmap

```
# import modules
import matplotlib.pyplot as mp
import pandas as pd
import seaborn as sb

# import file with data
data = pd.read_csv('FSR1.csv')

# prints data that will be plotted
# columns shown here are selected by corr() since
# they are ideal for the plot
print(data.corr())

# plotting correlation heatmap
dataplot = sb.heatmap(data.corr(), cmap="coolwarm", annot=True)

# displaying heatmap
mp.show()
```



Correlation Heatmap of Forces shows a 0.96 strong correlation between Thumb and Index Finger, indicating two fingers applying forces in a highly coordinated manner, proving finger coordination and accuracy training are crucial.

3/25/2024

Brunnstrom stage approach may be integrated in my system to evaluate stroke recovery status as future work.

https://care24seven.com/what-are-the-7-stages-of-stroke-recovery/

Stage One – Flaccidity

The first stage immediately after a stroke is flaccidity. This is where the muscles on the affected side of the body are completely limp and unable to move. Nerve damage in the brain means that there are no voluntary movements.

The best way to help at this stage is to assist with passive movement, the stroke victim themself is likely to be able to use the mobile side of their body to passively move the flaccid side, it's important to encourage this. It may not seem like it's doing much but it is increasing sensory input to the brain, by sending signals from skin and muscle about movement and touch. These actions will encourage that side of the brain to start waking up.

At this stage, passive movement can also help prevent atrophy. If long term paralysis does take place this can cause the muscle to start to wither and the overall rehabilitation will be more difficult, so it is important for the muscles to receive some form of stimulation. It is also good for the joints and tendons to experience regular movement.

Stage Two – Spasticity Appears

In the next stage of recovery, the muscles begin to show basic movements. Sometimes these are abnormal and generally a reflex to a stimulus like touch. The brain is still re-learning how to send signals to the muscles for voluntary movement. Involuntary movement can be worrying to see, but it is a step in the right direction.

At this stage, passive movement is still extremely important for all the same reasons as in stage one. If possible at this stage active-assisted range of motion can also be added to rehabilitation, this is combining passive movement with active movement, no matter how small the active movement in order to achieve a full range of motion. There are a number of resources available for AAROM exercises so it is likely that you will be able to find time to suit your loved one's progression.

Stage Three – Spasticity Increases

At this stage, there will be more frequent involuntary movement, but again this is nothing to worry about and is progress. This increase in involuntary movement is due to the neural connections between your brain and muscles improving, however, it can be difficult. The increased stiffness of muscles can interfere with speech and thinking, and when your loved one tries to move the affected side it will cause multiple muscles to fire together, this is known as muscle synergy.

At this stage, it is important for your loved ones to continue with rehabilitation exercises, and utilise muscle synergies to strengthen the connection between the brain and the muscles which will improve voluntary movement patterns in the long run.

Stage Four – Spasticity Decreases

At stage four, involuntary muscle movement starts to decline and the brain is more successful in sending signals to the muscle for voluntary movements.

Your loved one should be working on trying to isolate movements and make them more controlled. Repetition is extremely important for the brain to be able to re-learn controlled movement. Working on range of motion, stretching and weight-bearing exercises should be focused on.

Stage Five – Return of Complex Movement

More and more signals from the brain to the muscles will be successful, and involuntary movements will be minimal. At this stage complex actions like using cutlery, writing, walking and swimming can all be achieved through movement repetition.

At this stage, your loved one will have regained most of their movement, so they will be wanting to strengthen their muscles back to how they were pre-stoke. This can be done by adding small weights or resistance bands to previous rehabilitation exercises.

Stage Six – Spasticity Disappears

At this stage, there will be no unexpected involuntary movements and coordination will quickly improve.

Your loved one should continue strengthening the muscles and focus on fine-tuning motor skills with activities such as drawing, playing an instrument, shuffling cards or any other hobby they used to have pre-stroke.

Stage Seven – Return to Normal

Here is the stage where the brain has completely re-learned how to work and everything achievable before the stroke is once again possible.

Appendix

A Rigid-Elastic Hybrid Finger Exoskeleton Rehabilitation System (FERS)

for Stroke Patients with Motor Impairment

Presentation

A Rigid-Elastic Hybrid Finger Exoskeleton Rehabilitation System (FERS) for Stroke Patients with Motor Impairment

Brad Wu
Chandler, Arizona, USA

(All graphs, photos, figures, tables and diagrams in this document were created by the project author unless otherwise marked.)

Introduction: Background

The Problem

795k new strokes in US
15 million worldwide each year.
80% have Motor Impairment

- Hand Strength
- Range of Motion
- Finger Precision
- Fine Motor Coordination
- Isolated Finger Movement

Current Solutions on Hand/Fingers

Professional Physical Therapy & Occupational Therapy
Home-Based Robotic Technology - Hand Exoskeleton

Repetitive motions provide neuromuscular training and re-education to improve self-rehabilitation

The Gap – What is Missing?

