MOSAR: A Soft-Assistive Mobilizer for Upper Limb Active Use and Rehabilitation

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been published in whole or in part for consideration for any other degree or qualification in this, or any other University.

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Abstract

In this study, a soft assisted mobilizer called MOSAR from (Mobilizador Suave de Asistencia y Rehabilitación) for upper limb rehabilitation was developed for a 11 years old child with right paretic side. The mobilizer provides a new therapeutic approach to augment his upper limb active use and rehabilitation, by means of exerting elbow (flexion-extension), forearm (pronation-supination) and (flexion-extension along with ulnar-radial deviations) at the wrist. Preliminarily, the design concept of the soft mobilizer was developed through Reverse Engineering of his upper limb: first casting model, silicone model, and later computational model were obtained by 3D scan, which was the parameterized reference for MOSAR development. Then, the manufacture of fabric inflatable soft actuators for driving the MOSAR system were carried out. Lastly, a law close loop control for the inflation-deflation process was implemented to validate FISAs performance. The results demonstrated the feasibility and effectiveness of the FISAs for being a functional tool for upper limb rehabilitation protocols by achieving those previous target motions similar to the range of motion (ROM) of a healthy person or being used in other applications.

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Table 1 Abbreviations

ADL:	Activities of Daily Living
AT:	Assitance Task
AAM:	Active Assistance Mode
ASM:	Assistive Assistance Mode
CAD:	Computer Aided Design
CCP:	Cerebral Child Palsy
CLC:	Close Loop Controller
CP:	Cerebral Palsy
CPD:	Close Palm Design
DOF:	Degrees of Freedom
JCR:	Journal Citation Report
EFW:	Elbow-Forearm-Wrist
EMG:	Electromeography
FISAs:	Fabric Inflatable Soft Actuators
FRESAs:	Fiber Reinforced Elastomer Soft Actuators
OLC:	Open Loop Controler
OPD:	Open Palm Design
PAM:	Pneumatic Artificial Muscles
PD:	Proportional-Derivative Controller
PICs:	Pneumatic Inflatable Chambers
PMA:	Passive Mode Assistance
ROM:	Range of Motion
RT:	Rehabilitation Tasks
RTP:	Repetetive Task Practice
SCI:	Spinal Cord Injury
SEG:	Sof Exo Gloves
SPAs:	Sof Pneumatic Actuators
SWD:	Soft Wearable Devices
SR:	Soft Robots
TPU:	Thermoplastic Polyurethane
UI:	Usability Index

Chapter 1

Introduction

People with upper limb disabilities present restrict mobility and can not accomplished basic activities of daily living (ADL) by themselves. Therefore, the evolution of rigid and heavy exoskeletons to overcome upper limb dysfunctions has created a new direction of technological systems that provide safe human-robot interactions under a novel and alternative approach of Soft Robotics.

For example, soft wearable devices (SWD) have emerged as an alternative rehabilitation therapy and assistance for stroke survivors, people with cerebral palsy (CP) or spinal cord injures (SCI) [1]. The SWD for upper limb rehabilitation include soft exo-suits, soft exo-sleeves and soft exo-gloves (SEG) which all of them combine conventional therapy with worn technology to recover motor functions [2].

Several soft wearable devices for hand motions have been proposed for objects manipulation, whereby materials, actuation and control are the key factors during their design for their correct operation [3]. However, SEG are not able to exert mobilizations on arm, forearm and wrist muscles, which are crucial prior to start a rehabilitation at the distal region.

To overcome those problems, this project seeks to co-assist in the upper limb rehabilitation process of a hemiplegic child with minimal use of his right paretic side. This need will be satisfied with the development of a soft pneumatic assistive mobilizer with 4 degrees of freedom (DOF) that allows to contribute on a new therapeutic approach to exert and augment his impaired limb use.

Hence, a methodology based on Reverse Engineering principles was employed for the design concept: first casting model, then silicone model and finally computational model were obtained by 3d scan, which was the parameterized reference for MOSAR development. Unlike, the other methodologies that were reviewed on the State of Art and Technique, this research can systematically foster the active assistance mode and rehabilitation of a custom design for a particular solution, but can be generalized for any other anatomy.

Overall, Chapter 2 reviews the theoretical framework, Chapter 3 is related to the State of the Art and Technique about SWD for neuromuscular therapy and assistance to overcome upper limb and hand dysfunctions. In Chapter 4, a methodology was developed to provide useful guidelines for the MOSAR design, fabrication and control. Chapter 5 encompass the results and the products obtained from this research. Lastly, MOSAR effectiveness discussion along with conclusion and future work are reported in Chapter 6.

1.1 Project Definition

In medical applications, Soft Robotics has excelled as a potential area to overcome and ease rehabilitation or assistance protocols. Soft Robots are wearable devices that seek to be a natural extension of the body through smart materials and friendly actuation [4]. They are classified depending on their function: a) **rehabilitation** for exerting physical therapy and b) **assistance** for manipulation which is focused on grasping, lifting and pinching tasks [5].

This project arises from the need of a child of 11 years old with Hemiplegia on his right paretic side due to a perinatal stroke. Thus, Neurologist and Physical Therapist medical appreciations were made along with an surface electromyography (sEMG) test to evaluate his clinical condition. It was reported that even though he has problems for walking, he is able to drag his leg. However, high levels of Spastic Hypertonia occur at his upper limb because of his minimal use and clenched fist deformity.

When the problem was analyzed, the solution deals with the characteristics of design. There were two options: a) to mobilize the elbow-forearm-wrist (EFW) region or b) execute hand manipulation tasks. According to the results, elbow and wrist joints were identified as a critical joints where rehabilitation was urgently needed to prevent stiffness, stop spasticity and improve hand mobility with a wide ROM since he can grab objects with low precision and open-close his fist.

It was concluded that the impairment was more severe at the proximal region, because the muscles that move the distal segment are originated at this point. Thus, it was not feasible to start a rehabilitation process at the distal segment, if the proximal neither has mobility. It was primary to focus on mobilizing the EFW region to increase the active use and ROM of his proximal segment prior to assist him in manipulation tasks.

This research seeked to meet the priority need of the patient through the MOSAR development which provides a new therapeutic approach aimed at augmenting his upper limb active use, by means of a modular configuration to exert flexion-extension, pronation-supiantion on the arm and forearm respectively, along with flexion-extension and ulnar-radial deviations on his wrist. All these motions are crucial for regaining straight and decreasing spasticity at FW, otherwise atrophy and joint stiffness can not be prevented.

It is important to promote the active use of the affected upper extremity, in order to overcome the learned non-use of it and increase the usability index (UI) to improve the mobility displacements with a higher ROM at his work space. It is expected that once the EFW has been rehabilitated, the hand and phalanges will be easier to stimulate for manipulating and grasping tasks.

1.2 Justification

In the State of the Art and Technique several upper limb soft wearable devices have reported related to people with a CP or SCI due to the number of victims with those motor deficits continue to increase, worldwide more than 15 million are affected each year [6]. Unfortunately, they do not have the ability to execute motions at the proximal region, they are oriented at the distal segment rehabilitation and assistance in manipulation tasks.

Additionally, therapist availability and clinical facilities are struggling to provide optimal rehabilitation training and the cost of these health services has grown at the same time [7]. Particularly, in Mexico there is a lack of available and affordable Soft Robots that meet hemiplegic children demands. Unfortunately, this technology services are offered in other countries at high costs and the devices are most oriented to elder people [8, 9].

All those circumstances have motivated this research to propose a new methodological approach for the design and development of the MOSAR, a soft pneumatic assistive mobilizer for upper limb active use and rehabilitation which is focused on elbow, forearm and wrist mobility.

The current goal is to co-assist children with hemiplegia in their rehabilitation process, avoid heavy repetitive task practicing (RPT) and ease therapist job, but also look for future hand assistance tasks with wide ROM. MOSAR represents an alternative and cost effective solution applied to a particular case, but can be generalized to overcome upper limb motor disabilities. It meets with the evolution of available systems, both in technological design trends, as well as in methodological approaches.

During the process of this research, few methodologies for upper limb rehabilitation at the proximal region that use Soft Robotics were found. Even less that use the active motion guidance, and none that combines rehabilitation and foster active use of the impaired limb using a modular system, which all justifies the reason for being of the present work.

1.3 Objective

To develop a soft pneumatic mobilizer for upper limb active use and rehabilitation to be applied on a child with right paretic side, by means of exerting elbow (flexion-extension), forearm (pronation-supination) and (flexion-extension along with ulnar-radial deviations) at the wrist.

1.3.1 Specific Objectives

- To define the design criteria and constraints of the soft mobilizer.
- To design a soft mobilizer based on the upper limb characterization of the patient using Reverse Engineering.
- To manufacture and control the soft pneumatic actuators for driving the soft mobilizer.
- To do experimental test and validate the soft pneumatic actuators on a dummy limb.

1.4 Hypothesis

A soft assistive mobilizer called MOSAR will be able to achieve upper limb motions at elbow, forearm and wrist using fabric inflatable soft actuators.

