Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 12, December 2024

Design and Development of Soft Pneumatic Actuator for Rehabilitation

Laxminarayan P Shenoy(Student), Mr. Vinod Kumar Hp (Asst. Professor)
Dept. of Mechanical Engineering, The National Institute of Engineering, Mysuru-570008

ABSTRACT
Stroke has become a common ailment recently which usually leads to the patient losing motor control in the limbs due to nerve damage. To overcome this, physiotherapy or rehabilitation is very necessary. Due to the repetitive nature of rehabilitation, robots can be built and programmed to achieve precise control of the rehabilitation. Robots have been built using rigid links and actuators which may harm the patient and surroundings when used in medical environment. This drawback can be countered using soft robots which are compliant in nature which doesn't harm when used in medical and unpredictable environment. A soft robot consists of a pneumatic actuator, a pneumatic circuit and a control system. This paper mainly focuses on design and development of a soft pneumatic actuator for rehabilitation of hand. Kinematic analysis of the joints in a finger is studied before building the actuator. A single-channel multi-chambered bending pneumatic actuator is designed and it is fabricated by casting silicone into 3D printed molds. Finite Element Analysis of the Soft Pneumatic Actuators gave the values of deflection, which reflected the practical deformations. The results from the fabrication and testing show potential in the field of soft robotics in medical physiotherapy. Implementation of full-scale development in the field of soft robotics and physiotherapy shows a promising future.

Keywords: **Stroke, Rehabilitation, Soft Pneumatics, 3D printed**

I. INTRODUCTION

According to a recent study, around 15-20 million people worldwide suffer from strokes, fire accidents, automobile accidents, and industrial accidents each year, and more than 70% of survivors have hand function that has been damaged to varying degrees, making it difficult for them to perform daily tasks. Due to a sedentary lifestyle, the prevalence of stroke has been gradually rising in recent years. Stroke significantly reduces limb movement. Activities of daily living (ADLs) and leading an independent existence both heavily rely on the hands. Physical therapy is a crucial treatment for stroke patients to restore nerve function, but the current method is time-consuming, expensive, and dependent on the help of physical therapists. [1,2]

In the event of a stroke, paralysis, traumatic brain injury, or multiple sclerosis, therapeutic robots can aid in rehabilitation. Clinical studies show that there is a pressing need for these devices in the therapy and prosthesis fields for patients suffering from hand trauma after stroke or surgery recovery because they can perform controllable repetitive locomotion efficiently and accurately. According to the composition of the materials, the currently developed robot-assisted hand rehabilitation devices can be roughly divided into two categories: the traditional rigid material based and the soft material. Devices and Equipment used for traditional hand rehabilitation that mostly comprises of hard pieces can restrict hand movement and hurt the hands. It is so bulky and unsafe that one needs to find a new technique to construct a rehabilitation hand that is safer and lighter. In recent years. Soft robotics has potential option for creating unique robotic systems with pre-programmable characteristics that can survive considerable deformations in recent years. Soft robots hand joints can bend and extend safely and effectively due to its usage of light hyperelastic material and pneumatic inflation. In a variety of applications, such as bio-inspired robotic systems, object grabbing and manipulation, invasive surgical instruments, and assistive and rehabilitation technologies, these systems have showed potential. Continuous passive motion (CPM) is a form of therapy in which a machine moves a patient's joint without their involvement.[1,2,3,7,8]

Figure 1: Hand Rehabilitation Device

I. LITERATURE SURVEY

Development and evaluation of a hand rehabilitation glove fabricated using lobster-inspired hybrid design with rigid and soft components for actuation. The modular rigid shells constrain the radial inflation of the soft chamber inside and provide a full protection throughout the range of bending motion. In the meanwhile, the soft chamber provides necessary actuation through interaction with the rigid shells. The design complexity is much reduced for the soft actuator in this hybrid design, which can essentially take almost any form as long as it fits the internal geometry of the rigid shells.[15]

The robotic glove leverages soft material actuator technology to safely distribute forces along the length of the finger and provide active flexion and passive extension. A method for customizing a soft actuator complaint and demonstrate in a motion capture system that the ranges of motion (ROM) of the two are nearly equivalent.[18]