Existing exoskeleton devices only focus on providing finger movements and improving strength

- Missed Training on Finger Precision
- Missed Training on Fine Motor Coordination
- Missed Training on Isolated Finger Movement
- Ignored pain and injury caused by device itself
- Prolonged Rehabilitation Time

Need A New Finger Exoskeleton System to Resolve Gaps

Introduction: Latest Research and Engineering Goal

Existing Exoskeleton Research

Type	Pros	Cons
Rigid	Direct↑ DOF*↑	Volume↑ Weight↑
Pneumatic /Tendon (Soft)	Weight↓	Accuracy↓ Complication↑ Pressure↑

Key Takeaways

- ★Direct linkage provides straightforward control and more DOFs/ROMs.
- ★Plastic has lower weight and compact size if designed correctly.
- ★Index finger and thumb are the most crucial fingers.

Current Challenges

- ★Few systems have addressed training on precision, coordination and isolated movement of motor impairment.
- ★No known system has addressed patient protection when exposed to extra force, torque and pressure.
- ★Few systems have versatile user interface.

**DOF: Degree of Freedom, ROM: Range of Motion, F/E: Flexion/Extension, A/A: Abduction/Adduction*

Engineering Goal:
To Design an Effective Rigid-Elastic Hybrid Finger Rehabilitation System

Accuracy: DOF* on each joint of a finger. All F/E*, A/A* and Opposition.

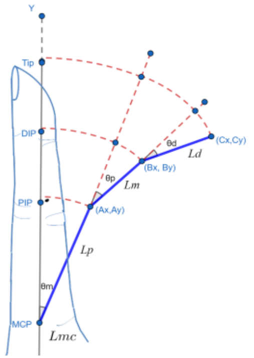
Flexibility: Elastic parts to avoid accidental pain and injury. Low Weight.

Comprehensiveness: Rehabilitation across a wide range of motor impairments.

Research Analysis

1. Human hand structure

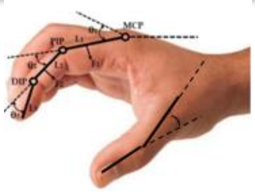
2. Finger Kinematic Model Analysis



Position Analysis

$$Ax = Lp \sin\theta m$$
$$Ay = Lp \cos\theta m + Lmc$$
$$Bx = Lp \sin\theta m + Lm \sin(\theta m + \theta p)$$
$$By = Lp \cos\theta m + Lm \cos(\theta m + \theta p) + Lmc$$
$$Cx = Lp \sin\theta m + Lm \sin(\theta m + \theta p) + Ld \sin(\theta m + \theta p + \theta d)$$
$$Cy = Lp \cos\theta m + Lm \cos(\theta m + \theta p) + Ld \cos(\theta m + \theta p + \theta d) + Lmc \qquad (1)$$

Index Finger Position Analysis



Inverse Kinematics

$$\theta m = \arctan(\frac{Ax}{Ay - Lmc})$$
$$\theta p = \arctan\left(\frac{Bx-Ax}{By-Ay}\right) - \arctan\left(\frac{Ax}{Ay-Lmc}\right)$$
$$\theta d = \arctan\left(\frac{Cx-Bx}{Cy-By}\right) - \arctan\left(\frac{Bx-Ax}{By-Ay}\right) \quad (3)$$

Index Finger Inverse Kinematics

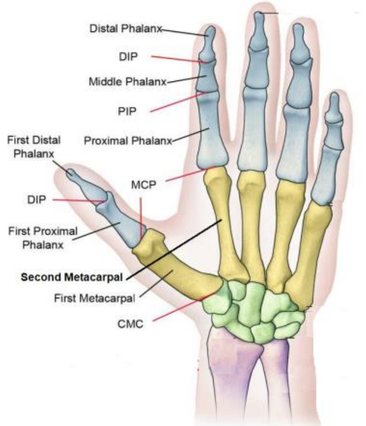


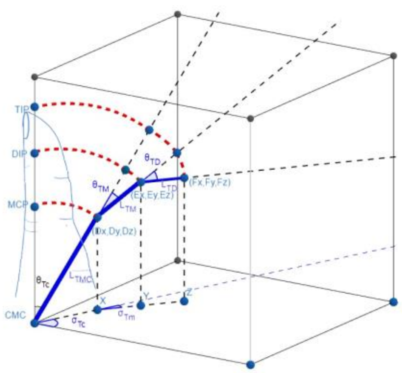
Fig. Carpometacarpal Joint (CMC)

Metacarpophalangeal Joint (MCP)

Proximal Interphalangeal Joint (PIP)

Distal Interphalangeal Joint (DIP)

