DESIGN AND DEVELOPMENT OF A SOFT ROBOTIC EXO-HAND FOR REHABILITATION OF STROKE PATIENTS

A Final Year Project Report
Presented to
SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING
Department of Mechanical Engineering
NUST
ISLAMABAD, PAKISTAN

In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

by

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2019

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Titled: "**DESIGN AND DEVELOPMENT OF A SOFT ROBOTIC EXO-HAND FOR REHABILITATION OF STROKE PATIENTS**" be accepted in partial fulfillment of the requirements for the award of BE-ME degree with grade **B+**

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ABSTRACT

This paper aims to present a portable, light-weight, highly compliant and economical soft-robotic exo-hand glove which can be used by recovering stroke patients (quadriplegics and hemiplegics) so that they mad indecently resume rehabilitation at home and may be partially enabled to carry out basic ADL. The aim of this project is to drastically improve the quality of life for these patients and use science for the noble purpose of helping the fellow man. The glove comprises of *Pneuflex* actuators that are pressurized by air using electromagnetic valves and an ingenuous control system that has low hysteresis and noise. PWM is used to actuate the valves and the whole system is embedded in a soft fabric by means of Velcro to form a wearable glove. The system will be pressurized by means of a compressor that may be mounted on the wheelchair of the patient for improved portability and a suitable LiPo battery may be used.

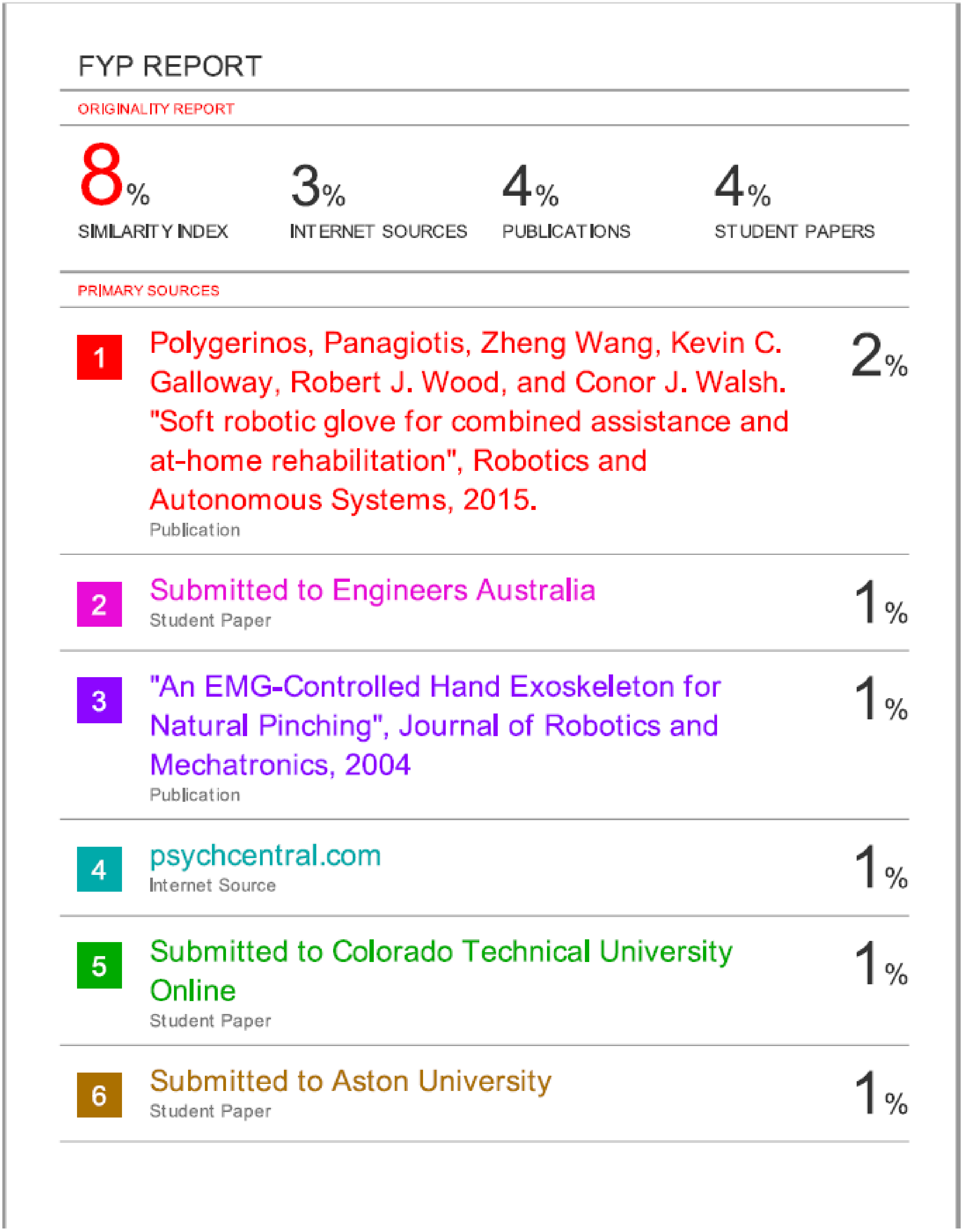
ACKNOWLEDGMENTS

We would like to thank the following people for this endeavor:

- Mr. Hamza Nizami and Dr. Jawad for their expertise and guidance
- Mr. Abdur Rahman for his understanding and support
- Ibrahim Bin Yasir and Abdur Rahman (ME06) for sharing their knowledge and passing on the torch to us

ORIGINALITY REPORT

We hereby declare that no portion of the work of this project or report is a work of plagiarism and the workings and findings have been originally produced. The project has been done under the supervision and guidance of SUPERVISOR and has not been a support project of any similar work serving towards a similar degree’s requirement from any institute. Any reference used in the project has been clearly cited and we take sheer responsibility if found otherwise.



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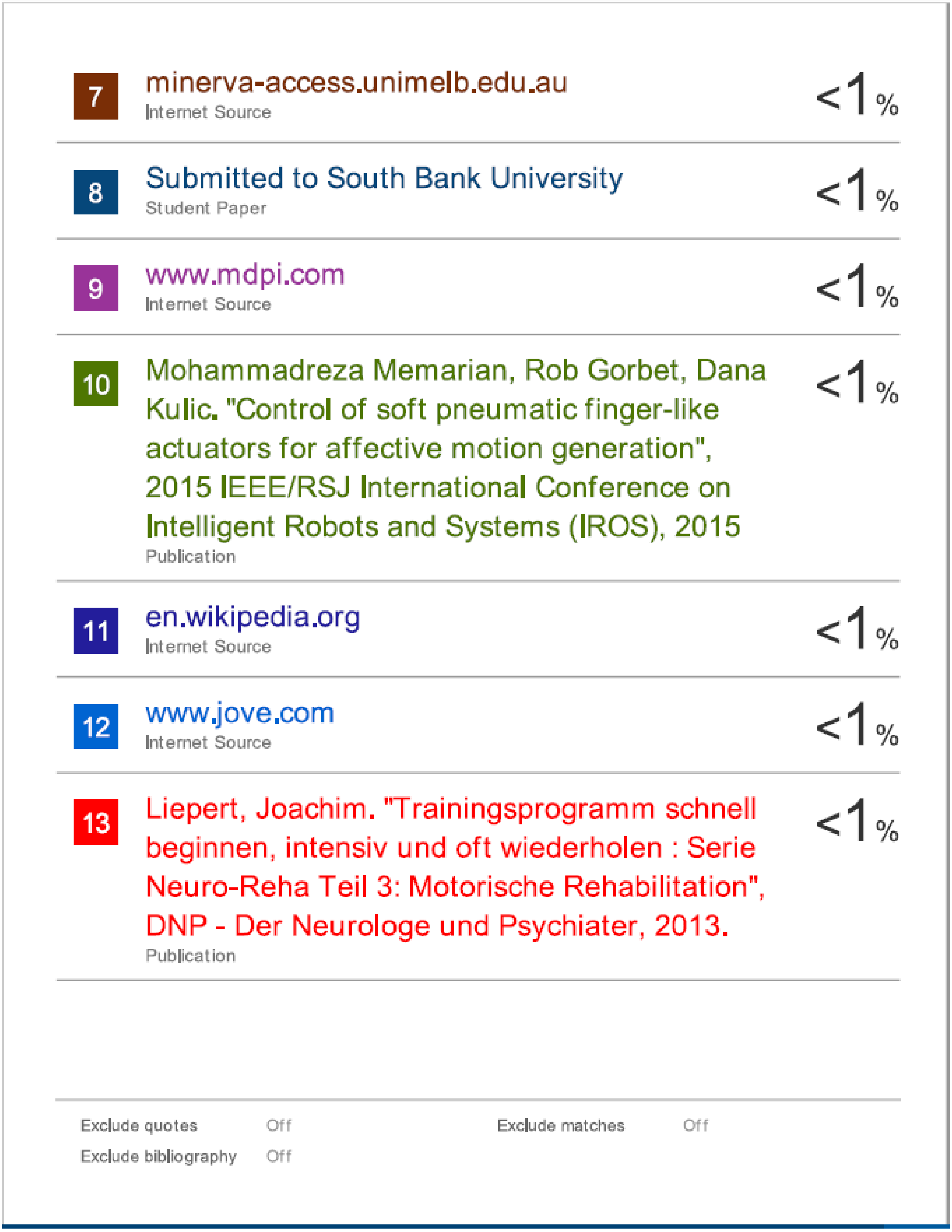