1.5 Scope and Limitations

1.5.1 Scope

- To create a design methodological approach to develop any soft wearable device for rehabilitation or assistance tasks which will be applied for the MOSAR system development.
- To manufacture the MOSAR actuators with the anthropometric dimensions of a child between 10-12 years.
- To control and do computer simulations on the the soft actuators for their validation.
- To exert elbow, forearm and wrist motions using a dummy hand from the patient.

1.5.2 Limitations

- A detail or optimal design of the MOSAR is not priority.
- MOSAR assessment on the case of study is not included.
- The mathematical model of the MOSAR is not included.
- Hand rehabilitation or manipulation tasks are not considered.

1.6 Thesis Structure

This thesis is organized as follows: Chapter 1 presents the introduction, motivation and the proposal for this project. Basically, the bases of a soft assistive mobilizer called MOSAR for upper limb active use and rehabilitation are established. In Chapter 2, the theoretical background and concepts related to this research are summarized. Chapter 3 reports the literature of soft wearable devices for upper limb rehabilitation and also includes soft exo-gloves devices for hand rehabilitation. Moreover, in Chapter 4, a design methodology for the development of soft wearable devices applied to the MOSAR case is provided. This methodology summarizes the manufacturing process and control of the soft pneumatic actuators of the MOSAR. Chapter 5 presents the results obtained from this research. Finally, conclusion and future work are discussed at the end of this document.

Chapter 2

Theoretical Background

2.1 Hemiplegia in Children

A CCP (Cerebral Child Palsy) is a neurological disorder caused by a lesion of an immature brain during fetal development, childbirth or infant growth [10]. This cerebrovascular accident mostly occurs in multiple birth and premature children since it is associated to the lack of oxygen supply, blood obstructions, perinatal strokes, infections and other complications between 1-28 weeks of gestation or on the first month of age [11].

Cerebral Palsy accidents are classified depending on how many structures of the body are paralyzed. Monoplegic patients have only one upper limb affected while people with Diplegia have upper or lower limbs paralyzed and quadriplegic patients have their whole body paralyzed. Regarding, patients diagnosed with Hemiplegia have one half of the body paralyzed, either right or left [12]. This classification is shown in Figure 2.1.

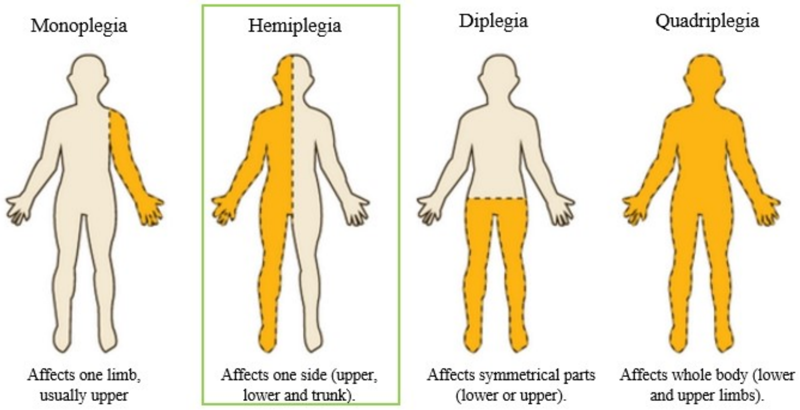


Fig. 2.1 Types of a Cerebral Palsy

In addition to former conditions, other consequences occur such as motor and sensory deficits, seizure, intellectual and cognitive disabilities, along with communication skills and behavior problems are associated to this condition [13]. Unfortunately, those dysfunctions are linked to a muscle skeletal impairment such as Spasticity, Dyskinesia, Ataxia or Mixed which let to abnormal muscle tone, weakness, lost of motor control, poor mobility, balance and dexterity [14].

Specifically, Hemiplegia is neuronal pathology however, it is reflected on the muscular system due to the misalignments between nervous tracts and muscles signals. Moreover, the limitations in motor areas which are responsible for regulating strength and tonicity of the body produce Spasticity on the muscles [15]. Therefore, stiffness and tightness are caused by continuous contractions that appear in specific muscles that affect coordination and gait of 12 million people around the world [16].

Mostly, postural stability is less affected than upper limbs one, since patients have more serious control of their legs [17]. However, upper limbs are weaker than the lower due to less use and high Spasticity levels.

Patients commonly present rigid and low harmonic movements occasioned by the excess of muscular tension; whereby joints flexion is an achievable movement but, not extension motions where patients show an abnormal resistance to protract them [18].

The anatomy of upper limbs are characterized by four postures that can be illustrated in Figure 2.2. **1)** Shoulder is depressed and extended. **2)** Arm is adducted to the trunk and internally rotated. **3)** Elbow is flexed and forearm is pronated as a natural positions. **4)** Wrist and fingers are over flexed, which is called clenched fist since the thumb is sunk in the palm [19].

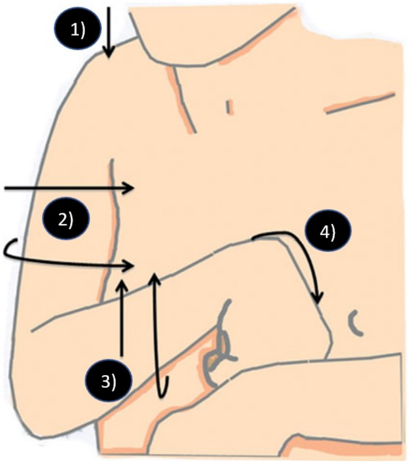


Fig. 2.2 Hemiplegic upper limb Posture modify from [19]

Another issues related to Spasticity are Hypertonia when the muscles are over flexed or present an abnormal increase of muscle tone [20]. This condition leads to the loss of bones motion and their functions due to an involuntary joint stiffness to the muscle movement [21].

In Mexico, the statistics reveal that 22% of children suffer from a Cerebral Palsy, 45% have Hemiplegia and 70% have severe damage at the upper limbs [22]. This means, children with this pathology are able to walk, but have residual ability to interact with their environment due to limited work area.

For example, eating and drinking are monotonous and simple actions of everyday life, nevertheless those vital tasks represent a tough challenge for children with Hemiplegia since they have severe difficulties to accomplish them. Also, children are limited on other activities for example playing, self-caring, dressing, writing, and drawing, etc [14].

2.2 Upper Limb Anatomy

The upper limb in the human body is composed by four segments: scapular waist, arm, forearm and hand which all are fixed to the upper part of the trunk [23]. The main functions of this upper extremity are related to perform manipulation and holding tasks in a proper work area. Figure 2.3 shows the regions in regards to the bones proximity from the torso-shoulder: ***a) proximal*** (clavicle, shoulder and humerus bones) and ***b) distal*** (ulna, radius, carpals, metacarpals, and phalanges) [10].

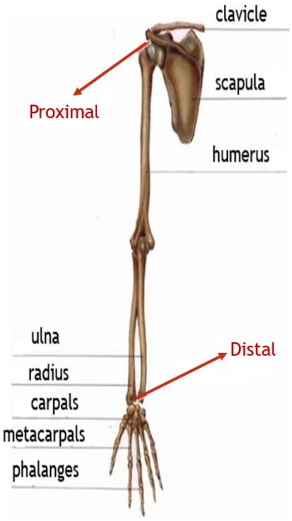


Fig. 2.3 Upper limb regions and their bones
Modified from [10]

Typical restrictions on children with Hemiplegia are *a)* lateral extensions difficulties to separate the arm with trunk, *b)* restricted rotations to make outward turns *c)* bending angles between elbow-wrist, *d)* swings or wrist twists with the palm of the hand up and open it [23].

Furthermore, the muscles that move a distal region are originated on the proximal segment. Therefore, is not feasible to start a rehabilitation process at the distal region, if the proximal components do not have mobility.

This project was focused on exerting the 4 functional motions of the elbow, forearm and wrist. The mobilizations are flexion-extension on the elbow, pronation-supination on the forearm and flexion-extension along with ulnar-radial deviations on the wrist. These 4 DOF (Degrees of Freedom) are necessary for rehabilitating the proximal region to separate the upper limb from the trunk, prior to think about achieving a manipulation task at the distal segment.

Figure 2.4 shows the muscles that are involved on previous joints motions. They include biceps-triceps on the arm, supinator-pronator on the forearm, along with flexor-extensor, carpi radials and carpi ulnar on the wrist.

All these motions are crucial for regaining straight and decreasing Spasticity, otherwise atrophy and joint stiffness can not be prevented. However, upper limb characterization turns difficult to emulate because each of their limbs have separate motions to their muscles, hence the number of DOF is proportional to the number of joints [24].