(Photo Source: Qianqian Tong/IEEE Transaction on Haptics)



$$Dx = L_{Tmc} \sin\theta_{TC} \cos\sigma_{TC}$$
$$Dy = L_{Tmc} \cos\theta_{TC}$$
$$Dz = L_{Tmc} \sin\theta_{TC} \sin\sigma_{TC}$$
$$Ex = L_{Tmc} \sin\theta_{TC} \cos\sigma_{TC} + L_{Tm} \sin(\theta_{TC} + \theta_{TM})\cos(\sigma_{TC} + \sigma_{TM})$$
$$Ey = L_{Tmc} \cos\theta_{TC} + L_{Tm} \cos(\theta_{TC} + \theta_{TM})$$
$$Ez = L_{Tmc} \sin\theta_{TC} \sin\sigma_{TC} + L_{Tm} \sin(\theta_{TC} + \theta_{TM})\sin(\sigma_{TC} + \sigma_{TM})$$
$$Fx = L_{Tmc} \sin\theta_{TC} \cos\sigma_{TC} + L_{Tm} \sin(\theta_{TC} + \theta_{TM})\cos(\sigma_{TC} + \sigma_{TM}) + L_{TD} \sin(\theta_{TC} + \theta_{TM} + \theta_{TD}) \cos(\sigma_{TC} + \sigma_{TM}$$
$$Fy = L_{Tmc} \cos\theta_{TC} + L_{Tm} \cos(\theta_{TC} + \theta_{TM}) + L_{TD} \cos(\theta_{TC} + \theta_{TM} + \theta_{TD})$$
$$Fz = L_{Tmc} \sin\theta_{TC} \sin\sigma_{TC} + L_{Tm} \sin(\theta_{TC} + \theta_{TM})\sin(\sigma_{TC} + \sigma_{TM}) + L_{TD} \sin(\theta_{TC} + \theta_{TM} + \theta_{TD}) \sin(\sigma_{TC} + \sigma_{TM})$$

Thumb Position Analysis

$$\sigma_{TC} = \arctan(\frac{Dz}{Dx})$$
$$\theta_{TC} = \arctan(\frac{\sqrt{Dx^2 + Dz^2}}{Dy})$$
$$\sigma_{TM} = \arctan\left(\frac{Ez - Dz}{Ex - Dx}\right) - \arctan(\frac{Dz}{Dx})$$
$$\theta_{Tm} = \arctan(\frac{\sqrt{(Ex - Dx)^2 + (Ez - Dz)^2}}{Ey - Dy}) - \arctan(\frac{\sqrt{Dx^2 + Dz^2}}{Dy})$$
$$\theta_{Td} = \arctan(\frac{\sqrt{(Fx - Ex)^2 + (Fz - Ez)^2}}{Fy - Ey}) - \arctan(\frac{\sqrt{(Ex - Dx)^2 + (Ez - Dz)^2}}{Ey - Dy}) \qquad (4)$$

Thumb Inverse Kinematics

Fig Finger Kinematic Model Analysis

Method – Finger Exoskeleton Design

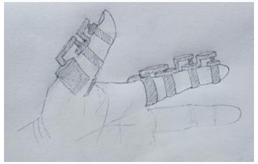
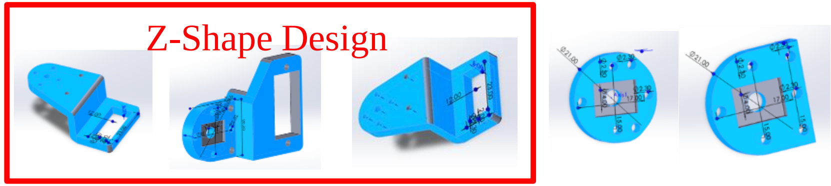
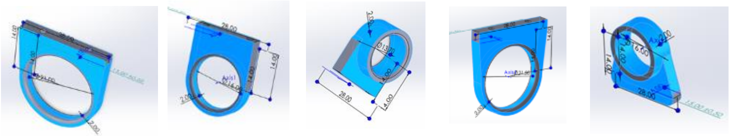


Fig. Design Sketch before AutoCAD

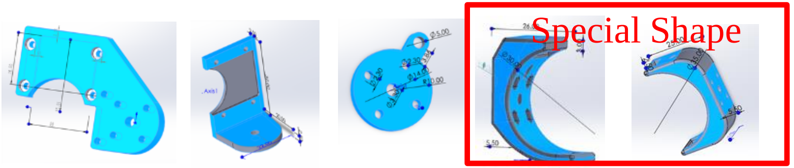
- **Parts Group 1: linkages and motor holders**



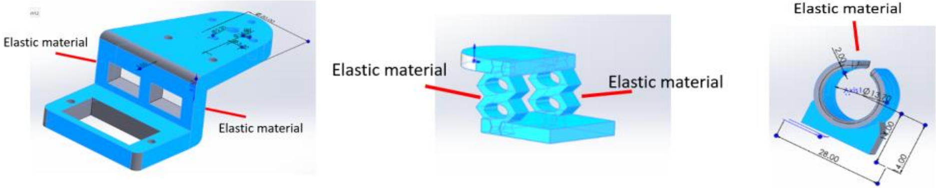
- **Parts Group 2: Finger rings**



- **Parts Group 3: Metacarpal and additional linkages**



- **Elastic Design of Force Relieving Connectors and Rings**



These elastic parts with flexible materials can effectively relieve extra force and protect patients from pain or injury.