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ABBREVIATIONS

ADL	Activities of Daily Living
RTP	Repetitive Task Practice
ROM	Range of Motion
EEG	Electroencephalography
EMG	Electromyography
FNIRS	Functional Near-Infrared Spectroscopy
DOF	Degrees of Freedom
PWM	Pulse Width Modulation
LPF	Low Pass Filter
SPAM	Soft Pneumatic Air Muscles
MCP	Metacarpophalangeal joint
DIP	Distal interphalangeal joint
PIP	Proximal Interphalangeal Joint

NOMENCLATURE

W_{in}	Input Work done on the Actuator
W_{out}	Output work done by the Actuator
$P_{\mathbf{in}}$	Input Pressure
$P_{\mathbf{atm}}$	Atmospheric Pressure (**A1, (3)**)
T	Output torque generated by the actuator
Θ	Bend angle of actuator (corresponds to joint angle)

CHAPTER 1: INTRODUCTION

Problem Statement: Design, Develop and Control an exo-hand capable of rehabilitation of stroke patients and potentially assist in ADL.

Motivation

Around 15 million people, globally, suffer from the menace that is stroke. [1] It proves mortal for one-thirds of these sufferers and renders another third permanently disabled. The debilitating consequences of stroke are tragic and often result in drastic degradation of the survivor’s quality of life.

A vast majority of these cases face a loss of hand functionality. This loss, be it partial or complete, severely impedes the sufferers in performing activities of daily life (ADL). Contemporary rehabilitation procedures involve physiotherapy of a repetitive nature (RTP; repetitive task practice). These procedures involve the breakage of individual tasks into singled out movements and then practicing them; often requiring the supervision of a trained therapist. The eventual outcomes are improvement in gripping power, precision and range of motion (ROM).

Our Approach

Although RTP does eventually lead to improvement, it must be noted that it is a very gradual and inconvenient process for both the patient and the physician as it is labor intensive and renders the patient dependent on others for their recovery. What we aim to do is provide a solution to this conundrum by means of soft robotics. While there does exist a plethora of alternate approaches using conventional mechanical systems, our approach is novel in a manner that it employs the use of soft-robotic pneumatic-continuum actuators. These actuators have been termed as the “*Pneu-Flex*” Actuators [2] and work by means of pressurization from an internal fluid (air or water).

It must be noted that our own predecessors at RISE Lab developed a very impressive solution using a conventional mechanical system approach which involved linkages mounted on an acrylic base and actuated by motors connected via flex-string. [4]

But we have ventured into the realm of soft-robotics for a multitude of **promising reasons** which are as follows:

1) *Pneu-Flex* actuators are highly ***compliant*** and involve deliberate mixing of multiple deformation modes which makes them all the more ergonomic.

2) They are relatively ***cheaper*** to manufacture (albeit material procurement process within Pakistan is still a little inconvenient but possible, nonetheless).

3) They are ***robust*** and unaffected by dust, dirt, liquids or impact! So there is dexterity as well as robustness to impact and blunt collisions (often unavoidable in ADL).

4) Soft-robotics is a fledgling of a field already carrying the present into flight to the future with extensive research and academic interest in this discipline. For perspective, the current Soft Robotics journal has an impact factor of 6.130. [3]

All these factors and a special interest in soft robotics rooting from our fascination and love for Big Hero 6 (Baymax), convinced us to address our problem statement by employing soft robotics!

Objectives

The primary objectives that we aim to accomplish are:

Physical Design Module Objectives:

- To develop a *top mounted, low weight*, *economical* and *ergonomic* soft-robotic exoskeleton embedded in a soft wearable glove.
- The exo-hand should be *compliant, robust and durable.*
- It should be capable of generating the magnitudes of forces necessary for rehabilitation as well as ADL.

Control Systems Module Objectives:

- Analyzing and implementing a suitable input for the control system (selection between EEG, FNIRS and EMG).
- The system should be self-sufficient and grant the patient the ability to rehabilitate independently.
- The response of the glove should be smooth and continuous.
- The system should have a minimum bandwidth of 10 Hz which is 20 times higher than the bandwidth of the glove that we are hoping to achieve.

CHAPTER 2: LITERATURE REVIEW

The first step following the establishment of the problem statement was to delve into the literature review. Since the goal of this project was to restore motor functions of a paralyzed hand, it was important to understand the capabilities and the structural motion of a fully functional hand.

Anatomy of hand

The hand is connected to the body via wrist which is a complex mechanical system of 8 bones known as the carpal bones. The carpal bones consist of two rows, one of which connects to the end bones of the forearm whereas one connects with the bones of the palm. The figure below shows how the bones are intricately arranged to form the structure of the hand which enables it achieve around 21 DOF allowing the performance of ADL.

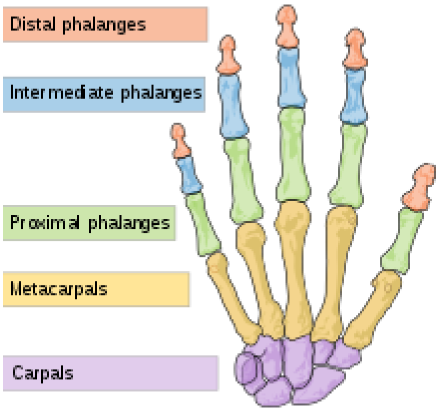

Fig. 1 (Anatomy of human hand)

The human hand consists of 27 bones five of which are the metacarpals which join the wrists with the fingers. The fingers are divided into 3 joints, hence resulting in 3 bones within each finger. The various ADL are performed by the hand using arches as shown in the figure below. The longitudinal arch (brown) is formed by the finger bones and their respective metacarpal bones. The transverse arches (dark green) are formed by the distal ends with the carpal bones. The oblique arches are formed by the thumb and the fingers.

