A Novel Method for Designing an Exoskeleton of Index Finger using Image Processing Tools in MATLAB

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Abstract - *This paper presents a novel method of developing and designing an exoskeleton system for fingers using image processing tools in MATLAB. The method involves analyzing finger movement by taking videos of arbitrary motion set. The results of the analysis provide us with valuable insights about the placement of joints inside the finger and the range of motion of these joints. Using this information we were able to design an ergonomic exoskeleton shell for a single index finger. Subsequently we following the same process we designed the shells for all four fingers. The range of motion of the design was compared with that of a finger in natural motion. Eventually we were able to design actuation mechanism for the shells based on the range of motion we observed. The final output of this process is a very lightweight 3D printable hand exoskeleton design.*

Key Words: exoskeleton, hand, CAD, image processing, MATLAB, robotics

1. INTRODUCTION

As we know, finger motor function or muscle movement is a crucial and necessary ability of humans to perform intricate and precision tasks. Unfortunately, due to diseases or injury this ability can be hampered severely. The possible solution to regain complete motor function is extensive therapeutic training, or rehabilitation.

In case of rehabilitating hand movements there have been a lot efforts and attempts to completely automate the process with the help of exoskeletons. Over the years, there have been a variety of ideas and designs published. for example: a research paper by the Mechanical Engineering Department, The University of Texas, Austin, shows a prototype of an Index Finger Exoskeleton based on series elastic actuation (SEA) [1]. Most research papers concentrate on the device-human interface [2], control (based on co-simulation [3] or based on EMG signals [4]) and movement [5] of the exoskeleton rather than design aspect. There has been significant research done on rehabilitating the upper limbs as well using exoskeletons [6]. For the purpose of this paper we are concentrating on the design aspect of the exoskeleton. Most of the published work has been concentrated on the actuation mechanism; some are based on traditional 6-link mechanisms [7], whereas some have taken up a much more novel approach and worked with cable actuation [8]. Exoskeletons have also been designed for very specific tasks like haptic interaction with virtual surroundings [9]. Commercially there are a lot of rehabilitation devices available in the market like, Kinetec Maestra Portable Hand CPM [10] and Waveflex Hand CPM [11]. This provides plenty of proof that exoskeletons are being actively used in the industry with a medical application [15] [16].

It can clearly be seen in all the above mentioned examples that the major focus has been on designing the actuation mechanism rather than the base structure of the exoskeleton. Due to this most of the times the range of motion (ROM) and the work space of the mechanism is a direct result of guess work or unreliable and inaccurate measurements. This paper elucidates a novel and intuitive method to design the base structure of an exoskeleton for the index finger using motion capture techniques based on image processing tools of MATLAB. There has been plenty of work done on human motion capture using image processing [12] and computer vision [13]. Based on this, the work starts off by taking a small video of a moving finger and analysing it. It was observed that the finger joints are bending in a fashion such that the location of the internal bone joints can be determined by the folding of the skin. So some points were marked on the finger and the video was recorded again. This time, after analysis, the location of the joints was clearly and accurately visible. Using this information, the base structure for a universal exoskeleton was designed that can be compatible with any type of actuation mechanism. The whole process is briefly explained in the Fig. 1 as a flow diagram.

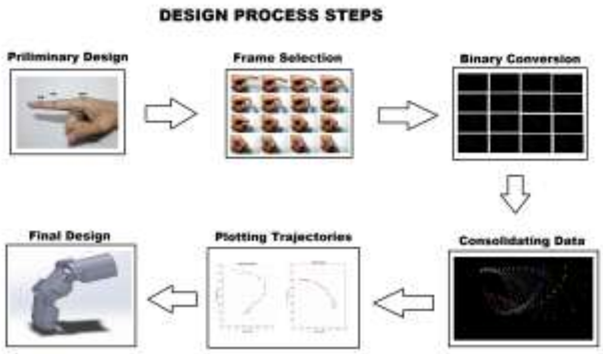


Fig -1: Brief description of the whole design process

The paper is outlined as: Section 2 covers the essentials of preliminary design stage. Section 3 describes the process of analyzing the movement of an index finger. Section 4 details the data that we obtained from the analysis. Section 5 showcases the final 3D model of the base structure based on the data obtained from the previous section. Finally, Section 6 gives us a discussion on the results and future scope as a conclusion.