The hybrid system seamlessly integrates rigid and elastic components, combining the benefits of each type while alleviating their respective drawbacks.

- **Modular integration design**

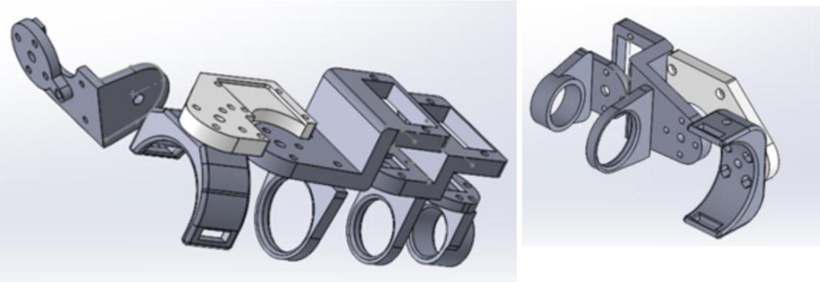


Fig. Modular integration

- **Integration with motors**

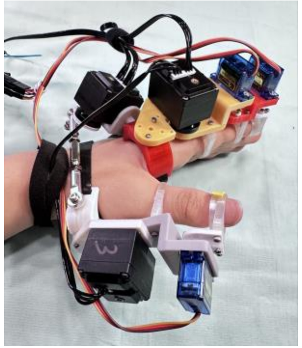


Fig. Integration with motors

Finger Exoskeleton Manufacturing Results & User Interface Design

Finger Exoskeleton Manufacturing

Light Weight & Compact Size

Parameters	Values
Total weight(with 6 motors)	<300g (10 oz)
Total Index Finger Size	~122.3x77.6x73.4mm
Total Thumb Dimension	~85.2x47.2x72.1mm
Length of Index Linkages	37.8, 31.9, 22.9mm
Length of Thumb linkages	41.8, 31.6mm
Index Finger Free Rotating Flexion angles	110º(MCP-PIP),95º(PIP-DIP),180º(DIP-tip)
Thumb Free Rotating Flexion angles	110º(MCP-DIP), 120º(DIP-tip)
Free Rotating A/A angles	360º
Materials	PLA, TPU, steel, rubber
Manufacturing	3D printing

Table: Parameters of the Finished Finger Exoskeleton

- **GUI Phone App Control**
- **Mechanical Switch**
- **Embedded Sensors**

Fig. Mechanical Switch

Fig. Phone APP

FSR Force Sensor, Inertial Sensor (IMU)