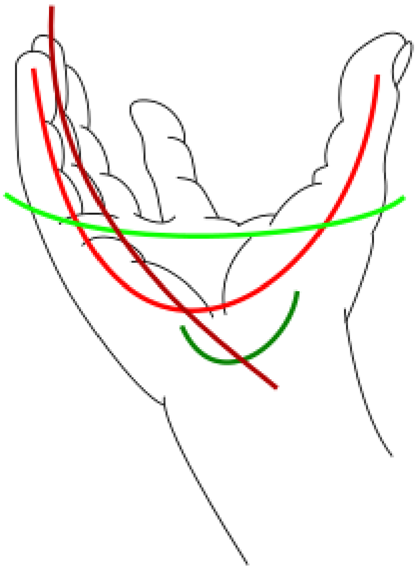

Fig. 2 (Degrees of Freedom of the Human Hand)

Rehabilitation Techniques

Since the major aim of this project is to cater for the rehabilitation requirements for stroke patients, it is of utmost importance to know exactly the expected outcome of this project. For this purpose, a thorough study was performed on the rehabilitation techniques employed by the medical officials to ensure best possible results. Some of these techniques are

- Motor Rehabilitation using VR [9].
- Brunnstrom movement therapy [10].
- Bobath treatment technique [11].
- Motor Relearning program [12].
- Constraint-induced movement therapy [13].
- Robot-aided sensorimotor stimulation [14].
- Repetitive Hand Movement [15].

The techniques mentioned above aim to align the neurological senses with the physical features by employing various physical activities all ultimately improving the neuro-physical behavior of the patient. The use of an exo-hand basically eliminates the need for supervised rehabilitation and gives the user the complete control in a very practical and efficient manner all the while ensuring absolute safety.

Motion and Force Requirements

There are certain requirements which the exo-hand must fulfill in order to achieve competence as a rehabilitation or an ADL device. The range of motion of a hand can be found in literature [6, 7] from which it can be deduced that the fingers must have a DOF of three, two DOF and a rotating one must be present at the carpometacarpal joint of the thumb in order to ensure proper grasping. The sum of the joint angles of the middle finger and the thumb is approximately 250° and 160° respectively. Similarly, the grasping force that a healthy hand can produce is 300N and 450N for females and males respectively. These are the peak forces which need not be achieved as the purpose of this project is merely to achieve rehabilitation and ADL.

During our literature review we came across an interesting investigation related to the control of “soft pneumatic finger like actuators”. The actuators mimicked hand gesture communication of humans and the degree of similarity was observed. The authors described the working principle in terms of energy conversion and stated that pneumatic artificial muscles (PAMs) convert potential energy (stored by virtue of pressure inside a fluid) into kinetic energy. This is achieved by means of an elastic membrane. The hand-like curvature is generated by a guiding mechanism which is flexible but inextensible. Hence, this layer limits *constrains* the expansion of the actuator in a certain direction while it continues its expansion in other unbounded directions. Modern developments have paved the way for highly compliant soft PAMs (SPAMs) which have superior power to weight ratio, an innate stability and high responsiveness (depending on the control regime applied). *Pneuflex* actuators are a subcategory of SPAMs and can be constructed relatively easily.

For a feedback control system to be developed, real time feedback of the end-effector location is necessary and can be achieved by a gyroscopic sensor. The gyroscopic sensor determines the end-effector position with respect to a fixed reference frame. Linear PID and position controllers in parallel configuration may be used to control position output. **[Fig. 6]**

Hard vs Soft Exo-Hand

The domain of exo-hands is classified into two categories namely hard and soft exo hands. The initiation of the project was based on the orthodox hard robotics as it was the approach employed by our predecessors. A deeper study on the whole subject led us to the field of soft robotics which was relatively newer and apparently a hot topic these days.

After thoroughly analyzing the design and the prototype left behind by our predecessors and comparing them with the newer soft robotic designs, it was concluded that soft type exo hand better served the problem that we had in mind. A brief review of both of these types is listed below.

Hard Robotics

This type of exo-hand has been under abundant study for the past two decades and as made a commendable progress over that time period. These designs are rigid and popularly employ the use of linkages. However, many pneumatic and hydraulic based designs have often surfaced as well aiming to produce smoother actuation.

J. Iqbal et al. [20] developed a portable and rehabilitative device for the hand. The device is in the category of hard exoskeletons and it is under actuated, top-mounted, reversible, provides position feedback, consists of three links and has a single point of attachment. Its main focus is towards compatibility with human hand force capabilities.

T. Tang et al. [21] developed a hand rehabilitation exoskeleton system consisting of kinematic chain of 4-bar linkages and shape memory alloy used as actuators. The device is top-mounted and does not consist of series elastic actuators. Gears are used to link one 4-bar linkage to another 4-bar linkage. Feedback system is not employed but it has been proposed that sensors can be employed in the exoskeleton to collect signals containing information regarding motion and force, and thus transforming into a feedback control system.

Shu-Wei Pu et al. [22] developed an under actuated, top-mounted and cable driven linkages-based hand exoskeleton system for rehabilitation. Feedback systems or series elastic actuators are not used.

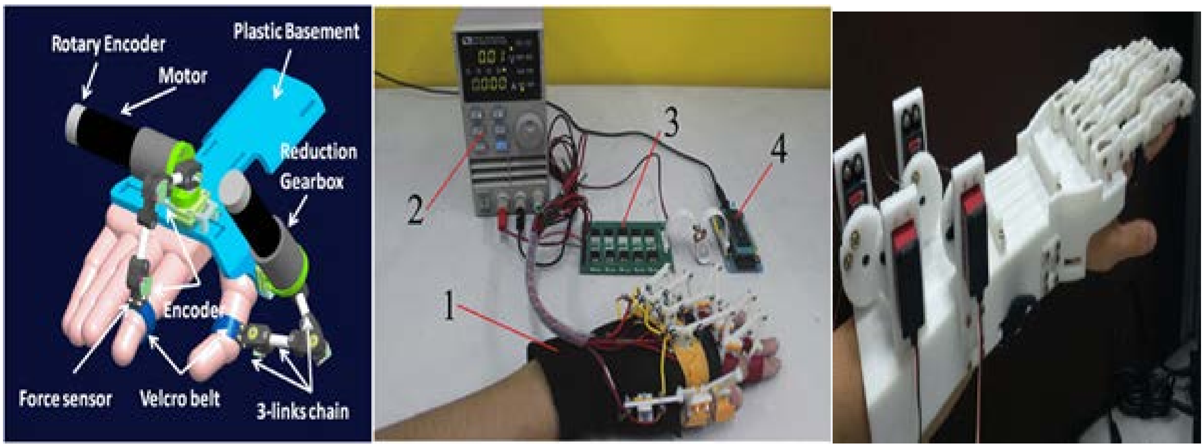

Fig. 3 (Shu-Wei Pu’s Hand Model)

Soft Robotics

This unorthodox approach has been gaining popularity over the past five years or so and is set to cement its status as the primary solution to the rehabilitation problem. These designs offer a high power to weight ratio and a compliance that the hard designs lack. Recent developments in this domain is what has led us to opt for a soft design. A summary of the recent and most notable soft designs is as follows

Wang et al. [23] developed a soft and portable exoskeleton hand designed to assist hand rehabilitation for individuals. This glove functions upon soft elastomeric chambers employed with fiber reinforcements to produce bending and twisting under actuation. These were designed and matched to replicate the range of motion of fingers. This soft glove has the capability to increase the freedom of the user through employing an open palm design. This achieves the force criteria for achieving activities of daily living.

S. A. Fischer et al. [24] developed a soft glove employed with cables to open and close a patient's hand and provide rehabilitation through Repetitive Hand Movement Technique.[21] The Bowden cables are attached at the rigid distal phalange of glove and controlled through servomotors. This incorporates cables on both sides of the hand. The glove can be position controlled through the use of EMG signals measured through electrodes. This rehabilitative glove actuates over the full finger's range of motion with maximum force of 15N.