Bending soft actuators, involve a higher degree of nonlinearity than linear ones, mostly due to their bending and even twisting motions in two- or three-dimensional space. The usual trend of output was liner increase in displacement initially and then it slows down. Radius of curvature and number of chambers

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 12, December 2024

in SPA is proportional when it comes for degree of bending.[10]
This robotic exoskeleton designed to provide the required force/motion to the affected hand to restore the ROM and grip force by using a novel soft-and-rigid hybrid actuator. Kinematics of Soft Robots modelled after Piecewise Constant Curvature. There are three types of Joints namely:

1. Metacarpophalangeal (MCP 0-90 degree).
2. Proximal interphalangeal (PIP 0-120 degree).
3. Distal interphalangeal (DIP 0-30 degree). [26]

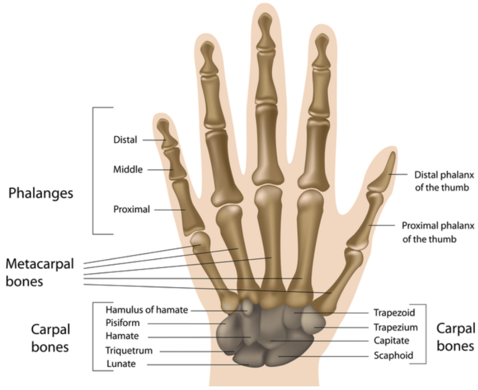


Figure 2: Human Hand Anatomy

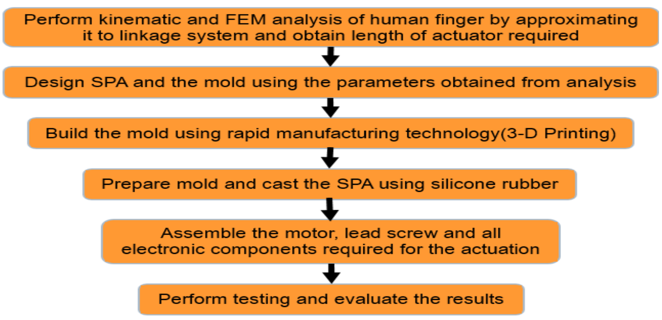
II. PROBLEM STATEMENT

- The Metacarpophalangeal joint in the finger is required to move 0-90 degree, proximal interphalangeal 0-120 degree and distal interphalangeal 0-30 degree.
- Soft robot needs to be compliant with human skin, use of hyper elastic materials is necessary. Major issues with these materials is the problem of hysteresis and the loss of stiffness over repetitive actuation over the life of the material.
- To manufacture the soft pneumatic actuator, using appropriate method.

III. OBJECTIVES

- To overcome the resistance offered by Metacarpophalangeal (MCP) joint. Also, obtain the required Bending Radius of curvature at three joints (MCP, PIP, DIP) in terms of actuation pressure.
- To Perform Kinematic study of finger movement.
- To design cost effective mold for room temperature Cast system for the actuator and fabricate it without defects.
- To perform Physical testing of the SPA, collect data and determine the effectiveness of the treatment.

IV. METHODOLOGY



V. KINEMATIC STUDY

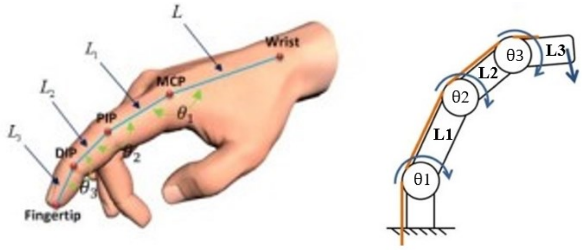


Figure 3: Kinematic Representation of Hand

Kinematic study of a human finger is done to find the locus of the tip of finger. The locus of the tip of finger shows how the behaviour of the soft pneumatic actuator needs to be in order to achieve the proper motion required for the rehabilitation. For the kinematic analysis, the MCP, PIP and DIP joint are considered joints connecting the linkages with lengths a_1, a_2, and $_{a3}$. The MCP, PIP and DIP rotates by θ_1, θ_2 and θ_3 respectively. This has been represented in the figure 3. In the current analysis only flexion and extension has been considered. Abduction and Adduction has not been considered to limit the complexity of the analysis and the design of the SPA. [27]