- **AI Voice Control**

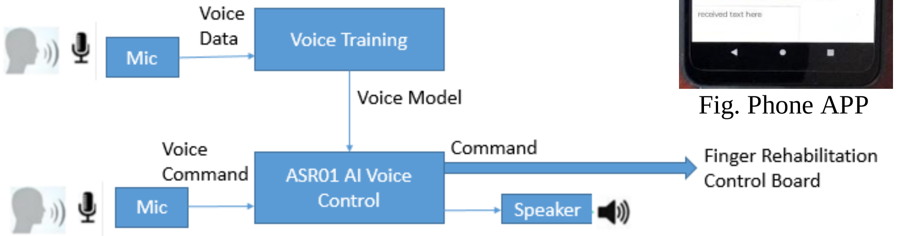


Fig. AI Voice Control Flow

- **Computer Vision Control with Machine Learning**

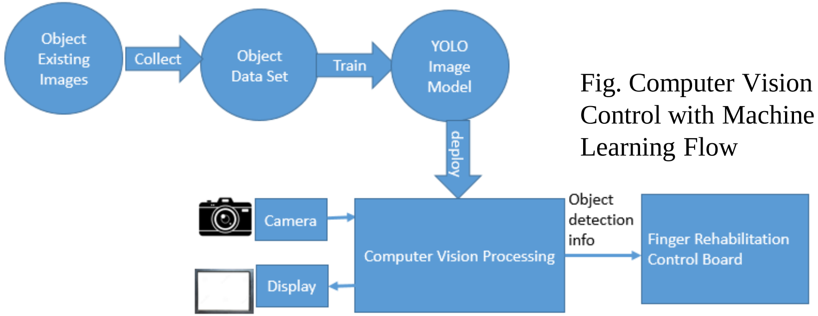
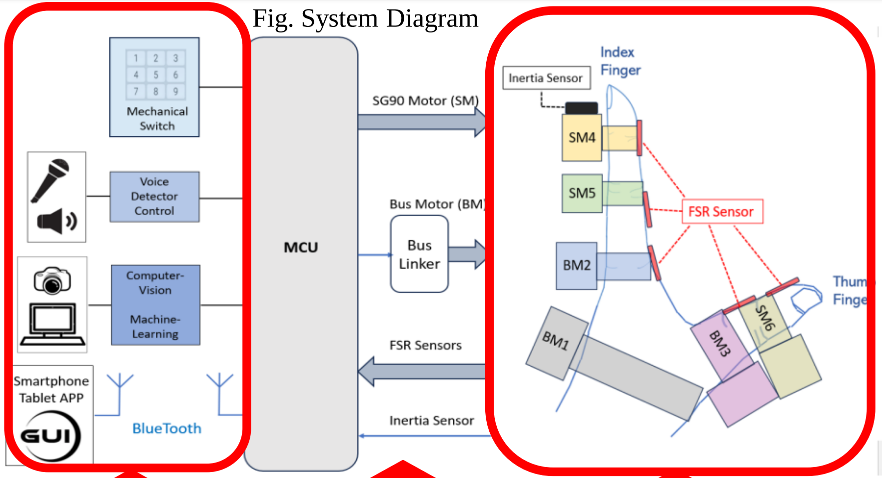


Fig. Computer Vision Control with Machine Learning Flow

Overall System Diagram, Implementation and Control Process

Fig. System Diagram



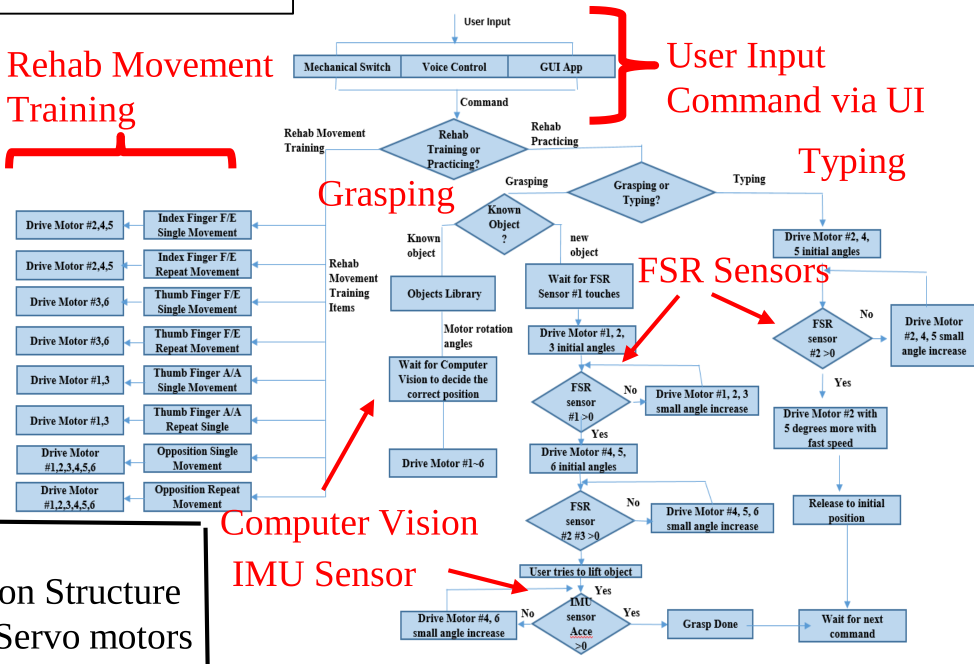
User Interface

Central Control

Exoskeleton

Control Process

Fig. Control Process Flow



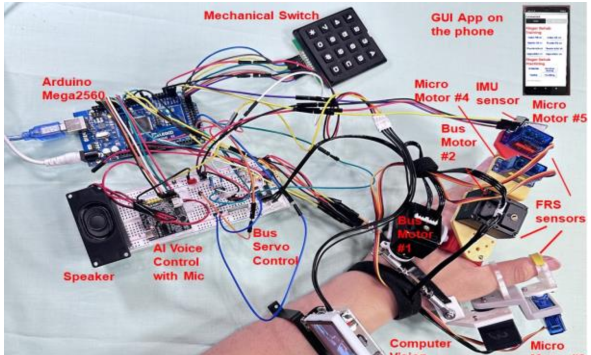


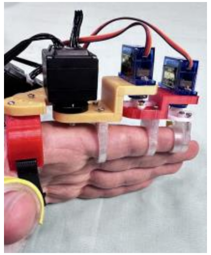
Fig. System Integration

Design elements:

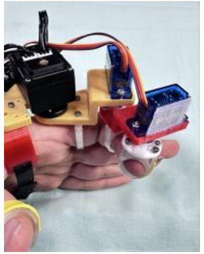
- Finger Exoskeleton Structure
- 3x HX-06L Bus Servo motors and Bus linker
- 3x SG90 Micro Servo motors
- MPU6050 Inertia sensor
- FSR force sensors
- Arduino Mega2560 and IDE
- HC05 Bluetooth
- ASR01 Voice Control Board, Mic and Speaker
- Camera Computer Vision with Machine Learning- OV7740 AI camera and K210 Board
- Smartphone GUI App
- Mechanical Switch- 4R x 4C mechanical keys

Experiments – Rehabilitation Training and DOF/ROM Tests

- **Index Extension/Flexion Movement Training**



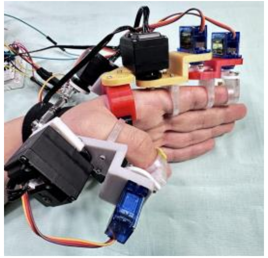
Before Movement



After Movement

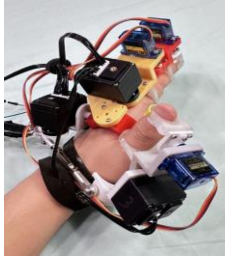
- **Thumb Extension/Flexion Movement Training**

Before Movement

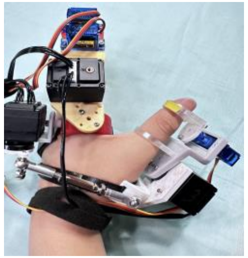


After Movement

- **Thumb Abduction/Adduction Movement Training**



Before Movement



After Movement

- **Opposition Movement Training**

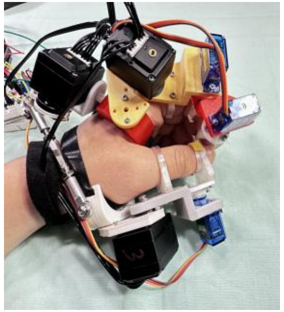
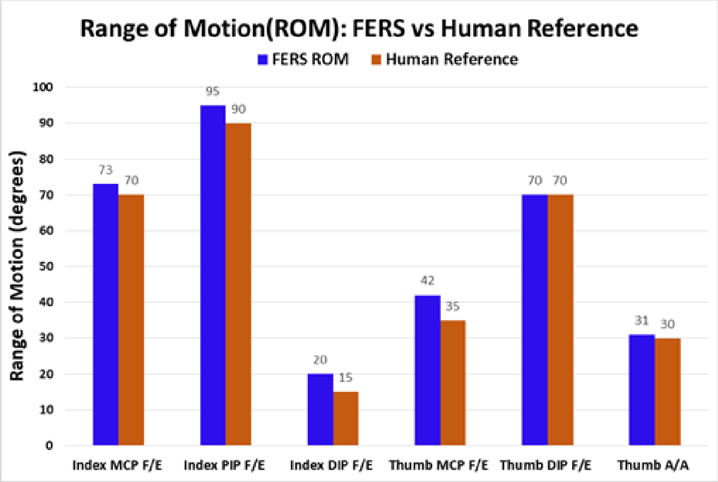
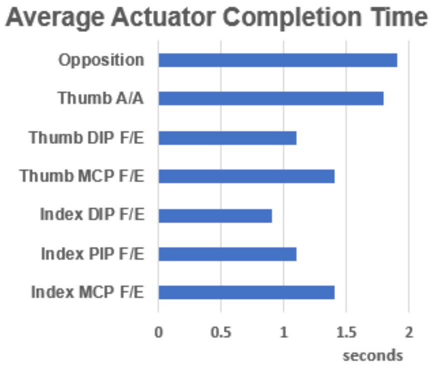


Fig Rehab Training photos

- **DOF (Degree of Freedom), Range of Motion (ROM) and Actuator Response Time Tests**

7 DOF(Degree of Freedom)
#1 Index Finger MCP Extension/Flexion(F/E)
#2 Index Finger PIP Extension/Flexion(F/E)
#3 Index Finger DIP Extension/Flexion(F/E)
#4 Thumb MCP Extension/Flexion(F/E)
#5 Thumb DIP Extension/Flexion(F/E)
#6 Thumb Abduction/Adduction(A/A)
#7 Opposition





Discussion: The design goal of "Accuracy" and "Comprehensiveness" are achieved.