Popov et al. [25] developed a soft structured exoskeleton hand for assistance in ADL. This glove allows soft and adjustable and allows the palm to grasp and manipulate grasped objects. The proposed glove achieves flexion/extension of three fingers and a thumb. The system designed is lightweight and offers an experimental force of 16N. This force puts the measured device at the maximum power to weight ratio among portable hand exoskeletons for ADL.

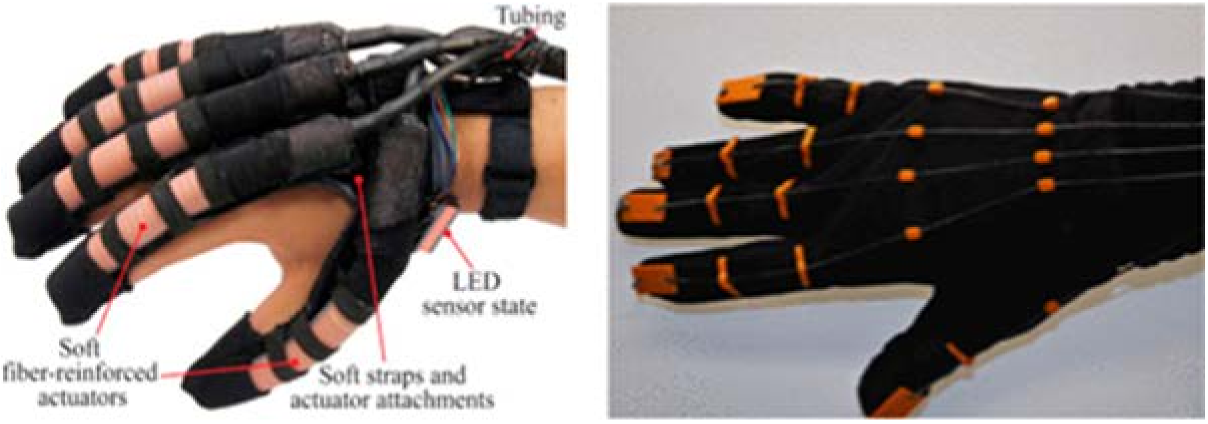

Fig. 4 (Harvard's Exo Glove)

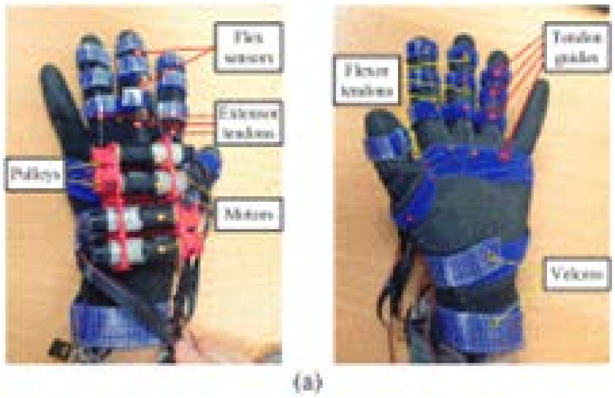

Fig. 5 (TU Berlin's Exo Glove)

PneuFlex Actuators

Through most of the literature reviewed, the design of the actuators has been mostly constant as most papers credit TU Berlin for their simple and genius design. [2] A compliant and under actuated soft robotic prosthetic hand was developed for the purpose of achieving dexterous grasping by the authors of the DIY. [18] The original pneuflex actuator design comprises of two layers, namely the active and the passive layer. The active layer is a layer of silicone that is flexible as well as extensible while the passive layer consists of silicone imbued with a fabric that renders it inextensible albeit flexible. The actuator is wound clockwise and counterclockwise with a polyester sewing thread of gage 50 in the original design. The thread restricts radial expansion of the actuator once it is pressurized. **[Fig 5.]**

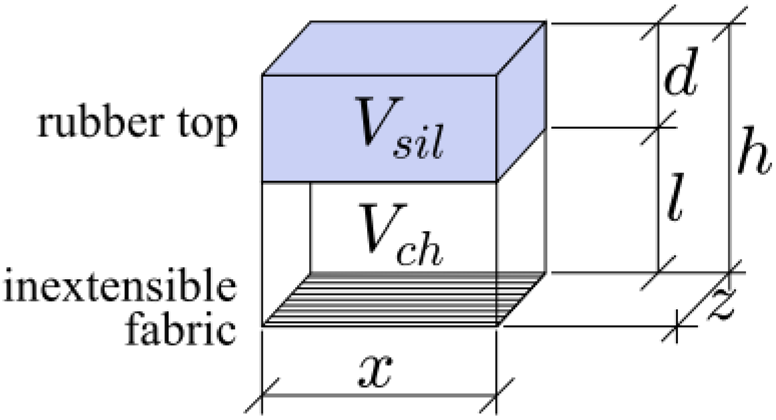

Fig. 6 (Cross-Section of a Pneu-Flex Actuator)

Authors from another paper observed that the original pneuflex design had the inlet tubing on the side which drastically reduced the mass flow rate of air that was allowed into the chamber and suggested insertion of the inlet tubing at the bottom of the actuator which drastically increased the inlet diameter to a quarter of an inch from a meagre 2mm. They also observed that the gage 50 polyester thread damaged the active layer it was wound around during pressurization and suggested the use of a wide ribbon threading instead of a polyester thread as an increase in area helped reduce stresses on the active layer. **[Fig. 7]**

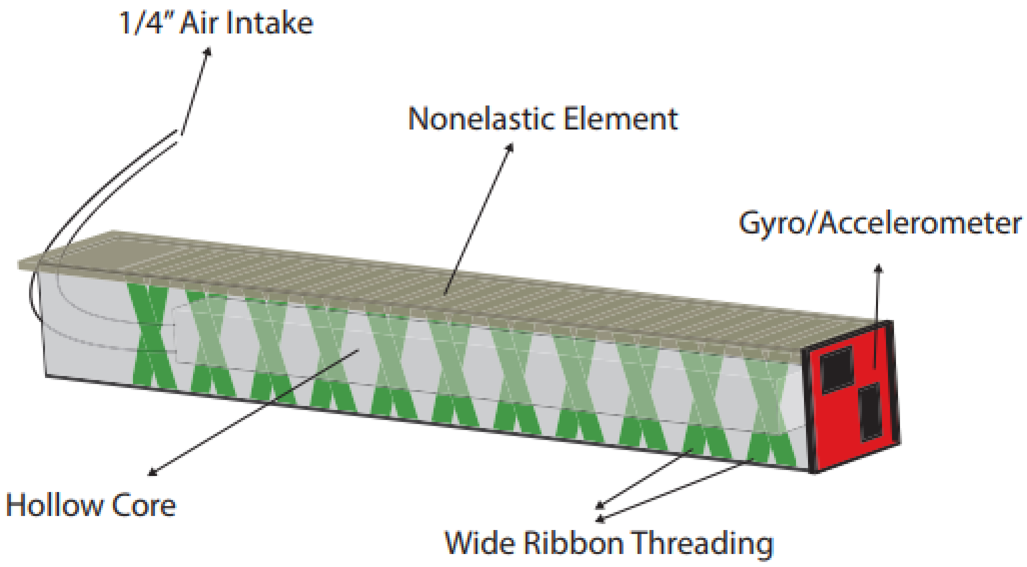

Fig. 7 (A proposed Pneuflex Design)

A clever design formulation was suggested by engineers at Harvard as well that worked upon the concept of Pneuflex actuators and suggested combining different deformation modes (linear and bending) to generate motion that very closely mimicked the human fingers and improved ergonomics. [24] **[Fig. 8 & Fig. 9]**

Our design takes heavy inspiration from this soft robotic glove. Albeit, there is a difference in the fluid used for pressurization. We will use air while the glove from Harvard used water. The *Elastosil M4601* required for developing hydro-actuators was expensive and unavailable at the time of procurement which is why we resorted to *Smooth On Dragon Skin 20* which has a Young's Modulus of 300 KPa while *Elastosil M4601* had a Young's Modulus of 600KPa.