$$^{0}T_{n} = \begin{vmatrix} Cos\theta_n & -Sin\theta_n Ccos\alpha_n & Sin\theta_n Sin\alpha_n & L_n Cos\theta_n \\ Sin\theta_n & Cin\theta_n Cosa\alpha_n & -Cos\theta_1 Sin\alpha_n & L_n Sos\theta_n \\ 0 & Sin\alpha_n & Cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

Upon solving the generalized D-H representation for each joint and then multiplying the three matrices, the final transformation matrix for flexion and extension considering the input from the table below the resultant matrix was arrived and it is shown in the matrix below.

Joints	A_n	θ_n	α_n	d_n
MCP (1)	L_1	θ_1	α_1	d_1
PIP(2)	L_2	θ_2	α_2	d_2
DIP(3)	L_3	θ_3	α_3	d_3

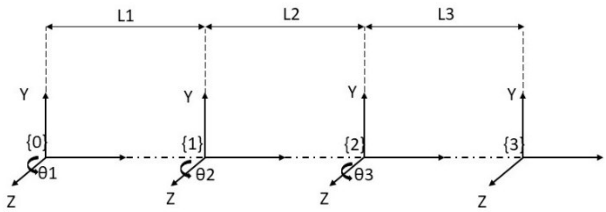
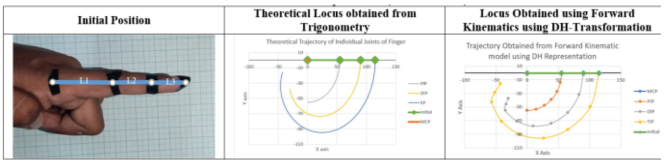


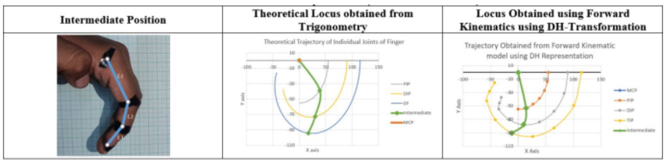
Figure 4: Frame assignment for the planar linkage system

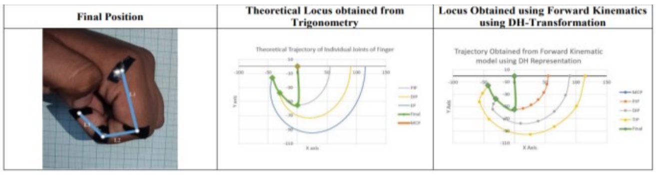
From the Figure 27 it can be seen that Z axis does not change its orientation about x-axis. Hence, $\alpha1 = \alpha2 = \alpha3 = \alpha = 0$ and d1=d2=d3=d=0. On substituting these values to 0Tn with values from Table 6 and multiplying $^{0}T_{1}X^{1}T_{2}X^{2}T_{3} = {}^{0}T_{3}$. This matrix is used to find the locus of the tip of finger using forward kinematics method, which shows the required behaviour of the finger movement.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 12, December 2024

$$
{}^{0}T_{3}=\begin{vmatrix} \cos(\theta_1+\theta_2+\theta_3) & -\sin(\theta_1+\theta_2+\theta_3) & 0 & a_1\cos(\theta_1)+a_2\cos(\theta_1+\theta_2)+a_3\cos(\theta_1+\theta_2+\theta_3) \\ \sin(\theta_1+\theta_2+\theta_3) & \cos(\theta_1+\theta_2+\theta_3) & 0 & a_1\sin(\theta_1)+a_2\sin(\theta_1+\theta_2)+a_3\sin(\theta_1+\theta_2+\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}
$$