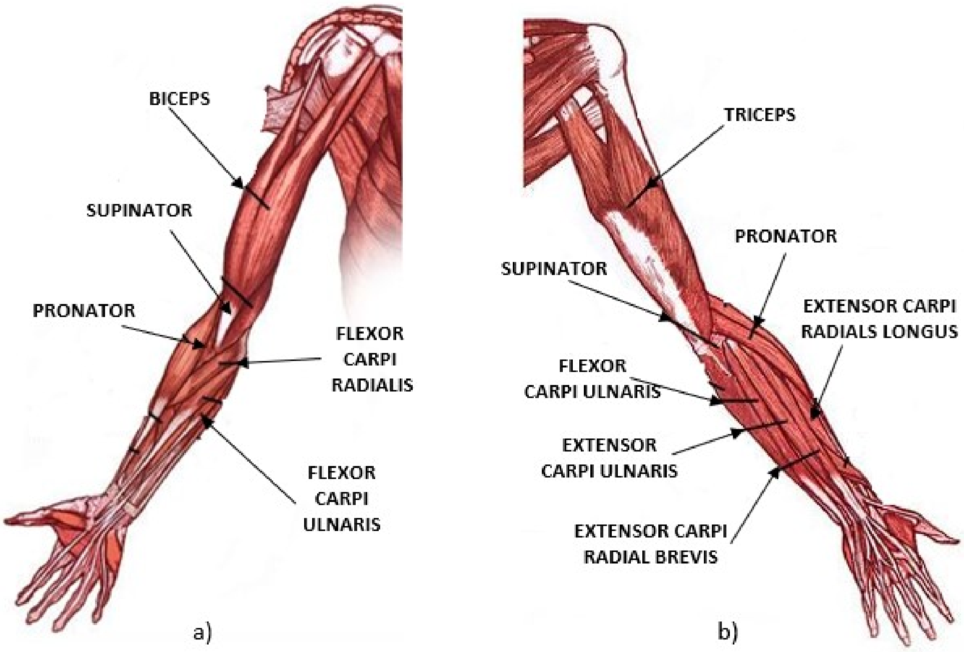


Fig. 2.4 Upper limb muscles a) Anterior superfical view b) Posterior superficial view Modified from [25]

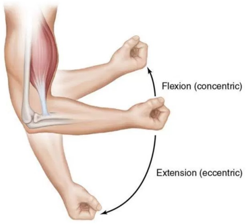
2.3 Range of Motion (ROM)

Human body is perfectly designed to perform many actions at different positions in appropriated work spaces thanks to joints mobility which can be measured by their full or partial ROM (Range of Motion) [26].

The full ROM is the natural anatomical perimeter of a particular joint [27]. However, people with upper limb motor dysfunctions have a limited ROM, so their joints mobility is measured through their FROM (Functional Range of Motion) [23].

Table 2.1 exemplifies each anatomical motion regarding to the limbs, type of motion, DOF, joint, muscle and natural ROM .

Table 2.1 Upper Limb Anatomical Features

Limb	Mobilization	DOF	Joint	Figure	Muscle	ROM
Arm	Flexion	1	Elbow		Biceps	180°
	Extension				Triceps	0°
	Pronation	1	Forearm		Pronator	80°
	Supination				Supinator	80°
Hand	Flexion	1	Wrist		Flexor carpi radials	70°
	Extension				Flexor carpi ulnaris	80°
	Radial Deviations	1	Wrist		Extensor carpi radials	20°
	Ulnar Desviations				Extensor carpi ulnaris	30°

2.4 Hemiplegia Rehabilitation

It is well known that upper limb dysfunctions from a chronic neuronal disorder such as Hemiplegia cannot be cured. However, patients are undergone to physical and/or occupational therapy for partial motor recovery to improve motor function and increase their independence and self-esteem [28].

Children with this chronic condition, present joint stiffness and muscular atrophy, not only in the injured joint, but also in those of their proximity, so it is vital to slow down their progress. The lack of strength is due to lost motor function and coordination of muscle recruitment, that is to say the brain is injured, nevertheless the muscles and nerves are still functional; therefore, a rehabilitation routine is necessary to prevent futures risks or severe damage on the joints.

Therefore, a rehabilitation protocol to recover a certain functionality of the impaired limbs is imperative [29]. Moreover, the rehabilitation process should be limited and have specific duration with a specific objective, which aimed at allowing a person with deficiency to reach an optimal physical, mental and social level to provide a better quality of life [30].

A successful program predicts more free interactions among the patient and environment. Particularly, children must be encourage to develop new abilities that allow them to perform more independently ADL. Normally, Hemiplegia used to be controlled with conventional therapy, robot rigid therapy and recently Soft Robotics, all these approaches are discussed as follows.

2.5 Conventional Therapy

Conventional therapy focuses on passive rehabilitation. Therefore, the presence of a therapist is necessary for patient assistance during the execution of the routines. Nevertheless, some people require more than one therapist during the process, one immobilizes a region and the other mobilizes targeted joints [11]. This type of rehabilitation demands for family assistance who also execute heavy jobs among with therapist.

Usually, therapists work with people whose dysfunctions have left them severe joint stiffness, spasticity or null ROM. Therefore, patients feel pain and keeps rigid the impaired limb or in a certain position, which makes difficult to move the joints [31].

Current treatments for upper limb include physical exercises for instance stretching, bending and rotation motions around the axis of joints. However, these rehabilitation programs are labor intensive and high cost, since they require the assistance of a therapist, do repetitive task practice (RTP) and hours of exhaustive routines [32].

Normally, children with an effective rehabilitation program are able to overcome up to 60% depending on their own capabilities [29]. The plan is aimed to regain strength and coordination on targeted muscles and decrease the Spasticity, as well as Tonicity to increase the ROM of the affected limbs.

Nevertheless, the lack of therapists and their exhaustion affects the execution of movements, therefore the length of period, amount of repetitions and intensity should be improved during the rehabilitation therapy, in to reduce therapist job and achieve optimal routines.

2.6 Robot Therapy

The support of a robot during a rehabilitation process varies depending on the amount of aid that is provided by the system. There are five training modalities **a) passive**, **b) assistive**, **c) active-assistive**, **d) active** and **e) resistive** [33]. On resistive modality, the user achieves the motion under the resistive force from the robot while on passive assistance mode (PAM) patients does not make any effort, the robot executes all the work. Regarding active assistance mode (AAM), patients attempt to move their muscles and devices are only an additional aid when is required, whereas in assistive mode the user is able to execute voluntary motions alon with robot support [3].

In order to support conventional rehabilitation training, since the number of people with upper limb deficits has increased, Robot-assisted therapies have been developed as an alternative approach and complementary treatments to regain motion and restore function of the upper limb impairment during the last years [34]. The Robot therapies seek two goals a) to accelerate the recovery motor process of the patients and b) support the therapist, who also execute hard physical work everyday, since more victims with a Cerebral Palsy demand for rehabilitation routines and struggle with their costs and availability [2].

Conventional exoskeletons are robots with heavy load structures like a shell made of rigid linkages that can exert high forces[35]. These exoskeletons are characterized to augment mobility performance through actuators or motors. However, they represent an extra load for the limb, which obstruct the natural movement of joints and in extreme cases represent a risk for the patient integrity or can get worse his/her physical condition [36].

On the other hand, effective solutions to overcome those disadvantages have been proposed to improve the design and control of devices that help in the recovery process of upper limb rehabilitation. A new recently assisted technology which has emerged is the “Soft Robotics”, a branch of robotics that helps to exert autonomously repetitive and heavy tasks, during the rehabilitation or works as a tool to assist the therapist.

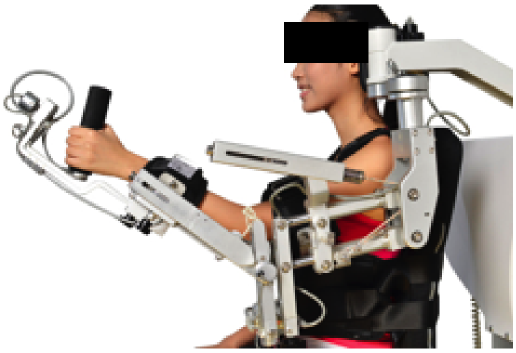


Fig. 2.5 Exoskeleton for upper limb motion Reproduced from [37]

Fig. 2.6 Exotendon BiomHED system Reproduced from [38]

Therefore, multiple soft robots have emerged as a more comfortable solution than traditional exoskeletons. These new wearable systems are attached to the limbs, they are based on biomimetic principles to emulate the mechanical and elastic tissues properties for improving functional and structural aspects of the neuromuscular system, they are easier to use, light-weight and consume less energy [39]. Figure 2.5 and 2.6 shows a rigid robot and soft wearable device for upper limb rehabilitation, respectively. Where, portability, weight and comfort are highlighted among them.

Chapter 3

State of the Art and Technique

3.1 Soft Wearable Devices

As aforementioned, the development of the MOSAR will be based on the novel approach of Soft Robotics, since this type of soft robots have the human skeletal as their main structure, mimic the natural motions of human beings and pretend to be a natural extension of the human body [40]. Moreover, they provide an intuitive use and are conformable for patients. Therefore, this chapter encompass a deep review about soft wearable devices: Soft Exo-Gloves systems and Soft Exo-suits, oriented to hand and upper limb rehabilitation, respectively.

According to [32], a design methodology of a soft wearable device should consider the following aspects.