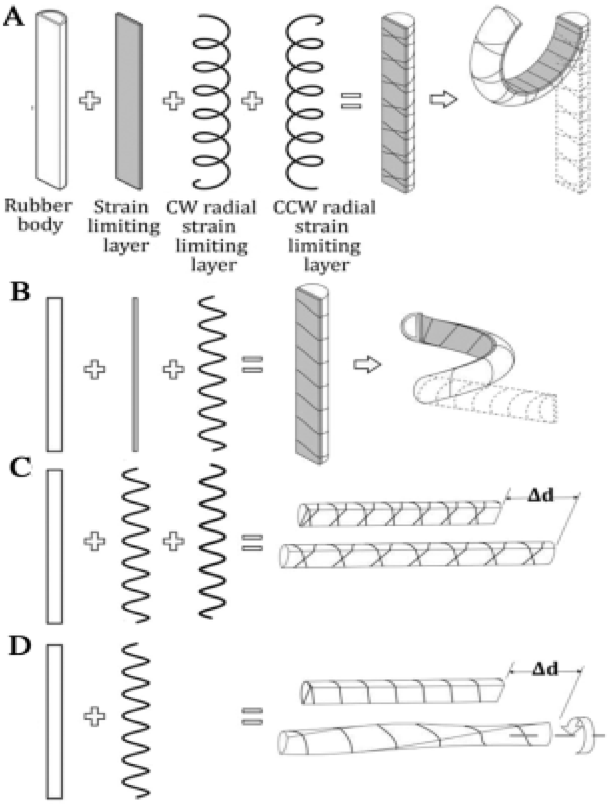

Fig. 8 (Deformation Modes of a PneuFlex Actuator)

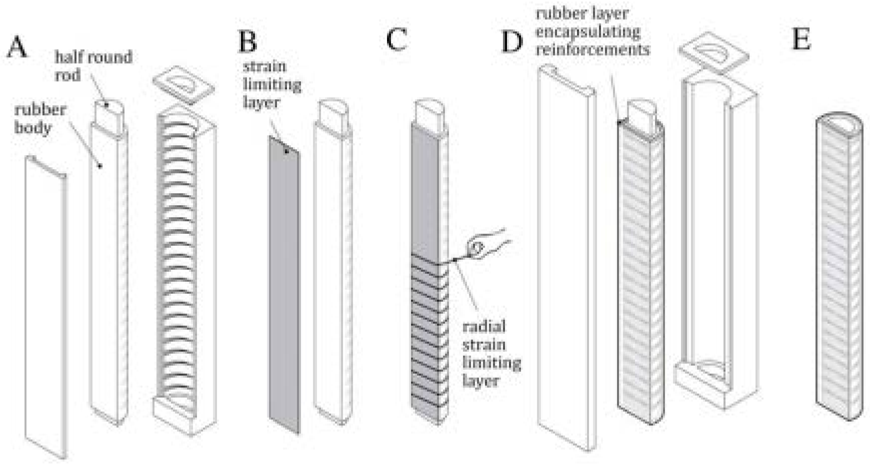

Fig. 9 (Threading of a PneuFlex Actuator)

Pneumatic Circuitry and Control Systems

For actuation and control of the actuators, development of pneumatic circuitry that provides variable pressures with reasonably low hysteresis and latency was crucial. The actuation by means of electromechanical valves also generates significant noise. [16]

It was realized that the best method of controlling the electromechanical valves was by means of PWM (Pulse Width Modulation). [19] The advantages of PWM included:

- Low size and cost
- Better response times
- Low hysteresis
- The system could be approximated as *linear* in certain operating regions which reduces the complexity of modeling

The pressure generated is a function of the duty cycle [**A1,(1)**]. The discrete application of pressure via high speed valves is non-smooth and generates noise. These problems can be catered for by the addition of a clever pneumatic LPF (low pass filter) [**A1,(2)**]. The LPF is added downstream of a high speed valve and consists of a LPF tank (eg. a syringe) and a pneumatic resistance (a porous plug into the output tube; eg. a pipe cleaner). **[Fig. 10]**

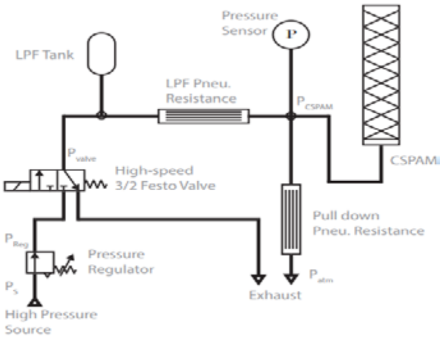

Fig. 10 (Pneumatic Circuitry)

The authors concluded that the overall control system comprised of two cascaded plants. An electrical circuit analog of the circuit was also drawn for clarity of explanation.

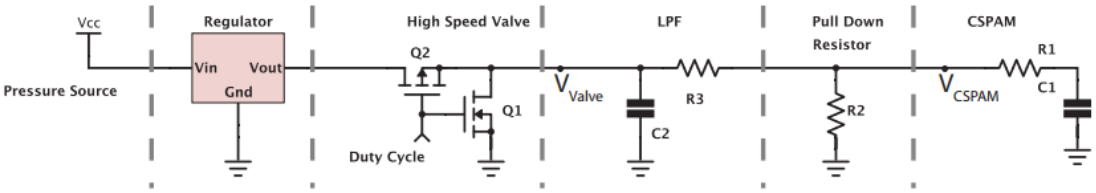

Fig.11 (Electro-Pneumatic Circuitry)

Compressor Sizing

The paper that we drew the greatest inspiration from [24] used water for pressurization and hence required a pump while our actuation was via air. Had we used a pump, it would have been convenient for mounting the pump and the water in a waist-belt pack **[Fig. 12]** as suggested for the Harvard soft robotic exo glove. For pressurizing air, a compressor is required and most literature that we went through mentioned actuation pressures in the ranges of 2-4 bars (absolute). We will procure a handy, portable and cheap compressor of that size. The compressor may be mounted on the wheelchair of the quadriplegic individual as compressors are generally heavy and unwieldy and cannot be mounted in a waist-belt like a pump.

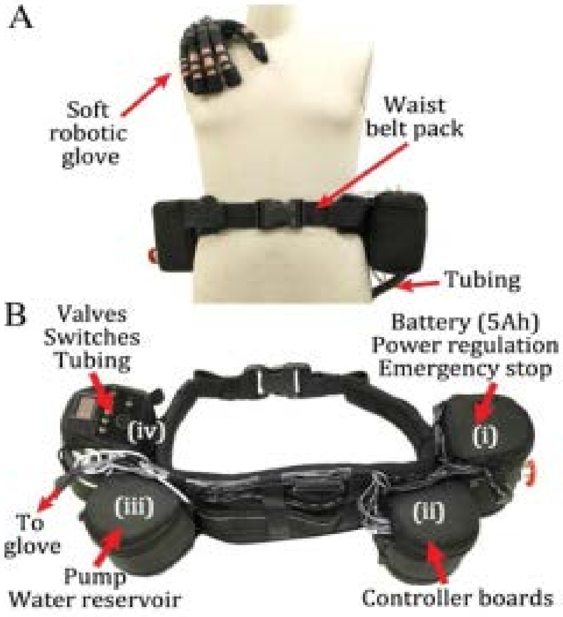

Fig. 12 (A Proposed Belt Design)

EEG vs EMG vs FNIRS: Selection of control inputs

Patients suffering from strokes or similar nervous system ailments have little to no electrical activity in the nerves which is needed for actuation of the hands and fingers. Numerous biomedical advancements have led to different techniques to extract electrical signals from the body and/or skin and map it to the desired hand motions according to user-set combinations. Electrical signals from the hands cannot be directly used since there is no space available other than for the actuators and glove. Thus, we will have to resort to using the forearms for this purpose, among other options such as the feet, biceps and shoulders etc. This is because much of the hand's actuation is carried out by tendons connected to the muscles in the forearm.