2. Preliminary Design

It is seen that usually in the process of designing an exoskeleton of the index finger, basic assumptions while modeling the finger are considered which simplifies it to a planar 4 link mechanism where the joints are taken up with standard nomenclature, i.e. DIP (distal-inter-phalangeal), PIP (proximal-inter-phalangeal), and MCP (meta-carpo-phalangeal) [8]. In this paper however, to achieve a more accurate workspace and ROM, the finger is modeled as a 3D cylindrical mechanism based on the measurements of the author’s hand as shown in Fig. 2. The measurements of the author’s fingers lie within the range that is similar to an average adult Indian male according to anthropometric studies [14], therefore it is an acceptable model for this design. The placement of DIP, PIP and MCP is arbitrarily chosen and is not accurate.

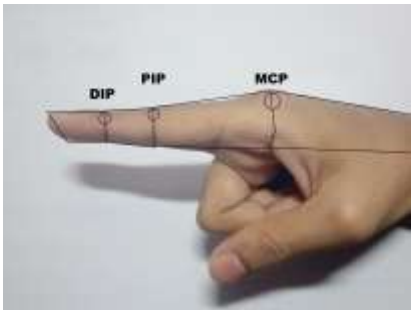
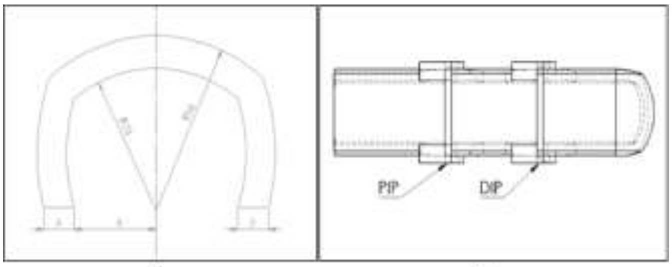


Fig. 2 Rough model of finger super-imposed on the author's finger

The exoskeleton is sketched as a shell covering this model finger leaving a clearance of 1 to 2 mm as shown in the Fig. 3.a. As the actual joints PIP, DIP and MCP are prismatic in nature, the COR (Centre of Rotation) of joints 1 and 2 of the exoskeleton, are kept in line with COR of DIP and PIP of the modeled finger as shown in Fig 3.b. The lengths l1, l2 and l3 in the figure will be determined by the analysis.



a) b)

Fig. 3 a) Cross-sectional sketch of the preliminary design, b) placement of PIP and DIP in the preliminary design

3. Analysis on finger

The purpose of this analysis is to find the location of COR of PIP and DIP joints accurately. The author’s index finger is considered for this particular analysis.

3.1 Preparation for the video

Side profile of the finger is taken in the same plane of motion of the modeled finger for video capture. Background of the video is chosen as white to provide a contrast so that proper color thresholds can be achieved in the later steps of the process. Using acrylic paint we mark small red dots on the finger in a line as shown in the Fig 4. The position of points is arbitrarily chosen because finally only relative distance of the COR from the fingertip will be considered.

a) b)

Fig. 4 a) Initial position of the finger, b) Final position with the red dots along the finger

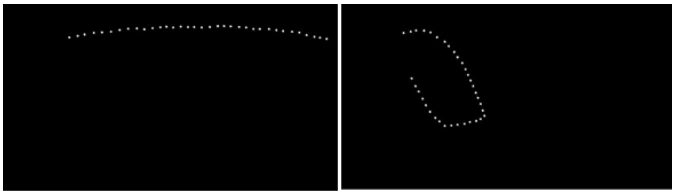
3.2 Recording the video

The finger movement is captured in a video, using a smartphone, from initial position shown in Fig 4.a, to final position shown in Fig 4.b. The chosen movement is flexion in the plane of motion as it gives an idea of the ROM of the finger. The recorded video is 8 seconds long. 16 frames are selected, at intervals of 0.5 seconds of the video for image processing as shown in Fig 5.