- To not increase joint stiffness
- To not obstruct with natural motions
- To be safe and do not hurt anytime to patient
- To be donn and doff intuitive
- To be endowed with a customizable design

In order to enhance the performance of soft wearable devices, this research has proposed a novel methodology along with the design criteria and guidelines for the development of those systems in [2]. Table 3.1 summarizes all the attributes and features that are suggested to consider during the design methodology of a soft wearable device. A detail description about each of those criteria can be found [3].

Table 3.1 Parameters for the Design Methodology of a Soft Exoskeleton

Nº	FEATURE	DESCRIPTION
1	**Function**	a) Rehabilitation: physical therapy. b) Assistance: act as a supportive aid
2	**Application**	Stroke survivors, people with a Cerebral Palsy, Grasp pathologies, (Neuronal Disorder)
3	**Task**	a) Mobilazation: to exercise the impaired limb b) Manipulation: grasping, holding, releasing
4	**Motion Guidance**	a) Passive: Patients do not make any effort b) Active : Patients attempt to do the motion
5	**Intervention Mode**	a) Unilateral: Patients do not make any effort b) Bilateral : Patients attempt to do the motion
6	**Portion of the body**	Regions, limbs and joints that will be benefited
7	**Actuation**	a) Tendon drive: electrical motors b) Fluid pressurization: pneumatic- hydraulic
8	**Material**	Sythetic Polymer, Fabrics
9	**DOFs**	Number of the Degrees of Freedom per joint
10	**Motions**	Rehabilitation exercises
11	**Control**	Close Loop Control to sense the actuation
12	**User intent detection**	To monitor patient attempts to augment the intensity of motions
13	**Safety Input**	Feedback signal as an emergency button
14	**Assesment**	EMG test, joints ROM, ROM indices or scales
16	**Weight**	To measure the extra load on the impaired limb
17	**Configuration**	a) open design: free motions b) close design to cover the whole limb
18	**Portability**	Enables Home rehabilitation
19	**Modularity**	Allows to exert motions at different regios
20	**Customization**	To fit with the user size
21	**Costs**	The cost-benefit of the system
22	**Manufacturing Process**	Methods for their development (3D printing)

For example, soft wearable devices must be able to offer from 2 to 6 hours for continuous and intermittent home operation [41], to be consider as a portable device. Regarding, costs, authors in [42], suggest that SWD and components assembly should be less than $30 for being a competitive and commercial rehabilitation choice.

3.2 Soft Exo-gloves for Hand Rehabilitation

From the State of the Art, mostly soft exo-gloves are dedicated to hand rehabilitation, assistance or manipulation tasks in stroke survivors and people with hand disabilities [6]. SEG evolution has been diversified over the last decade. Overall, SEG development has been determined by their design, fabrication and control [4, 43]. Additionally, materials [44], actuation [45] and the number of DOFs [46, 47] have also defined their operation.

SEG systems are driven by pneumatic, hydraulic or cable driven actuators [4, 45]. For example, with electric energy, SEG systems include cable-tendon made of shape memory alloys, Teflon tubes [48–54] or muscle wires [55]. Regarding fluid pressurization, compressible fluids such as air are use in [56–60], hydraulic in [41, 61] or hydro-pneumatic pressurization in [62].

Recent developments have focused on improving soft exo-gloves actuation to avoid joint misalignments compare to traditional rigid hand exoskeletons, increase hours of operation and reduce weight to the system [39]. Mostly gloves have closed or open palm configurations for strong grasping as it is shown on Figure 3.1. From the reviewed works, a great diversity of these systems can be found in [3], with a detailed description about their design criteria of each exo-glove.

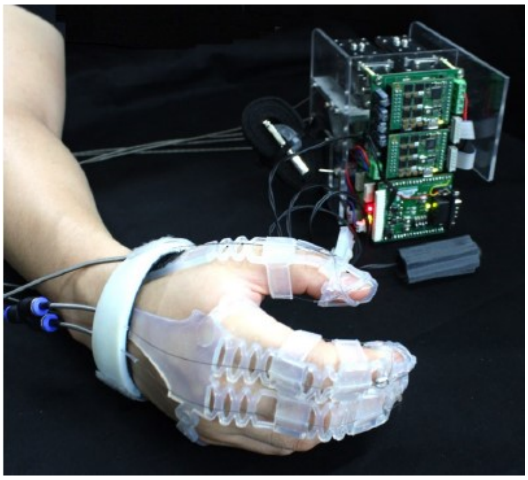


Fig. 3.1 Exo-Glove Poly, a Soft Exoskeleton polymer-based tendon-driven wearable robotic hand [63]

The first developments were adapted to sport gloves with an attached control [5, 64, 65]. Then, SEG started exploring different materials where such as synthetic leather [66], silicon, neoprene [67] and fabrics [44, 68]. Nevertheless, elastomers have become the main choice for SEG fabrication. Recent developments have opted for soft polymers to resemble skin elasticity and empower flexion motions using less material [69, 70]. Also, polymers have been the preferable choice for [63, 71, 72], since lightweight, modularity and flexibility are desired for an open palm design to get strong grasping with the object as it shows Fig. 3.2.

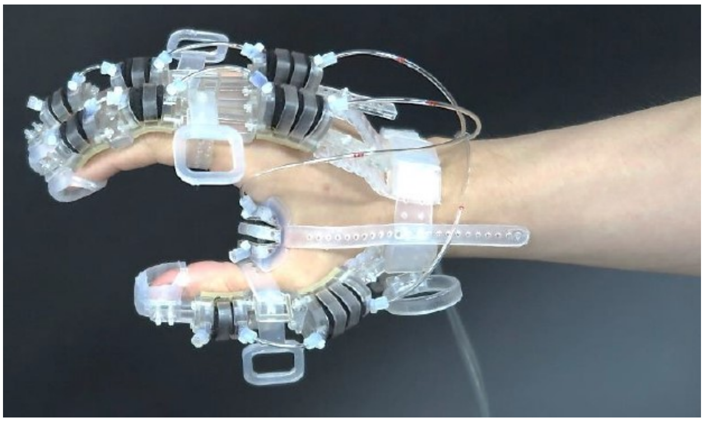


Fig. 3.2 Soft Modularized EXO-Glove PM for Hand Assistance
Reproduced from [72]

SEGs motions are focused on bending and extending fingers to open-close fist for objects manipulation [50]. Soft Exo-Gloves are oriented to provide active and passive assistance depending on the impaired fingers. With active assistance, users attempt to move their fingers [73]. On the other hand, in passive assistance mode the soft device execution the whole desired motion, since patients have no mobility due joint stiffness or spasticity [74].

Normally, thumb, index and middle finger are required in order to achieve activities of daily living [53, 54]. Nevertheless, hand characterization for rigid [36, 75] and soft [40, 76] exoskeletons have turned out a tough task, since this end effector is one of the most complex kinematics structures of the human body due to their multiple joints and degrees of freedom.

In spite of, SEG systems are only focus on hand mobilization, this research has analyzed their design criteria for further developments. Additionally, Table 3.2 illustrates five different designs of Exo-gloves for hand rehabilitation or assistance tasks. Table 3.3 provides a list of the main authors who have excelled due to their multiple contributions about the development of SEG systems. These authors also represent the reference point for future designs, since they have provided the pioneering guidelines.

Table 3.2 Soft Exo-gloves for Hand Rehabilitation

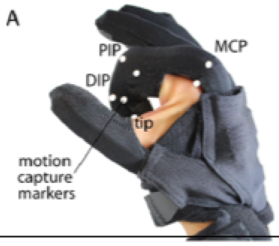
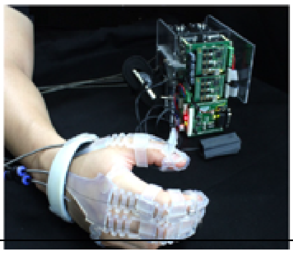
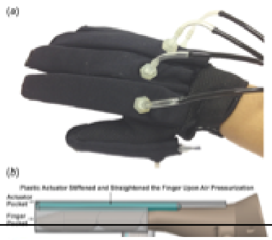
Name	Soft Exo-gloves	Mode	Actuation	Performance	Motions
Glohera [7]		Passive	Pneumatic	Rehabilitation system	Flexion Extension thumb fingers
Exo-glove [48]		Passive	Pneumatic	Rehabilitation system	Flexion Extension Thumb Index Middle
Exo-Poly [49]		Passive	Tendon	Assistance	Flex-Ext Rad-ulnar Fingers Wrist Thumb
Iron Hand [53]		Passive	Pneumatic	Rehabilitation	Flex-Ext Hand
AE glove [54]		Passive	Tendon	Assistance	Flex-Ext Thumb

Table 3.3 Authors of Soft Exoskeletons for Hand Rehabilitation and Assistance

Year	Author	Publication
2015	Panagiotis Polygerinos	Soft Robotic Glove for combined assistance and at-home Rehabilitation [41].
2016	Brian Byunghyun Kang	Development of a Polymer-Based Tendon-Driven Wearable Robotic Hand [63].
2017	Hong Kai Yap	A fully Fabric-Based Bidirectional Soft Robotic Glove for Assistance and Rehabilitation of Hand Impaired Patients [62]
2018	A. Mohammadi	Flexo-glove: A 3D Printed Soft Exoskeleton Robotic Glove for Impaired Hand Rehabilitation and Assistance [77]
2019	M. M. Ullah	A Soft Robotic Glove for Assistance and Rehabilitation of Stroke Affected Patients [78]

3.3 Soft Exo-suits for Upper Limb Rehabilitation

Upper limb dysfunctions restrict mobility and basic activities of daily living (ADL). Thus, wearable soft exo-suits have emerged as an alternative rehabilitation therapy for stroke survivors and people with spinal cord injures (SCI) [79].