- Electromyography (EMG) is a non-invasive technique of assessing and extracting electrical activity usually used to assess the health of muscles and nerve cells. Electrodes are used to translate these electrical signals into numeric values or graphs. A Myo-Band available in RISE lab will be used for this purpose as it enables ease of use, functionality and results.

- Electroencephalography (EEG) is an invasive method which is used to find and diagnose problems in electrical activity of the brain. It tracks and records brain wave patterns through electrodes placed in the scalp. The electrodes are connected to an amplifier and EEG recording machine. This technique is the least suitable solely due to its invasive nature. Apart from that, it is unfeasible to have to set it up every time for a trial and certainly impractical to have it in place for extended periods of time.

- Functional Near-Infrared Spectroscopy (FNIRS) is a non-invasive neuroimaging technology that allows safe, portable and low-cost monitoring of brain activity. By measuring changes in near-infrared light, it allows researchers to monitor blood flow in the front part of the brain. The sensor is attached to the person's forehead and can be directly connected to a computer. This method is certainly more appropriate than EEG but is yet trumped by EMG in the sense of practicality and track record.

The availability, feasibility, robustness and non-invasive nature of EMG make it the best contender among the three most popular and proven techniques of extracting electrical and brain activity that is needed for actuating the pneumatic actuators. Certain prescribed gestures and hand configurations in ADL will be replicated by the patient; the corresponding EMG signals will be filtered and then normalized according to the maximum and minimum voltage values.

Binary control vs variable control

The actuator valves can either be controlled with a binary control algorithm or a variable control algorithm. The binary control algorithm's output to the pneumatic valves is either on or off. This output binary value is determined by the EMG signal; when it was above a specified threshold value, it is on and when it is below, it is off.

The variable control algorithm can be used to control the valves to a more variable degree. This can be accomplished with a simple proportional controller employing the filtered EMG signal.

[32] shows that the binary control algorithm performs faster execution of the pinching motions for a set of objects as compared to the variable control algorithm **[Fig. 13]**. For this reason, binary control algorithm for the pneumatic valves is chosen.

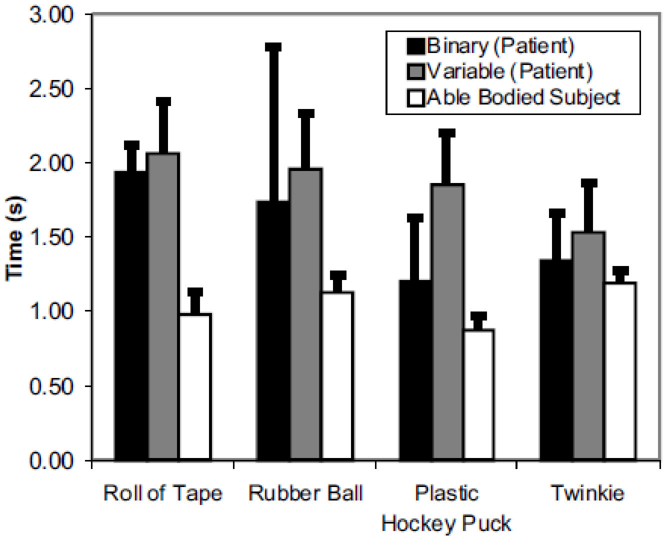

Fig. 13 (Variable vs. Binary Input Results)

CHAPTER 3: METHODOLOGY

Given our problem statement, our first objective was to choose between conventional mechanisms or soft robotics. Although conventional mechanisms seemed promising especially after seeing our predecessors at RISE Lab do a fine job with their exo-hand, we chose soft robotics as per our sound reasoning for reasons mentioned formerly (refer to Introduction and Literature Review for an in depth contrast).

We take heavy inspiration from the soft-robotic glove for combined assistance and rehabilitation. [24] 3D modeling of our soft robotic Pneuflex for deformation and elongation are nearly impossible to accomplish via software. The concept of what we aspire to achieve is shown. **[Fig. 14]**

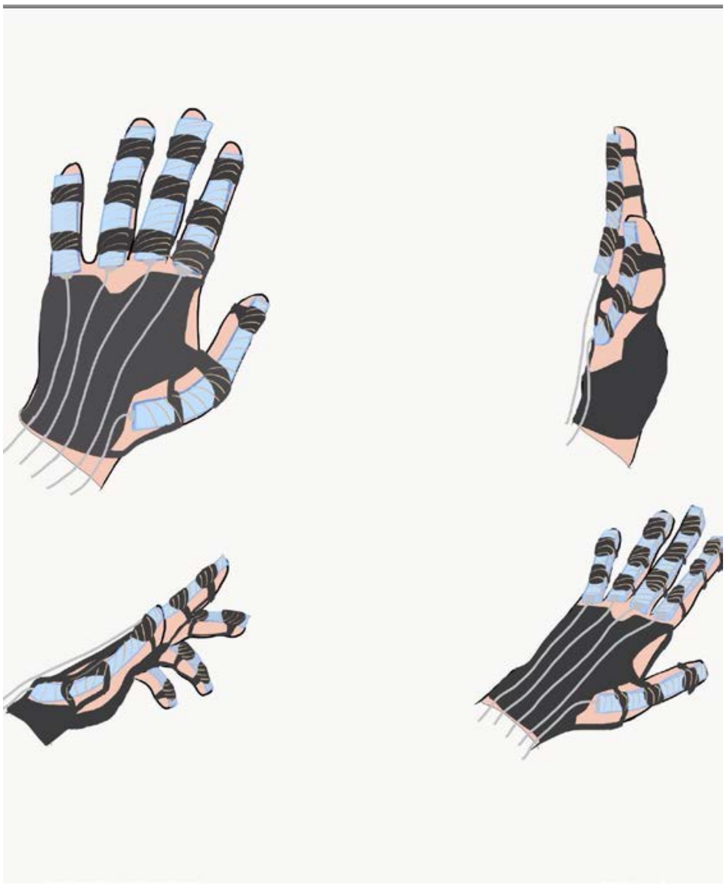

Fig.14 (Our Concept Design)

Distal Forces

Before the development of any prototypes or models, it was essential that the range of motion of the hand was studied. Empirical values were taken from an EM sensor analysis on the 5 fingers [24]. A healthy human hand can generate grip forces of up to 300N and 450N for females and males, respectively. [26, 27] However for impaired patients, grip strengths can be as low as zero and it was realized that the actuators do not necessarily have to generate the maximum force values for proper functioning. A study by Matheus et al. observed grasping and manipulating forces for basic ADL (e.g. grasping a fruit or a glass of water or picking up the keys or stirring) indicated that everyday objects do not weigh more than 1500 grams. Therefore, a conservative force estimate with a **friction coefficient of 0.255** [31] would require each distal end to exert a tip force of around **7.3 N**.