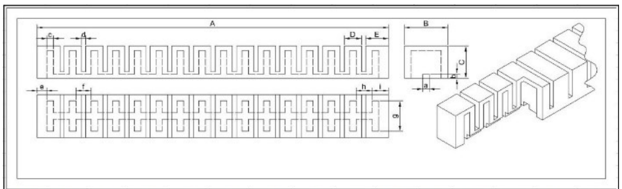






VI. DESIGN OF SPA

The length of the SPA was determined by looking at the anthropomorphic data for human finger. The anthropomorphic data. To obtain a length, which conforms to the majority of human fingers, 95th percentile lengths has been used. The lengths of each digit have been added and additional length has been added to attach the pneumatic circuits. After the calculations, the length of the SPA arrived is 163 mm. This length proves to be sufficient to actuate an average person's finger when worn on glove.[34]



Trial No.s	A	B	C	D	E	a	b	c	d	e	f	g	h	i
1	103	20	15	8	10.5	2	2	3	1	4.5	6	14	6.5	7.5
2	103	20	15	8	10.5	2	2	3	1	4.5	6	14	6.5	7.5
3	103	20	15	8	10.5	2	2	3	1	4.5	6	14	6.5	7.5
4	103	20	15	8	10.5	2	2	3	2	4.5	6	14	6.5	7.5
5	163	20	15	8	10.5	3	2	3	2	4.5	6	14	7.5	7.5
6	163	20	15	8	10.5	3	2	3	2	4.5	7	14	7.5	7.5
7	163	20	15	8	10.5	3	2	3	2	4.5	7	14	7.5	7.5
8	163	20	15	8	10.5	3	2	3	2	4.5	7	14	7.5	7.5
													All Dimension in mm	

Figure 5: SPA Design Iteration

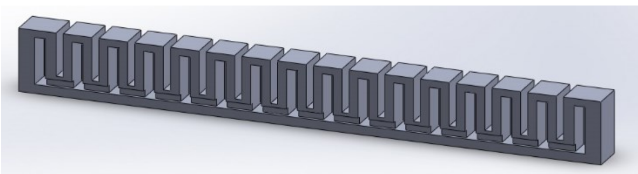
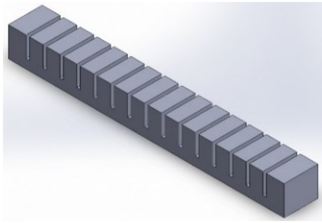


Figure 6: Cross-section view of SPA



VII. DESIGN OF MOLD

Five primary factors that were considered for the concept screening and scoring process to choose the final mold design and have a significant impact on fabrication and resource availability are as follows:

- Modularity.
- Ease of Manufacturing 3DP.
- Ease of Use/ Application.
- Extraction of Cast Part.
- Ease for Adjustable Feature Properties of cast.