For upper limb rehabilitation, SWD are characterized to augment mobility performances through soft actuators, they are intended to support and correct patients limbs, compensate anatomical inequalities and increase stability to improve their functions [80]. Additionally, SWD are able to exert upper limb-hand motions using Virtual Reality [50].

Moreover, soft devices ergonomics and size makes them comfortable and allow their portability. Thus, they are a feasible choice for home rehabilitation, since patients are no longer required to attend to clinical facilities which represent extra costs [2].

Soft wearable upper limbs devices are oriented to provide more intensive treatment ensuring correct movement patterns compared to conventional rigid exoskeletons, since they avoid complicated mechanical setups with rigid frames [81], they pretend to be a natural extension of the human body as it shown in Figure 3.3.

At present, smart and light materials with a friendly actuation are necessary to improve the design and control of upper limb soft devices that help in the recovery process of spastic hemiplegia [83, 84].

Therefore, since the target of this thesis is to develop a soft mobilizer for upper limb rehabilitation, an exhaustive search about soft robots aimed to rehabilitate the proximal segment or include elbow, forearm and wrist motions was done.

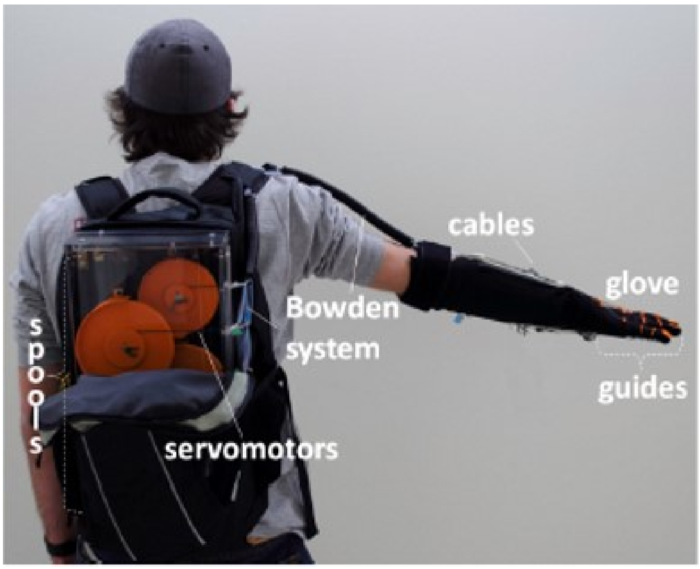


Fig. 3.3 A soft wearabkle device for wrist rehabilitation from [50].

Also, for this section, five authors related to the development of soft wearable devices for upper limb rehabilitation were chosen from the State of Art. Those authors represent the bases for the design methodology for this project, due to their multiple contributions. Particularly, all of authors have proposed pneumatic actuation as the best option for driving soft wearable devices in order to achieve high forces. Table 3.4 summarizes these five authors along with their developments since they achieved at least 2 DOF that are required for the performance of the MOSAR mobilizer.

Table 3.4 Authors for Pneumatic Soft Wearable devices for Upper Limb Rehabilitation and Assistance

Year	Author	Publication
2015	N. W. Bartlett	A soft robotic orthosis for wrist rehabilitation [82].
2016	V. Oguntosin	Development of a wearable assistive soft robotic device for elbow rehabilitation [85].
2017	T. H. Koh	A Soft Robotic elbow sleeve with passive and intent-controlled actuation [86].
2019	Se-Hun Park	A Lightweight, Soft Wearable Sleeve for Rehabilitation of Forearm Pronation and Supination [87].
2020	Junghoon Park	Design of an Inflatable Wrinkle Actuator with fast inflation/ Deflation Responses for Wearable Suits. [88]

Table 3.5 Soft Pneumatic Exosuits for Upper Limb Rehabilitation

Name	Soft Exosuits	Mode	Actuation	Transmision	Motions
Exo Muscle [82]		Passive	Tendon	Bowden system	Forearm Pronation Supination Hand Flex-Ext
Elbow sleeve [85]		Passive	Pneumatic	Inflatable chambers	Elbow Flexion Extension
Elbow sleeve [86]		Passive	Pneumatic	Fiber reinforced chambers	Flex-Ext Rad-ulnar Elbow Wrist Hand
Soft elbow [94]		Passive	Pneumatic	Fabric chambers	Elbow Flexion Extension
Soft sleeve [87]		Passive	Passive	Inflatable chambers	Forearm Pronation Supination

Table 3.5 summarizes a detailed description about previous Soft Exosuits for upper limb rehabilitation, however not all data is provided. The goal of this summary is to compare the available devices and highlight their main properties in to offer a framework and guidelines for the MOSAR development.

Nevertheless, the lack of pneumatic Soft Exosuits for upper limb rehabilitation with cost effective manufacture processes is still a significant challenge to face [35]. Therefore, the objective of this project is to develop an available soft wearable devices as support aid during upper limb rehabilitations protocols through the MOSAR perFormance.

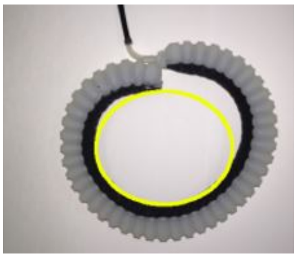
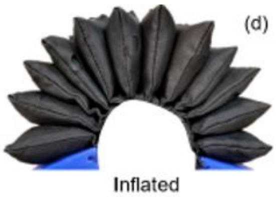
3.4 Soft Pneumatic Actuators

From the methodology proposed in [2], it was concluded that the design and manufacture of the soft actuators for any wearable device, represent the main processes for their correct operation. No matter what type of power supply is used, soft actuators are the core component of any SWD, it could be said that they are the soft wearable device assembled with other components such as fixing, batteries, control boxes, etc.

Therefore, considering the advantages from pneumatic actuation above the other choices, this research also provides a review classification about soft pneumatic actuators (SPAs). According to the State of the Art, 4 types of soft pneumatic actuators have been developed during the last decade under the approach of Soft Robotics for being used in medical applications such as rehabilitation or assistance tasks. This classification includes: a) pneumatic artificial muscles (PAMs), b) plastic inflatable chambers (PICs), c) fiber reinforced elastomer soft actuators (FRESAs) and d) fabric inflatable soft actuators (FISAs). Table 3.6 illustrates their design configurations along with their perks and drawbacks. The main features are described below.

- SPAs provide high forces and torques than cable driven actuation
- SPAs have less manufacturing costs than cable driven and hydraulic actuation
- Mostly SPAs are able to provide custom designs and adapt to different morphologies
- Flexion and Extension motions can be achieved with low pressure values
- SPAs are characterized by their low weight assemblies
- SPAs configuration and designs could be diversified and simple
- SPAs can provide linear motion, twist and rotatory motions

Table 3.6 Classification of Soft Pneumatic Actuators

Type	**Soft Actuators**	**Advantages**	**Disadvantages**
PAMs [89]		Commercially available Variaety of sizes Small workspace Linear motion	High costs Muscles injuries Low contractions Sudden motions
PICs [85]		Low cost Low weight Simple designs Low pressure Custom design	Bulky designs Air leaks Variable stiffness
4e44444e4e FREAs [86]		High forces Faster actuation Long lifetime Custom designs Hight Torque	Time consuming manufacturing Variable stiffness High pressure
FISAs [96]		High payload Low weight Low cost Simple designs Long lifetime	Bulky structures Air Leaks Variable Stiffness

3.5 Conclusion

In this chapter, the design parameters of a soft wearable device were established from the design methodology provided in [2]. Also, the main aspects for the development of a soft mobilizer for upper limb rehabilitation oriented to the MOSAR were highlighted.

Additionally, an exhaustive review of the soft wearable devices for hand and upper limb was done. In order to identify the new trends and the available devices that offer elbow (flexion-extension), forearm (pronation-supination) and wrist (flexion-extension along with radial-ulnar deviations), since those 4 DOF are imperative to rehabilitate the proximal region.

From this revision, it was founded that there are plenty of soft exo-gloves that include wrist or forearm pronation, but mostly designs are oriented to hand manipulation tasks. On the other hand, most soft exosuits offer one DOF. They are oriented to rehabilitate the elbow, forearm or wrist, separately. But none of them offer two DOFs at the same time.

With all this information, two papers were published, one for the methodological approach of soft robots and one more for a review of SEG systems design criteria. Both papers offers the bases for people who starts exploring the Soft Robotics field.