Fig. 5 all 16 frames of the video, starting from the top left corner towards the end at the bottom right corner

3.3 Processing the frames

The obtained images have a resolution of 800x350 pixels. An 800x350 -resolution image corresponds to 800 horizontal and 350 vertical pixels on a computer display. These images are coded in MATLAB as red, green and blue (RGB) color-coding system based on 800x350×3 (Rows × Columns × Layer). In this study, the obtained images from the frames are converted into binary formats in MATLAB as shown in Fig. 6.



a) b)

Fig. 6 a) Binary image of the initial position of the finger, b) binary image of the final position of the finger

Using the color threshold tool, the images are converted to binary format which essentially is a 2D matrix. Pixels in binary images with a value of 0 are displayed as black, and pixels with the value of 1 are displayed as white as shown in Fig 6. The binary images of all the 16 frames are shown in the Fig 7.

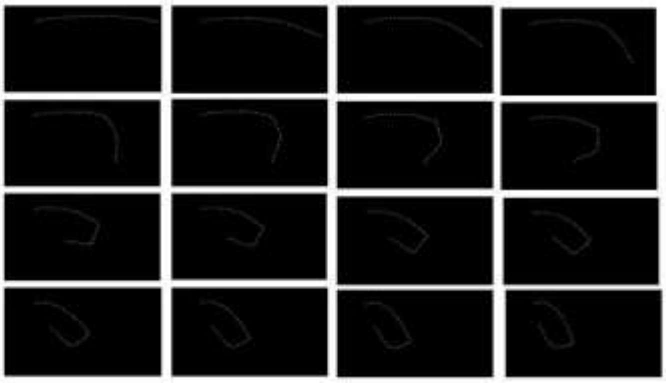


Fig. 7 the binary equivalent images of the 16 frames of the video as shown in Fig 5

4. Data from analysis

Due to the threshold now only individual dots on the finger can be observed. These images are consolidated and layered onto each other to give a final motion image.

4.1 Consolidating data

Once the binary images are created the coordinates of each dot in each frame are extracted. Using the coordinates, the trajectory of each dot individually is mapped.

4.2 Selecting points

Once the trajectories of all the points are mapped, it is seen that at certain points the trajectories start changing. The points between MCP and PIP have the same trajectories but shifted to their location. Similarly the points between PIP and DIP have same trajectories and so do points between DIP and fingertip. However, these trajectories differ drastically from the next set of points. This is understandable as the fingertip covers the largest angular distance, then DIP and PIP covers the least angular distance. Now to determine the exact location, the points where the trajectories change are selected. These points are suitable for considering PIP and DIP. In the Fig. 8 the selected points are highlighted. The Fig. 8 shows the trajectories of selected points throughout the video.

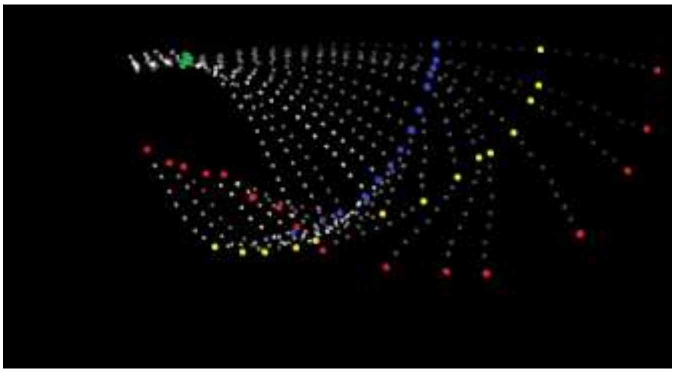


Fig. 8 the binary images of the 16 images superimposed onto each other. Red dots show the fingertip positions, yellow dots show the DIP positions, blue dots show the PIP positions and green dots show the MCP positions