Experiments– Finger Practicing Functional Tests

- **Grasping test**
- **Pen-Holding test**
- **Typing test**
- **Touching test**

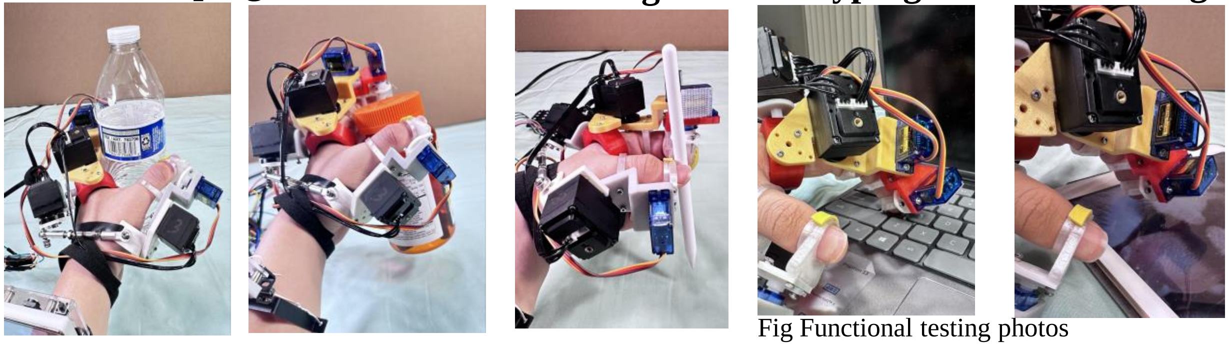


Fig Functional testing photos

- **Grasping Force Tests**

To perform grasping tests and record the force sensor data vs Time on Thumb and Index finger

*weight ~150g.

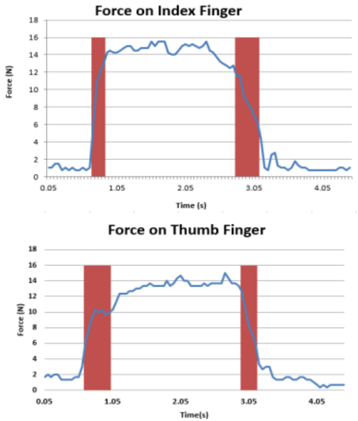


Fig. Grasping Force tests results

Results: The Grasping Force test shows the force 14~16 N on Index finger and 12~14 N on Thumb finger. This result matches the force by human fingers.

Discussion: Correlation Heatmap of Forces shows a 0.96 strong correlation between Thumb and Index Finger, indicating two fingers applying forces in a highly coordinated manner, proving finger coordination and accuracy trainings are crucial.

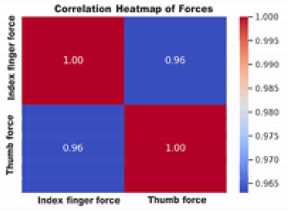


Fig. Grasping Object Correlation Heatmap

- **Elastic Part Force Relieve Test**

Extra force is exerted on the elastic parts to measure the twist or stretch.

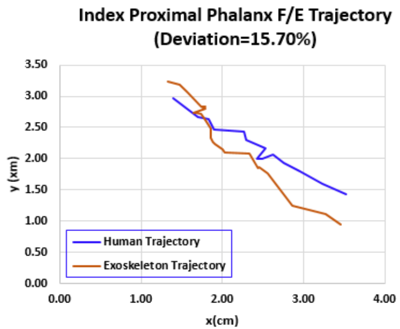
Fig. Elastic parts relieve force

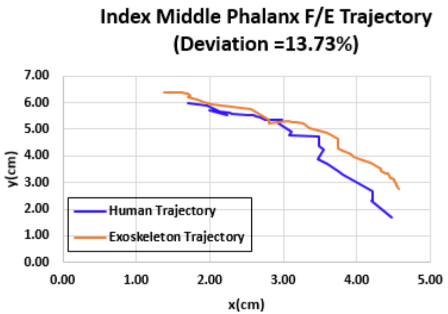
Results: The Elastic Z-part is twisted for more than 10º on each side and the ring stretches without being broken, proving its elastic capability to relieve force and protect patients from accidental pain and injury.

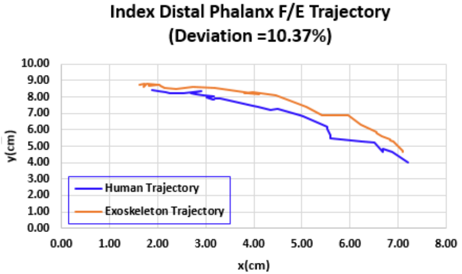
Discussion: The design goal of “Flexibility” is achieved.