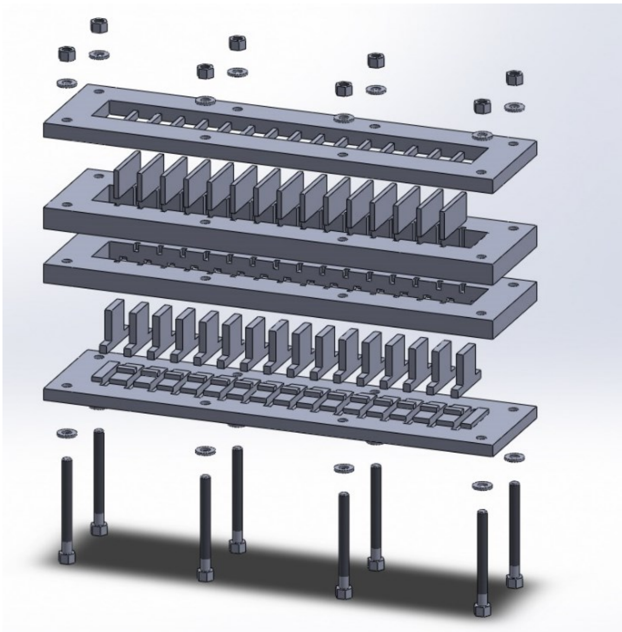


Figure 7: Exploded View of Mold

VIII. FABRICATION

A. 3D Printing the molds.

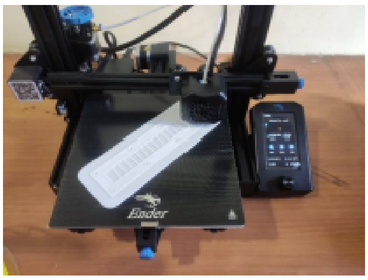


Figure 8: 3D Printing Setup Creality Ender Pro3

Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 12, December 2024

Sl. No's	Print Parameter	Print Setting
1	Nozzle Diameter	0.4 mm
2	Layer Height	0.2-0.28 mm
3	Wall Thickness	0.8-1.2 mm
4	Top/Bottom Thickness	1.2-1.5 mm
5	Infill Density	40 %
6	Infill Type	Gyroid, Tri-Hexagonal
7	Printing Temperature	200-210 °C
8	Bed Temperature	50-60 °C
9	Print Speed	50-60 mm/s
10	Build Plate Adhesion	RAFT
11	Build Material	PLA

Figure 9: 3D Printed PLA Mold Parts

B. Casting of SPA

A hyperelastic material is used to create the Soft Pneumatic Actuator. Thermoplastic Polyurethane (TPU) and Silicone Rubber are two examples of hyperelastic materials. Silicone was chosen because it can be cast in liquid form, it cures quickly, and it can be handled relatively easily. The Silicone used here is LSR-2. Because of the high viscosity of LSR-2, casting is the preferred method of fabrication. Casting is more affordable than other fabrication techniques. The major steps in casting are as follows:

1. MOLD PREPARATION
2. RESIN PREPARATION
3. POURING AND CURING
4. EXTRACTION AND POST PROCESSING

C. Assembly of Device

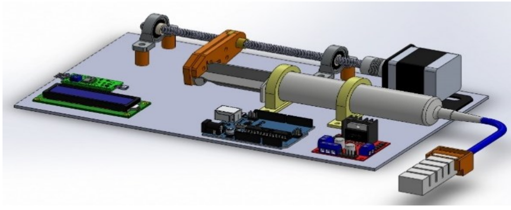
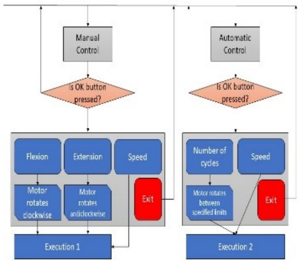


Figure 10: Assembly of Device

Exercises involving repeated motion must be done as part of the physiotherapy for the Continues Passive Motion treatment. This necessitates that a specially trained individual in person administer the therapy. Since robots can execute precise and repetitive activity, medical assistive robots have been used in recent years. However, the program's adaptability to various conditions and environments is a limitation. By employing glove-mounted Soft Pneumatic actuators, this problem can be solved. Since each actuator is flexible, they may be adjusted to accommodate varied finger lengths by just donning the glove. This automation model has been put together to demonstrate how the continuous workout can be carried out utilizing a leadscrew stepper motor arrangement to actuate the syringe pump. The final setup is shown in Figure 10.



IX. RESULTS

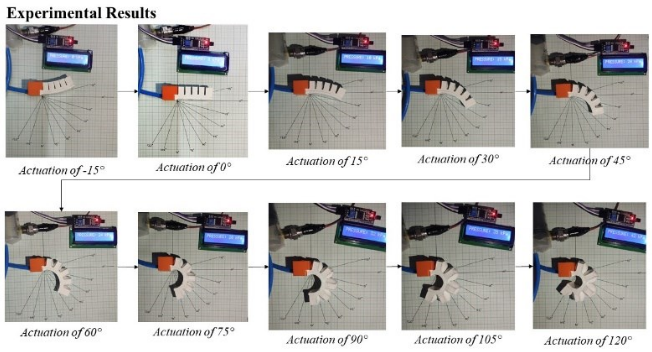


Figure 11: Experimental Results

Upon studying the graph, it can be observed that the angle of deflection increases with pressure. The displacement increases till the angle of deflection reaches 90° and then displacement decreases since after 90° because the tip of the SPA starts rolling inwards. This happens because after 90° deflection, the SPA starts rolling inwards into itself. These results can be validated by comparing the experimental results to the FEA results.

Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 12, December 2024

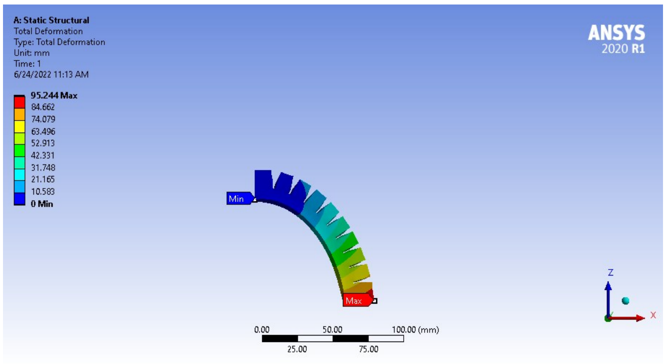


Figure 12: FEA Non Linear Analysis results

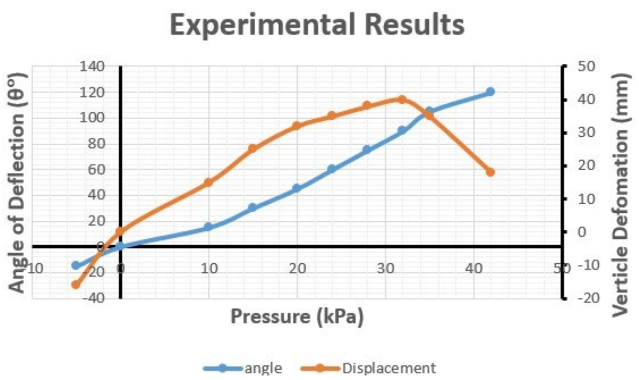


Figure 13: Experimental Result

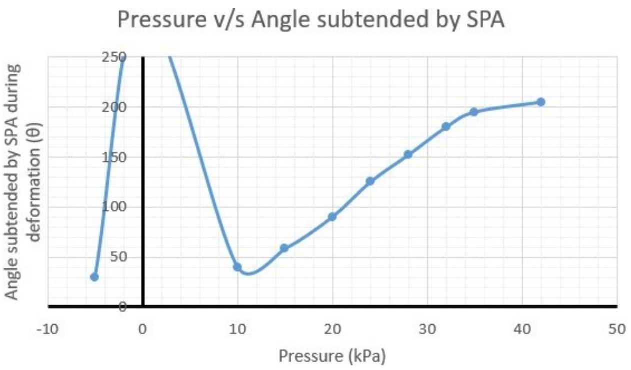


Figure 14: Experimental Results Pressure vs angle subtended

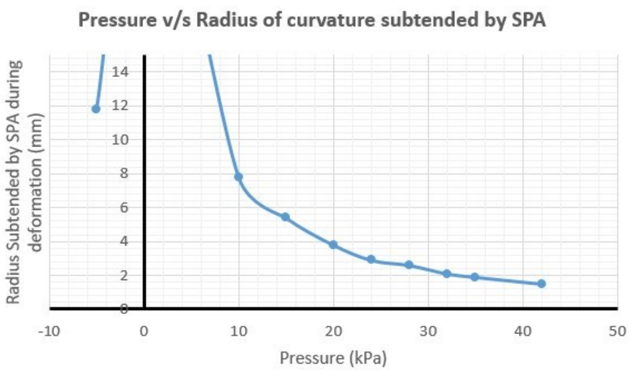


Figure 15: Experimental Results Pressure vs Radius of Curvature

X. CONCLUSION

In this paper, a novel soft robotic rehabilitation device for stroke and paralysis patients has been presented. The anatomy of the human finger has been researched, as well as the bending of each joint. The range of motion of the joints was found to be 0°-90° for MCP, 0°-120° for PIP and 0°-30° for DIP. The location of the fingertip has been studied using kinematic analysis of the finger. Denavit-Hartenberg representation of the finger was found which gave us the locus of the tip and joints. The locus obtained from D-H matrix was compared with the actual locus and both loci were found to be similar. The Finite Element Analysis of the Soft Pneumatic Actuator was done by considering a Yeoh 2nd order polynomial model of hyperelastic material. In this case, utilization of Liquid Silicone Rubber (LSR-2) was used for casting. The FEA results showed deflection of 95.244 mm in the vertical direction. When comparing it to the real model, it showed 73 mm deflection in the vertical direction. The results were further studied for pressure v/s deformation and also pressure v/s deflection. The plots of pressure v/s deformation in FEA and the experimental test were studied and the relationship between pressure and deflection was found to be linear up to 90°. Additionally, the study of plots pressure v/s angle subtended by the SPA and pressure v/s radius of curvature show that as pressure increases, the angle subtended increases and radius of curvature decreases. The data from all the testing shows that rehabilitation devices using soft pneumatic actuator have a promising future. The effectiveness of these devices need to be studied upon in the future.