Based on the trajectories the angular range of each joint is measured and tabulated in the Table 1 along with the distance of those joints from the fingertip in initial position. For the joint MCP, it is observe that the range is from 0^0 to 90^0, for PIP the range is from 0^0 to 94^0 and for DIP the range is from 0^0 to 90^0. After locating the points (red dots marked on the finger) associated with the MCP, PIP and DIP, the distance of each of these from the fingertip is measured using a calibrated Vernier calipers set. These values were then used in the design of the exoskeleton to position the hinge joints that imitate MCP, PIP and DIP respectively.

Table -1: The angular range and the distance from the finger tip for mentioned joints

Angular Range and Distance			
Joint	**MCP**	**PIP**	**DIP**
Angular range (Degrees)	0-90	0-94	0-90
Distance from Fingertip (mm)	96	48	27

The trajectories of the joints are mapped on a 2D graph with pixels as the unit of measurement, as shown in Fig 9. Graph a) shows the trajectory of the fingertip throughout the captured motion, while b) shows the trajectory of the DIP throughout the captured motion and c) shows the trajectory of the fingertip throughout the captured motion. It can be clearly observed that the variation in slope of all these graphs is regular but drastically different from each other. This is to be expected as the phalangeal bones are similar to links with joints.

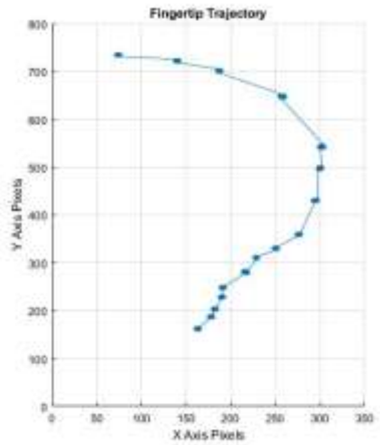


Fig. 9 a) Trajectory of the fingertip point

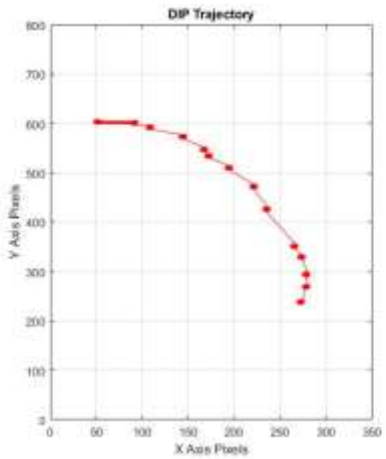


Fig. 9 b) trajectory of the DIP point

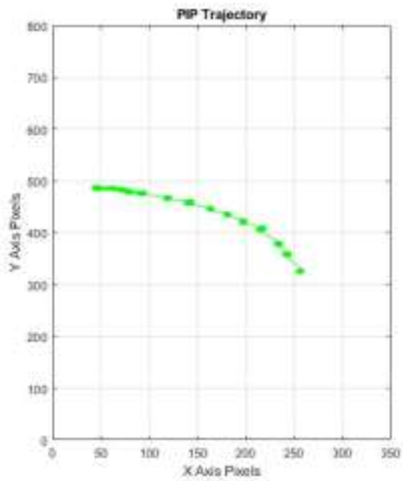


Fig. 9 c) trajectory of the PIP point

5. Final Design

Once the location of the COR for joints 1 and 2 is obtained, the 3D modeling for the exoskeleton starts using SOLIDWORKS software. The design is made for the purpose of 3D printing, therefore less number of parts and print ready assembly is designed. In Fig. 10, it can be seen that the whole structure is made up of 3 components, each corresponding to the respective phalangeal bone: Part 1 covers the Distal Phalange, Part 2 covers the Intermediate Phalange and Part 3 covers the Proximal Phalange. The shell thickness is kept 2mm throughout to give structural stability. A curved shell is provided at the end of Part 1, to cover the finger tip. The sides of the shell are also curved about a few degrees to grip the finger in place.