We calculated the tip forces using a Newton meter and attaching the end of the spring to the tip of the actuator. The actuator was then pressurized up to 70 KPa (Reading taken from the pressure gage on compressor) and reading from the newton meter was taken to be around almost **7.75 N** which is slightly greater than the minimum required distal force of **7.3 N** to perform basic functions of life.

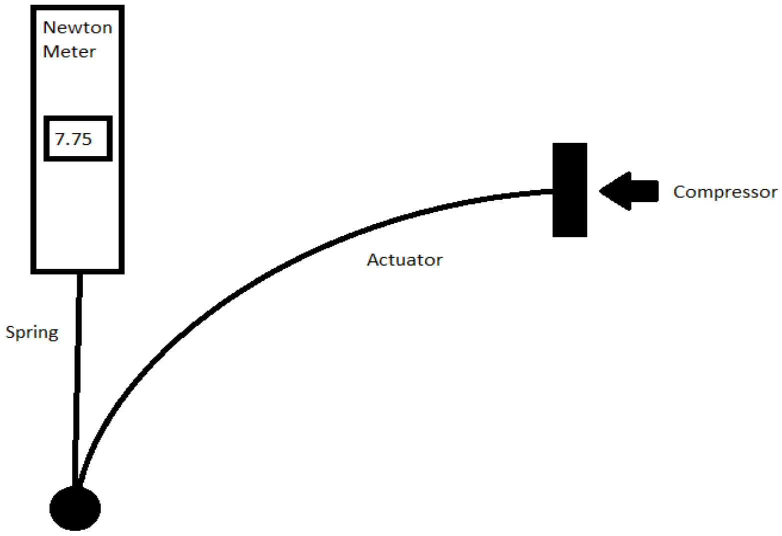

Fig. 15 (An Appropriate Measurement Technique for Tip Forces)

For rehabilitative purposes, a hand’s open/close frequency of around 30 per minute was a reasonable estimate.

Material Procurement

For the development of the PneuFlex Actuators, a list of materials was required which is as follows:

- A suitable pourable silicone that cures at room temperature was required for the general actuator body. We shortlisted our chemicals to two contenders namely ***Elastosil M4601*** by WackerChemie AG [29] and ***Smooth On Dragon Skin 20*** [30]. *Due to ease in procurement, the Smooth On Dragon Skin 20 was used.* ***Elastosil*** has a higher tensile strength and can be used to build actuators that can be pressurized by water and it was desirable but procurement was hard as Wacker Chemie, even within Germany, only deals with the industry and it was unavailable in the limited quantity that we required. ***Smooth On Dragon Skin 20*** is a pourable silicone as well that cures at room temperature with a reasonable tensile strength of 3800 kPa. It can be used to make actuators pressurized by air. This was available on Amazon and we had it delivered to Germany and it shall reach us by the 30th of January (fingers crossed).

- A polyester thread of gage 50 or a ribbon that winds around the actuator to resist radial deformation

- A silicone sealant (RTV) to seal the hole where the air tubing is inserted into the actuator chamber.

- A 3D printed mold of the geometry of the actuator. A CAD model was designed and dimensioned through Solidworks. The design is completely our own and SLT files may be requested from the authors of this work.

- 3D printing facilities are available within SMME. Although a mold made from ABS was desirable but due to ease of availability of PLA, we printed our mold with PLA once permission from relevant authorities was granted.

- A vacuum chamber is essential for the casting of the silicone as it ensures that all air bubbles within the silicone in the mold are exhausted and this guarantees a quality mold finish. However, under dire and exigent circumstances, it may be possible to cast an actuator by means of ensuring that the mold is overfilled so that there is a reduced likelihood of air bubbles that, otherwise, compromise structural integrity.

- Additionally, plastic tubing was inserted by means of piercing through the rear of the actuators.

Fig. 16 (Our mold and a sample silicone casting)

Our fabrication method follows the tutorial. [2] (Courtesy of TU Berlin). Albeit, some necessary modifications to the casting process were made as our mold design differed from theirs.

Mathematical Model

The mathematical model developed for the purpose of this project is aimed to be simple yet also be able to capture the essence of the phenomenon at play.

As per the dictates of energy conservation:

$$\mathbf{d}W_{in} = \mathbf{d}W_{out} \qquad (1)$$

It can also be realized that:

$$\mathbf{d}W_{in} = (P_{\mathbf{in}} - P_{\mathbf{atm}})\mathbf{dV} \qquad (2)$$

$$\mathbf{d}W_{out} = -\,\boldsymbol{\tau}\mathbf{d}\theta \qquad (3)$$

Substituting (2) and (3) into (1):

$$(P_{\mathbf{in}} - P_{\mathbf{atm}})\mathbf{dV} = -\,\boldsymbol{\tau}\mathbf{d}\theta$$

It must be noted:

- that $P_{\mathbf{atm}}$ is a constant value.(101.325KPa)
- **d**V is also constant since this is dependent upon the predetermined geometry of the actuator. (not accounting for the deformation)

A corollary to this model is that the **τ and** θ values are solely a function of $P_{\mathbf{in}}$**.** This drastically reduces the complexity of our mathematical model and we hope to prove it empirically as well.

Control System Modeling

An Arduino, paired up with an NC relay board was used to turn the valves on/off in a binary fashion. All 5 valves were fed power through the external 12V power source with each having a relay switch in between. This relay board was fed “LOW” and “HIGH” signals according to the finger actuation and that resulted in two states of the valve, full open and full closed respectively.

PWM was tried but it did not work with the actuators because the air was not quick enough to pressurize the actuators in tandem with the PWM frequency. For that to work better, a much higher air pressure would be required with minimal actuator cavity.

CHAPTER 4: RESULTS AND DISCUSSION

Due to soft robotics being a relatively fledgling of a field, we must reiterate that our final project displayed at our open house was just another further iteration in the painstaking process of experimentation and development and there is immense room for improvement and perfection is yet to be achieved.

Results on Mold Geometry and Actuator Design Iteration

We initially proceeded to try and cast actuators based on the mold files available on the TU Berlin DIY but the geometry seemed to be delicate and improper for our particular design. We, then proceeded to design our own actuator based on a cubic spline that had an impressive anthropomorphic factor which made the design all the more ergonomic. The first iteration was casted but structural flaws existed, specifically at proximal base of the actuator which had a relatively thin cross-sectional profile. This resulted in an insufficient strength of the silicone in the region to resist radial deformation, which is pivotal to the functional “bend” of our actuators. The radial expansion not only compromised functionality but also resulted in fatigue stresses that eventually led to the actuators bursting in that region.

The problem is illustrated below:

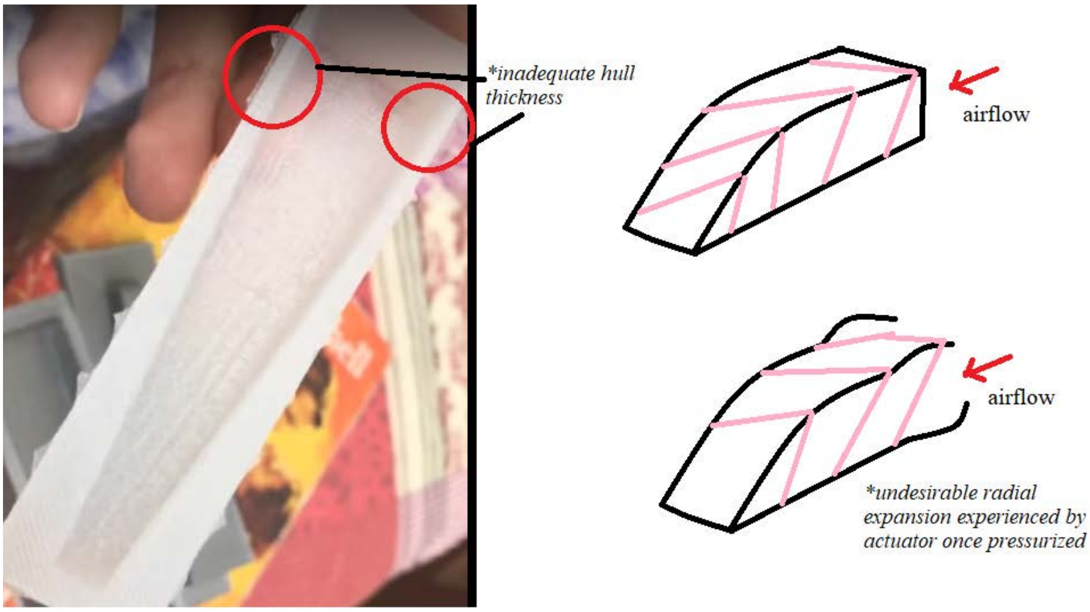

Fig. 17 (An Illustration of the Initial Design Flaws)