From these reviews, pneumatic actuation has excelled above cable driven or hydraulic actuations. Upper limb soft devices started using cable actuation, but recent developments are more oriented to the use of pneumatic actuation. Thus, several types of pneumatic actuators have been proposed since fluid pressurization provides higher forces and torques than cable-driven actuators.

Nevertheless, potability is still restricted, since pneumatic soft wearable devices require a deposit or air compressor for power supply. Therefore, materials of the chambers can be improved in order to avoid air leaks and low-weight supplies are needed to be part of the soft devices.

Chapter 4

Design Methodology

4.1 MOSAR Design Methodology

Following the design criteria for the development of a soft wearable device that is provided in [2], this chapter presents the design methodology that was adapted for the MOSAR performance. The design methodology focuses on the creation of SWD based on a patient-centered design as an alternative solution that minimizes trial and error tasks. The proposed design methodology seeks to empathize with patients' needs and provide them a custom SWD depending on their physical condition.

In order to achieved this goal, the methodology is divided into 2 stages and 4 phases. Phase 1 consists to identify the necessity. Moreover, specialists' feedback from Neurologist, Therapist was requested to define the appropriate SWD task depending on each necessity. This valuable information is important since the specialists are the ones that will be supervising the SWD's operation everyday. Phase 2 involves the design of a virtual, mathematical and experimental physical models. Phase 3 is related to the fabrication and control of the soft pneumatic actuators. Finally, Phase 4 encompass the experimental validation of the system on the case of study, a deep description is presented as follows:

1. On phase 1, a complete assessment about the clinical condition of the child was done with the assessment of a Neurologist, Therapist and EMG tests to evaluate the physical condition of the right paretic side of his upper limb. From this assessment, the main necessity of the patient was clearly identified. The damage is more severe at the forearm, elbow and wrist, these joints must be rehabilitated before starting hand manipulation tasks.

2. On phase 2, the preliminary concept of the MOSAR was built using Reverse Engineering on the upper limb of the patient. First casting model, silicon model and finally, a

virtual model was obtained from 3D scann. Also, at this phase, from the digitalized upper limb of the patient, a dummy limb was made of silicon, for future testing bench for the MOSAR performance assessment.

3. On phase 3, the design criteria for the development of the MOSAR were defined. Moreover, the manufacturing process of the soft pneumatic actuators of MOSAR were achieved along with other components that allow the system actuation.

4. On phase 4, a law closed loop control was proposed to achieve the inflation and deflation process of the pneumatic chambers to reach the desired upper limb motions and their validation was achieved. Figure 4.1 illustrates this process with the four phases.

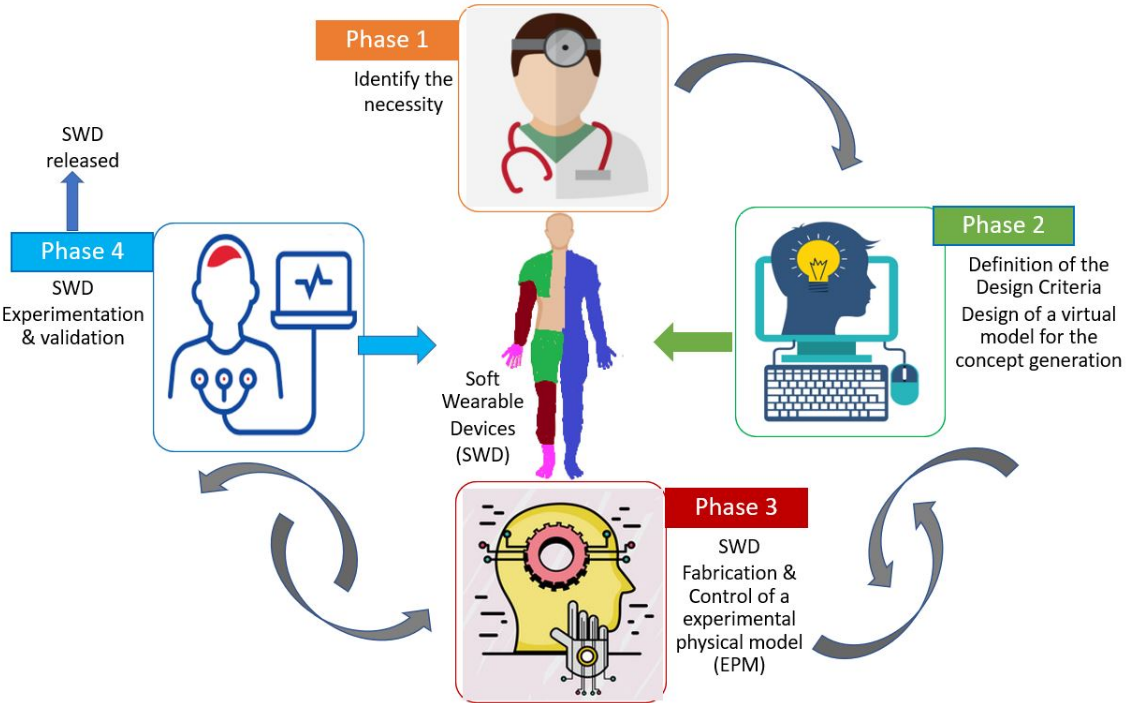


Fig. 4.1 Design Methodology for Soft Wearable Devices: the MOSAR case

4.2 MOSAR Design Concept

From the accurate diagnosis about patient's condition that was provided from the experts and with the results obtained from the EMG tests at biceps, triceps, pronator, supinator, wrist flexor and wrist extensor [2]. The main necessity of the patient was identified in order to define the target tasks associated to the MOSAR attributes and constraints.

Patient active and passive ROM were measured at **1)** elbow-flexion, **2)** elbow-extension, **3)** forearm-supination, **4)** forearm-pronation, **5)** wrist-flexion, **6)** wrist-extension, **7)** wrist-radial-deviation and **8)** wrist-ulnar-deviation using a manual goniometer. Figure 4.2 and Table 4.1 illustrates a comparison between those values and the natural ROM of a healthy person. The results were analyzed by the Therapist who determined which joints should be evaluated. Those measurements served as reference to define MOSAR pressure values and operational ROM. More details about those assessments can be found in [2].

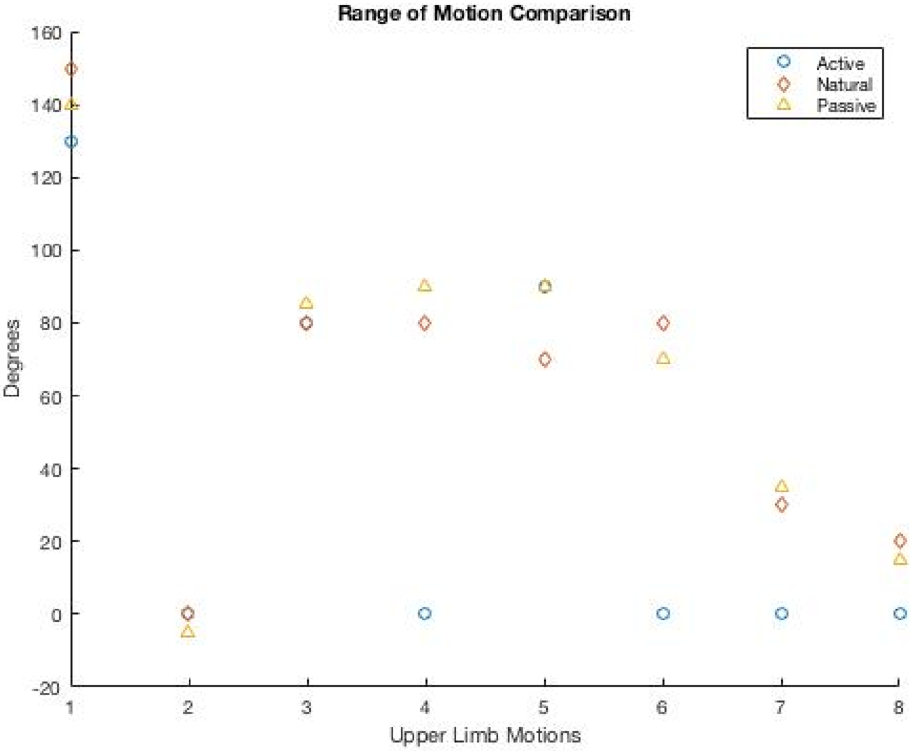


Fig. 4.2 Upper limb passive and active range of motion at elbow, forearm and wrist joints

Additonally, pressure [86], torque [92] and force [91] values were obtained from the reported literature in order to establish the MOSAR constrains. Table 4.2 reports their respective values required for the development of the MOSAR system.

Once the MOSAR criteria and constrains have been identified, the design concept generation of the MOSAR is obtained from patient's upper limb characterization through the development of three models: 1) casting model, 2) silicon model and 3) computational model. All these models represent the parameterized reference of the experimental physical model for the MOSAR fabrication. All this process was carried out at the Materials Laboratory of the Faculty of Engineering (UAEM), deep description is illustrated in Figure 4.3.

Table 4.1 Patient active-passive and functional ROM measurements from [2].