XI. FUTURE SCOPE

The SPA designed in this project is a single channel, multichambered type which limits it to have a constant bending radius throughout its span. This means that each joint is actuated equally. To ensure that each joint can be actuated independently, a multichannel, multichambered SPA can be developed and its benefits can be studied. Alternatively, another design of single channel, multichambered SPA can be arrived where the chamber length is different for different joints which can be used to obtain the same effect with a single channel. A compressor and solenoid valve system can be implemented which ensures proper pressure delivery and better control over the pressure. Behavior of SPA made of other hyperelastic materials can be studied. To further study the effectiveness of the rehabilitation glove, the glove and its effectiveness must be tested on multiple patients with the consultation of the doctor. The effectiveness can also be studied by giving rehabilitation through soft robotic glove to one group of patients and normal physiotherapy rehabilitation to another group of patients and surveying on the treatment given.

REFERENCE

[1] Jeyaraj Durai Pandian, Paulin Sudhan, “Stroke Epidemiology and stroke care service in India”, ”Journal of STOKE”, “National Library of Medicine.
[2] “Stroke, Cerebrovascular accident”, World Health Organization, Regional office for the Eastern Mediterranean centre.
[3] “Robotics in Healthcare to Improve Patient Outcomes”, “Medical robots assist with surgery, streamline hospital logistics, and enable providers to give more direct attention to patients.”
[4] Hong Kai Yap, Fatima Nasrallah, Jeong Hoon Lim, Fan-Zhe Low, James C.H. Goh, Raye C.H. Yeow. “MRC-Glove: A fMRI Compatible Soft Robotic Glove for Hand Rehabilitation Application.”

Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 12, December 2024

[5] Agostino Stilli, Arianna Cremoni, Matteo Bianchi, Alessandro Ridolfi, Filippo Gerli, Federica Vannetti, Helge A. Wurdemann, Benedetto Allotta, Kaspar Althoefer. "Air Ex Glove - A Novel Pneumatic Exoskeleton Glove for Adaptive Hand Rehabilitation in Post-Stroke Patients."
[6] James Walker, Thomas Zidek, Cory Harbel, Sanghyun Yoon, F. Sterling Strickland, Srinivas Kumar, Minchul Shin. "Soft Robotics: A Review of Recent Developments of Pneumatic Soft Actuators."
[7] Jiaqi Guo, Shuangyue Yu, Yanjun Li, Tzu-Hao Huang, Junlin Wang, Brian Lynn, Jeremy Fidock, Chien-Lung Shen, Dylan Edwards, Hao Su. "A Soft Robotic Exo-Sheath using Fabric EMG Sensing for Hand Rehabilitation and Assistance."
[8] Stuart Biggar, Dr Wei Yao. "Design and Evaluation of a Soft and Wearable Robotic Glove for Hand Rehabilitation."
[9] Patricia A. Vargas, Fabricio Lima Brasil, Alistair C. McConnell, Marta Vallejo, David W. Corne, Adam A. Stokes, Renan Cipriano Moiol. "Combining Soft Robotics and Brain-Machine Interfaces for Stroke Rehabilitation."
[10] Hongying Zhang, Yiqiang Wang, Michael Yu Wang, Jerry Ying Hsi Fuh, A Senthil Kumar. "Design and Analysis of Soft grippers for hand Rehabilitation."
[11] Hong Kai Yap, James Cho Hong Goh, Raye Chen Hua Yeow. "Design and Characterization of Soft Actuator for Hand Rehabilitation Application."
[12] Quan Liu, Jie Zuo, Chang Zhu, Sheng Quan Xie. "Design and Control of Soft Rehabilitation Robots Actuated by Pneumatic Muscles: State of the Art."
[13] Yongkang Jiang, Diansheng Chen, Pengyong Liu, Xiaofang Jiao, Zilong Ping, Zi Xu, Jian Li, Ying Xu. "Fishbone-Inspired Soft Robotic Glove for Hand Rehabilitation with Multi-Degrees-of-Freedom."
[14] Alberto A. Reymundo, Elvin M. Munoz, Marcelo Navarro, Emir Vela, Hermano Igo Krebs. "Hand Rehabilitation using Soft-Robotics."
[15] Yaohui Chen, Sing Le, Qiao Chu Tan, Oscar Lau, Fang Wan, Chaoyang Song. "A Lobster-inspired Robotic Glove for Hand Rehabilitation."
[16] Useok Jeong, Hyun-Ki In, Kyu-Jin Cho. "Implementation of various control algorithms for hand rehabilitation exercise using wearable robotic hand."
[17] Chia-Ye Chu, Rita M. Patterson. "Soft robotic devices for hand rehabilitation and assistance: a narrative review."
[18] Panagiotis Polygerinos, Kevin C. Galloway, Emily Savage, Maxwell Herman, Kathleen O' Donnell, Conor J. Walsh. "Soft Robotic Glove for Hand Rehabilitation and Task Specific Training."
[19] Yongkang Jiang, Diansheng Chen, Jiacheng Que, Zhe Liu, Ziqi Wang, Ying Xu. "Soft Robotic Glove for Hand Rehabilitation Based on a Novel Fabrication Method."
[20] Lizhen Wang, Guangshuai Peng, Wei Yao, Stuart Biggar, Chaoyi Hu, Xiaofei Yin, Yubo Fan. "Soft robotics for hand rehabilitation."
[21] Zheng Wang, Michael Z Q Chen, Juan Yi. "Soft robotics for engineers. "Soft robotics for engineers."
[22] Lizhen Wang, Guangshuai Peng, Wei Yao, Stuart Biggar, Chaoyi Hu, Xiaofei Yin, Yubo Fan. "Soft robotics for hand rehabilitation."
[23] Panagiotis Polygerinos, Stacey Lyne, Zheng Wang,Luis Fernando Nicolini, Bobak Mosadegh, George M. Whitesides, Conor J. Walsh. "Towards a Soft Pneumatic Glove for Hand Rehabilitation."
[24] Jing Bai, Aiguo Song, Ting Wang, Huijun Li. "A novel back stepping adaptive impedance control for an upper limb rehabilitation robot."
[25] Ghaith J. Androwis, Brian M. Sandroff, Peter Niewrzol, Farris Fakhoury, Glenn R. Wylie, Guang Yue, John DeLuca. "A pilot randomized controlled trial of robotic exoskeleton-assisted exercise rehabilitation in multiple sclerosis."
[26] Mahdi Haghshenas-Jaryani, Rita M. Patterson, Nicoleta Bugnariu PT, Muthu B.J. Wijesundara. "A pilot study on the design and validation of a hybrid exoskeleton robotic device for hand rehabilitation."
[27] R K Mittal, I J Nagrath, "Robotics and Control", "Mc Graw Hill Education-2003"
[28] "Technical Data Sheet Workday PLA", www.3DFuel.com
[29] https://www.sae.org/standards/content/j1739_202101
[30] https://softroboticstoolkit.com/book/modeling-soft-pneumatic-actuators
[31] https://www.nature.com/articles/s41598-020-65003-2
[32] https://www.frontiersin.org/research-topics?domain=all&query=soft%20robotics
[33] http://www.rehab-robotics.com.hk/
[34] Joydeep Majumder, "Anthropometric dimensions among Indian males - A principal component analysis"-"ResearchGate-2014"