The second mold iteration catered to this with a thicker hull thickness throughout and the overall structural integrity as well as functionality were drastically improved. But it must be noted that our specific design, albeit anthropomorphic, may be improved and alternate designs may be explored specifically semi-circular prismatic shapes as they are expected to demonstrate better structural integrity.

Bend Angles

EM tracking sensors were placed along the bottom face of the soft actuators for the index finger to capture its behavior and angles. Actuators were then pressurized to achieve maximum bend angle while observing the integrity of the material (Dragonskin 20). Pressures up to 70 kPa (Reading taken from the pressure gage on compressor) were achieved, further pressure could be provided however due to significant radial expansion beyond this point, such actions were avoided.

Angles achieved are shown below:

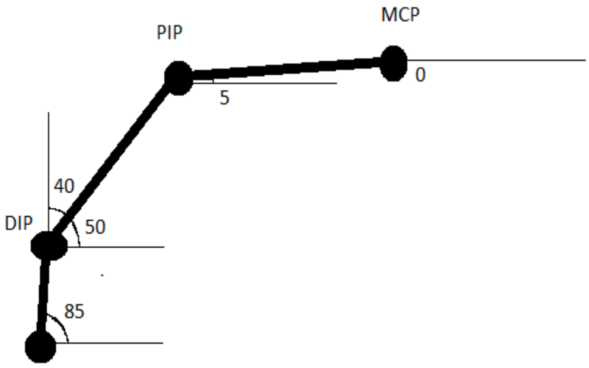

Fig. 18, Fig. 19 (Real-time Bend Angles)

Grips and Relevant Forces

Through our glove, we were able to achieve two primary functions:

1) Rehabilitative opening and closing of the hand
2) A series of grips that promise ADL potential

Different grips were tried and are demonstrated below:

Fig. 20 (A wide hand grasp of a container)

Fig. 21 (A diagonal volar grip)

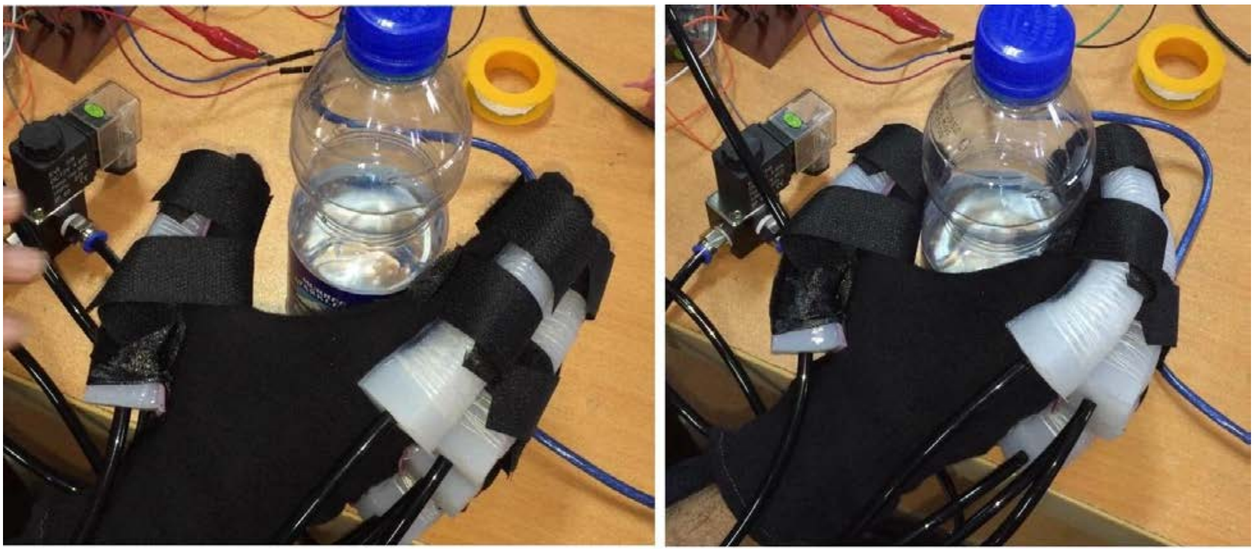

Fig. 22 (A grasp)

Fig. 23 (Opposing Grip)

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

The design was aimed at restoring motor functions of an impaired hand by providing assistance in performing ADL and at home rehabilitation. The proposed design is planted on the dorsal side of the hand thus allowing the complete and uninhibited interaction with the everyday objects that the user might come across.

The pneumatic circuitry proved unwieldy for powering the pneumatic glove because of the leakages associated with the pneumatic valves and the subsequent pressure drop at distributor block. The available solenoid valves in the market proved to be slower in response than the desired PWM on/off cycling frequency; this resulted in the air muscles not being able to sustain the current pressure and hence the current position by means of rapid on/off action. However the extreme movements proved promising in that we were able to test out multiple hand grip/grab orientations as associated with ADL. Multiple objects were used to test the grips. Exceeding values of force greater than 8 N were not achieved because a higher pressure would have ruptured the feeble pneumatic muscles. Therefore, the *geometric properties* of the actuators proved to be the *dominant controlling factor* in the design. For forces and pressures of higher magnitudes, the following should be investigated:

- A complete ‘zero’ kPa vacuum casting of the silicone actuators to ensure *perfect degassing* of the silicone to generate actuators without air-bubbles that compromise structural integrity and stress concentrations
- A *stronger* polymer thread ‘*winding*’ around the actuators to minimize torsional and axial strains
- Solenoid valves with *higher* switching frequency
- Actuators with *thicker* side walls to sustain higher pressures and hence, generate *greater* forces

The future works on the concept can focus on improving the design by making it more compact and lightweight. A better control system can also be developed to improve the functionality and increase the DOF available to the user. More developments can be made to increase the force generation at the distal tips of the hand. This could cater for the increased stiffness of the fingers which is observed in cases of paralysis. Tests can be carried out to quantify the robustness and the fatigue life of these actuators under standardized operation.

In addition to this, a haptic feedback can be introduced without making the system bulky which could improve the sensitivity of the system and provide better and a more effective operation of the hand. This would also enable the user to regulate the forces in a more effective manner.

Since the compressors, valves and Arduino are powered by external power source, a sufficiently powerful battery can be introduced in the design to reduce dependence but portability will still be an issue because small, handheld compressors are not available.

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A1: Definitions of Relevant Terms

1. **Duty Cycle:** The fraction of a period in which a system/signal is active. It is commonly expressed as a ratio or percentage of the period. [8]
2. **Low Pass Filter:** A filter that passes signals only with a frequency lower than a certain reference cutoff value. This aids in eliminating noise. It also attenuates signals with values greater than the cutoff frequency. [17]
3. **Atmospheric Pressure:** The pressure of atmospheric air exerted on the surface of the Earth.