Joint	Motion	Muscle	Active ROM	Passive ROM	Functional ROM
Elbow	Flexion	Biceps	130°	140°	150°
	Extension	Triceps	0°	−5°	0°
Forearm	Pronation	Pronator	80°	85°	80°
	Supination	Supinator	0°	90°	80°
Wrist	Flexion	Wrist Flexors (6)	90°	90°	70°
	Extension	Wrist Extensors (4)	0°	70°	80°
	Radial deviation	Flexor-Extensor Carpi Radialis	0°	35°	30°
	Ulnar deviation	Flexor-Extensor Carpi Ulnaris	0°	15°	20°

Table 4.2 MOSAR design constrains values from [2].

Joint	Body mass %	Motion	ROM	Torque Nm	Pressure kPa	Force N
Elbow	1.60	Flexion Extension	150°	1.2	350 80	20 16.5
Forearm		Supination Pronation	78°	1.9	50	10
Wrist	0.70	Flexion Extension	91°	0.2	50	5
		Radial dev. Ulnar dev.	32°	0.5	30	5

Fig. 4.3 Generation process of (**a**) patient upper limb characterization. (**b–d**) casting models. (**e**,**f**) silicon models made of (Polysil P-48™) and (**g**,**h**) dummy limbs from [2]

For the conceptual design, Reverse Engineering was applied on the whole paretic upper limb including the hand of the patient to build a complete skeletal frame of his anatomy and future works. First, (1) two casting molds, (2) two silicon models: hand and forearm and (3) one assembled virtual model: hand-forearm. The hand was digitalized with the ATOS 3D ™ while the forearm digitalization was obtained from the AMETEK™ scanner, at Unidad Santiago Tianguistenco (UAEM) and Tecnológico de Jocotitlán, respectively. Figure 4.4a and 4.4b illustrate those previous digitalizations on their facilities.

(a) ATOS 3D ™scanner **(b)** AMETEK ™scanner

Fig. 4.4 Upper Limb 3D Digitalizations

Moreover, Figure 4.5 shows the 3D digitalization of the forearm-wrist region and the hand using the ATOS III™ and AMETEK™, respectively. Using the silicon models, the scanning process consist to create a point cloud around the dummy limbs. Then, a mesh model of each component is created. Finally, solid virtual models are obtained from the target limbs.

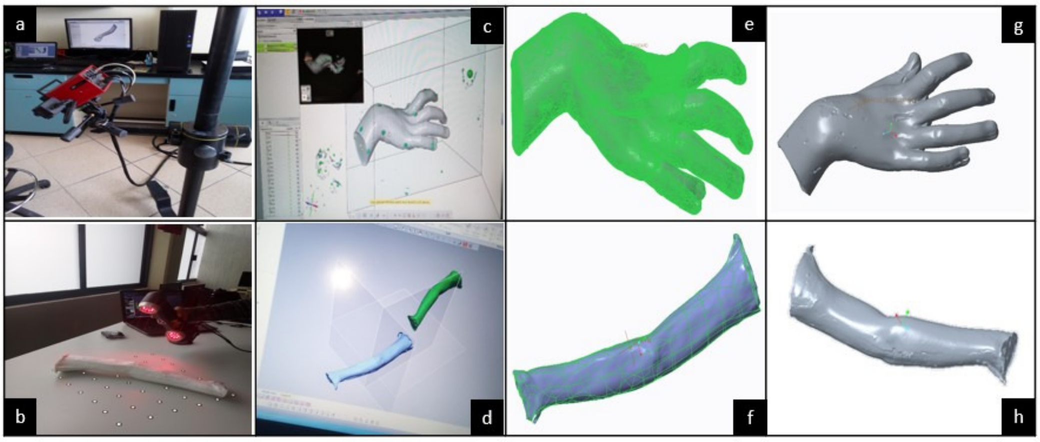


Fig. 4.5 3D digitalization process of the hand and forearm-wrist taken from [2]

Figure 4.6 and Table 4.3 summarize the design criteria for the MOSAR assembly with all its components and features. Detailed features have been already published in [2].

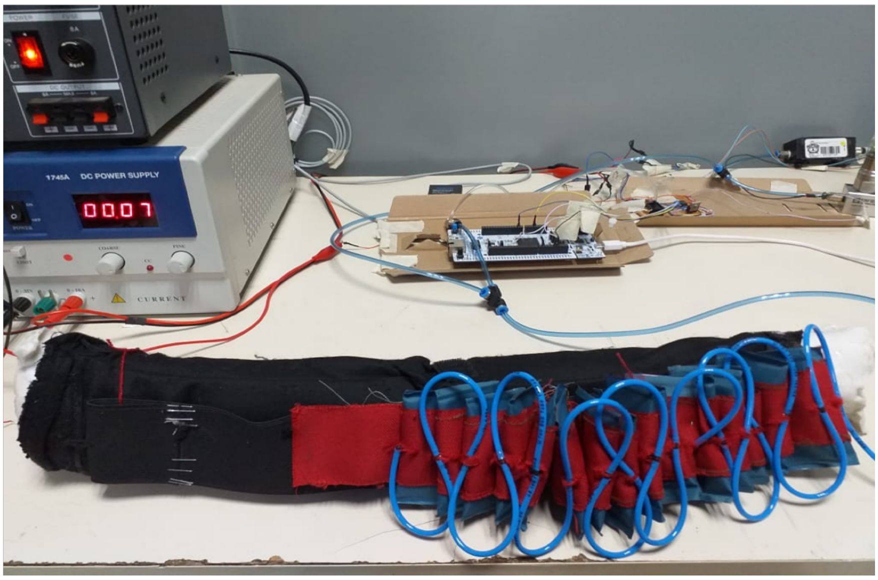


Fig. 4.6 MOSAR assembly

Table 4.3 Customized design criteria and constrains for the MOSAR development from [2].

Design Criteria	Description
Function	Rehabilitation
Assistance mode	Passive
Mode of intervention	Bilateral
Configuration	Closed
Target joints	Elbow, Forearm,Wrist
DOF	4
Elbow flexion-extension	0° to 150°
Forearm pronation-supination	70° to 80°
Wrist flexion-extension	70° to 80°
Wrist ulnar-radial deviation	15° to 30°
Actuation	Pneumatic Pressurization
Actuators	6
Shoulder-elbow length	23 to 26 cm
Elbow-wrist length	18 to 20 cm
Wrist diameter	13 to 15 cm

4.3 MOSAR Soft Pneumatic Actuators Fabrication

This section describes the fabrication process for the FISAs actuators that drive the MOSAR. The FISAs are integrated by a set of fabric inflatable chambers that are attached similar to a musical accordion. Since this configuration produce a domino effect that causes high pressure between each of the chambers to reach flexion-extension motions [88].

The design of the fabric inflatable soft pneumatic chambers is based on the geometrical parameters that have been reported in [96]. The shape of the chambers is define also by their height, **h**; gap between chambers , **g**; number of chambers, **n**; distance between chambers, **n**; total length, **l**; width of the chambers, **w** [32]. Figure 4.7 shows a side view of a set of inflatable chambers along with a front view of a single chamber.

FISAs performance is determined by the design and manufacture of each of their chambers based on the aforementioned geometrical parameters. Overall, the distribution of the chambers must cover the length of target limb. It is important to highlight that this manufacturing process was learned during the research stay at Arizona State University along with their control strategies. A description about the steps for their fabrication is shown in Figure 4.8 and is described as follows.

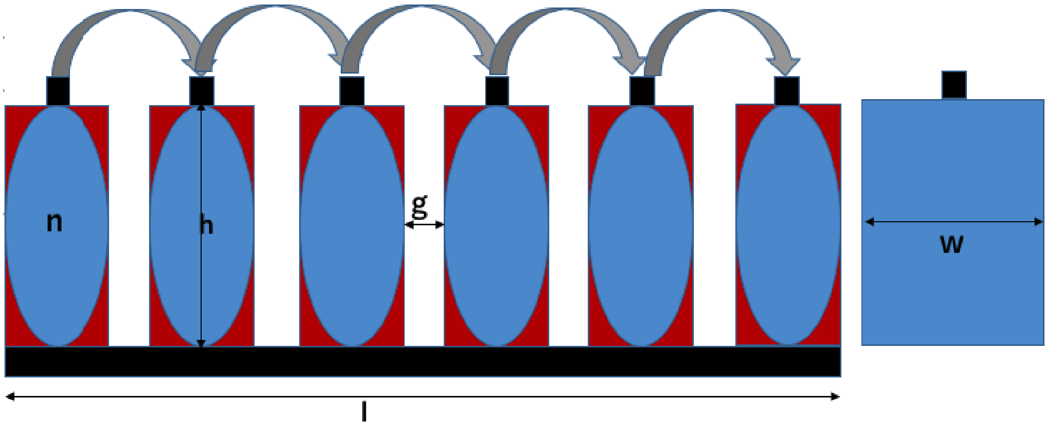


Fig. 4.7 Geometrical parameters on a set of chambers

1. Use any computer aided design (CAD) software to draw the desired profile of the chambers depending on their dimensions.
2. Overall, fabric chambers are made of thermoplastic polyurethane (TPU) material. Thus, chamber profiles can be cut manually or use laser cutter. The MOSAR blades profiles were cut on the gloveforge™ to save time and ensure accuracy.
3. After the blades have been cut, T , elbows or Y plastic tube fittings are inserted on the hole and tide with nuts and Teflon tape to avoid air leaks. Then, the blades were folded in half and the edges were sealed with a heat machine that works like an iron.
4. Lastly, fabric layers are sewn on elastic fabrics that must cover the target area. Then each of the cavities is drilled to content the bladders and avoid any radial expansion. Finally, tubing is connected for air flow circulation in all chambers.