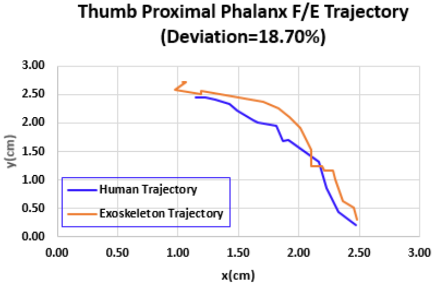
Experiments– Trajectory, Position Accuracy, Repeatability Tests

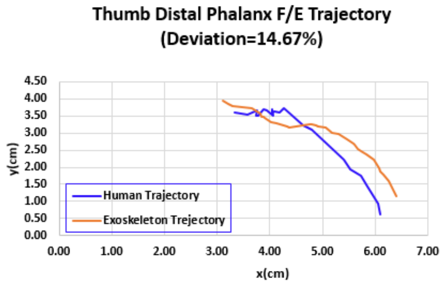
- **Fingers Trajectory Experiments with Deviation Analysis**

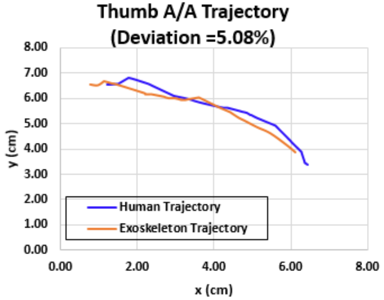




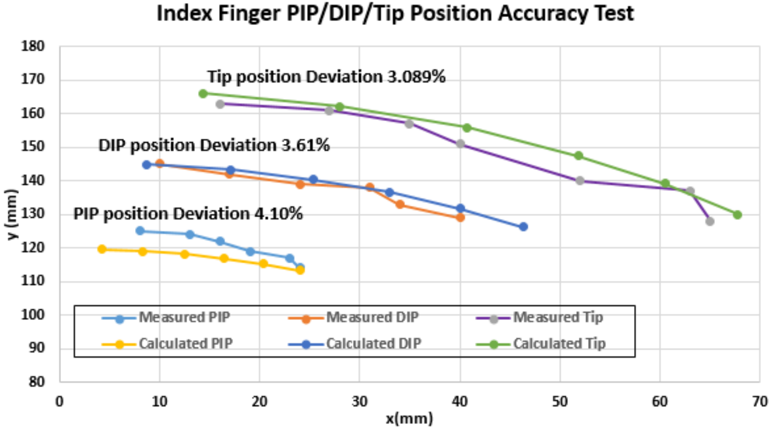








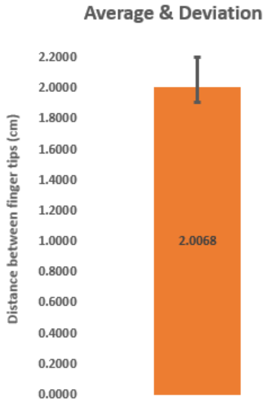
- **Position Accuracy Tests (Deviation < 4.1%)**



- **Repeatability and Accuracy tests**

Repeat an opposition with movements of all finger joints of index finger and thumb for a total of 100 cycles. Measure the distance between index finger tip and thumb tip and calculate the deviation of the distances.

The result shows 100% repeatability rate and 3.96% deviation.



Grasping Object Detection Tests and Conclusion

- **Grasping Object Detection Tests**

Machine Learning method is used to detect the object and send the location coordinate to the control board to decide the best time to grasp the object.

Results: The cup is successfully detected and the location coordinate is sent to MCU. The exoskeleton grasps the object successfully.

Discussion: The Grasping Object Detection test shows the object is detected and the exoskeleton grasps the object successfully.
The preliminary autonomous grasp is achieved.

Fig. Grasping Force tests results

Conclusion

- Innovations of this Rigid-Elastic Hybrid Finger Exoskeleton Rehabilitation System (FERS) include:

  ● Accurate control and 7 DOFs ● Light weight(<300g) and flexible material(TPU) ●Hybrid design with elastic parts to relieve extra force and rigid parts for main linkages and stability ● Optimal multi-bar serial linkage ● AI Voice Control with Machine Learning ●Computer Vision with Machine Learning for preliminary autonomous object grasping ●Phone APP

- Key contribution of this FERS to the field of rehab technology:

  ● **Hybrid Design: A novel approach** to enhance patient comfort and safety without compromising the effectiveness of the therapy is introduced.

  ● **Enhanced 7 DOFs & DOM**: Achieving this level of control and flexibility marks **a significant advancement over current technologies**.

  ● **Versatile User Interface**: FERS **sets a new standard** for interactive and accessible rehab technologies. Those features not only enhance the user experience but also allow for more personalized and adaptive therapy session.

Future Work and References

Future Work

- A method will be developed to fit the exoskeleton structure on wider range of hand and finger sizes.
- Enhanced components, such as advanced force sensors and actuators, are needed for better integration & performance.
- Different computer vision method such as object segmentation will be developed for object detection and grasping.
- Rehab training data and tools will be added to the APP for practitioners and patients to review and improve training.
- A rehabilitation evaluation process such as Brunnstrom stages will be integrated into the system.
- Consolidation of all control and user interface functionalities, including AI Voice Control and Computer Vision, into a single MCU system may be needed from prototype phase through to the final product.

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