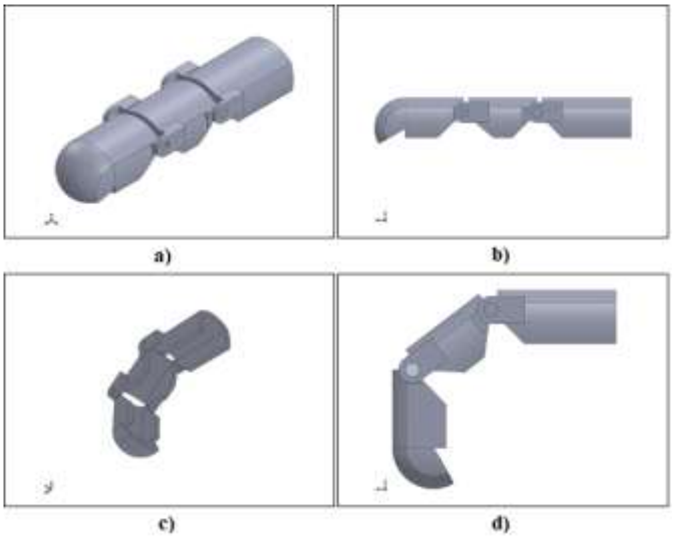


Fig. 10 a) Isometric view of the exoskeleton in completely flexed position; b) Front view of the exoskeleton in completely flexed position; c) inverted isometric view of the exoskeleton in bent position; d) front view of the exoskeleton in bent position

This structure is meant to be the base of a complete functioning exoskeleton. Due to its simplistic design, any type of actuation mechanisms can be mounted on top of this, making it universally adaptive design. Another salient feature of this design is that it's 3D print friendly. The proposed design can be printed very accurately with appropriate tolerances because there are no complicated joints in the assembly. This adds to the simplistic nature of the geometry of the exoskeleton's design. Fig. 11 shows an attempt at 3D printing the parts.

Fig. 11 3D printed parts of the design

Furthermore, the actuation mechanism for these shells was also developed. Fig. 12 shows the sketch of an index finger exoskeleton capable of moving and converting linear actuation into natural finger movement.

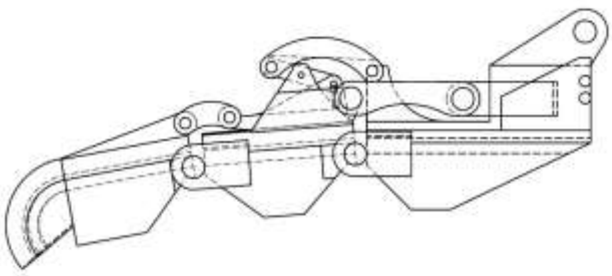


Fig. 12 Sketch of actuation mechanism built on the previously designed shells

Finally, a complete hand exoskeleton was designed based on the data from the analysis shown above. The same method was used for middle finger, ring finger and little finger. Fig. 13 shows a rendering of the final product obtained from the complete design process.

Fig. 13 Final Rendered product

6. CONCLUSION

After testing the design for workspace and ROM, it can clearly be concluded that the design does not hamper the natural movement of the index finger at all. By using the above explained method it was possible to accurately find the location of the COR of physical joints of an index finger. The design based on the image analysis can prove to be a universally adaptive exoskeleton base. For further work, building a design that is adaptive to not only different actuation mechanisms but also to different finger sizes will be the next step for this research. This will help in accommodating more number of patients. I believe that this research paper will prove viable for further work on exoskeletons.

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