During FISA's fabrication, different attempts were made on their structure not only to develop a pneumatic blade without air leaks or be perfectly sealed. Additionally, different layer materials were tested in order to reach high pressure. On the first try, the layer was done of elastic fabric material and the cavities of the chamber were made of rigid fabrics, however the chambers have different gap between them. On the second try, the materials of the cavities and the base layer were made of fabrics, but an accurate gap of 2cm between chambers was defined. Finally, on the third trial, the base layer was replaced by rigid fabrics instead of elastic material and the gap was 2.5 cm between the center of each chamber to avoid being crushed.

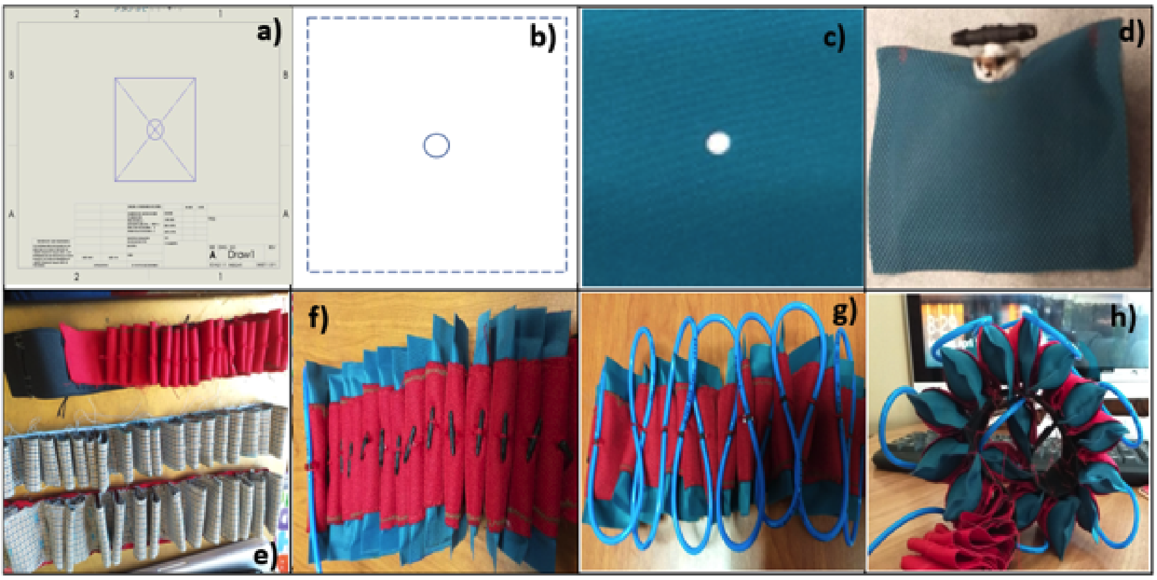


Fig. 4.8 FISAS fabrication process a,b) chamber profile, c,d) cutting lasser, e,f) folding and sealing and g,h) sewing adn tubbing connectors

The assembly of the FISAS has a modular configuration in order to adapt of the size of the target limb, that means that the chambers can be added or removed depending on the length that will cover. Additionally, since the FISAs actuators must be attached to a soft wearable device, the assembly of the chambers of the MOSAR was attached to a soft exo-sleeve with Velcro straps for upper limb rehabilitation, that eases the donn-doff from other limbs. Figure 4.9 illustrates a inflation process where the domino effect can be observed to reach flexion motion.

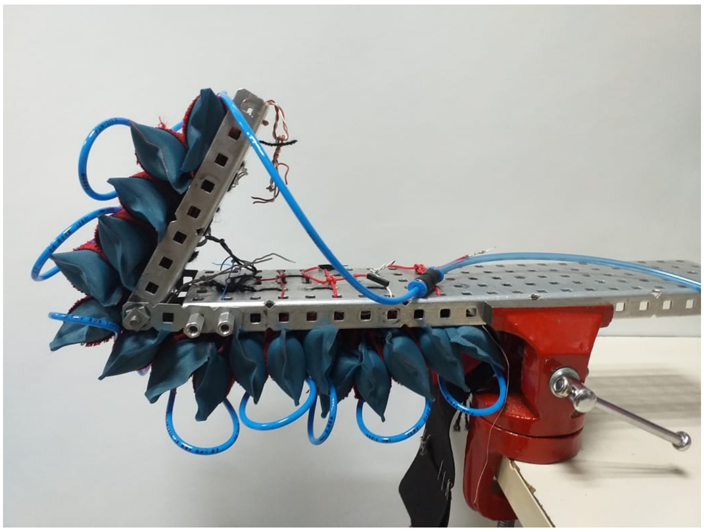


Fig. 4.9 A pressurized fabric inflatable soft actuator

4.4 MOSAR Actuators Control

After the fabric inflatable soft actuators were manufactured, a law control strategy for their inflation-deflation process was developed. The FISAs were controlled using a similar hybrid valve array from [97] in order to take the advantages of quick response in short time, accurate performance on the steady-state and broad range of pressure values.

The proposed control scheme is integrated by **A)** an air compressor for input source up to 60 psi. **B)** a maintenance unit from FESTO attached to the compressor. **C)** a 2/2-way proportional valve, (PFV-W24E05-M100C-0500 ™, Enfield Technologies) for precise pressure regulation. **D)** a pressure sensor 577020™, FESTO only for a reference to monitor pressure values. **E)** a 3/2-way binary valve, (MHE3-MS1H-3/2G-1/8-K ™, FESTO) for fast switching time. **F)** a fabric inflatable soft actuator with 16 chambers. **G)** a MOSFET circuit for 3.3 V signal of solenoid valve. **H)** a pressure sensor (ASDXAVX00PGAA5™, Honeywell International Inc.) for sensing upx to 100 psi inside the FISAs on the steady-state. **I)** an amplifier circuit up to 6.5 V. **J)** an embedded system NUCLEO-STM32F767ZI™board for all the electronic control of the system. **K)** a computer with (Matlab/Cube/Putty) software for being the interface between the controll board and FISA actuator. This experimental setup of the FISAs actuators can be observed in Fig 4.10.

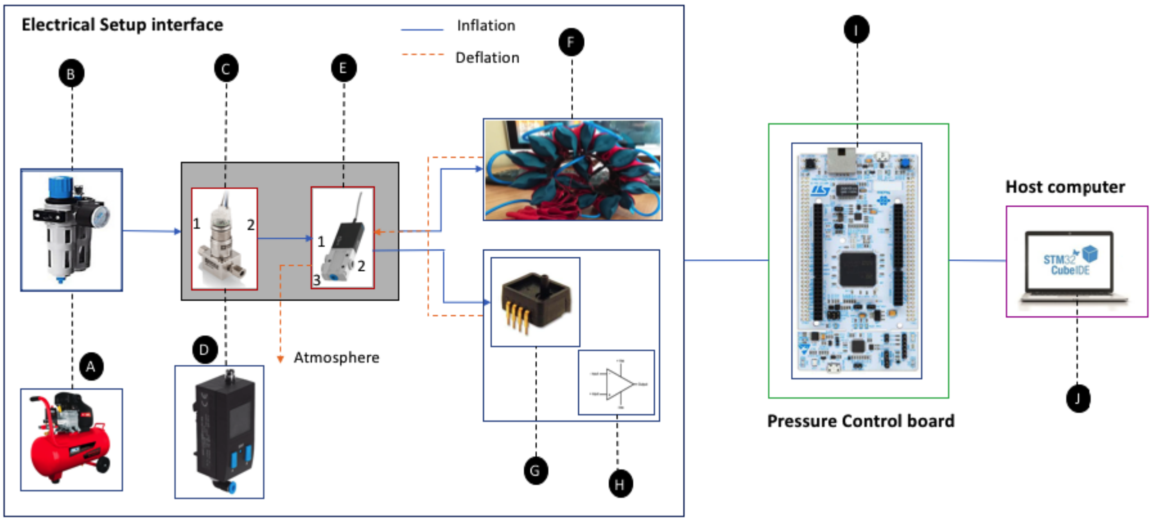


Fig. 4.10 Diagram of the electronic operating setup

During this phase the next steps were done to achieve a closed loop control system (PD), from 0 psi to 50 psi for different testing, based on the reference, output and measured pressure feedback values as shown in Figure 4.11. However, not all this information is provided in detail since it will be published on an article which is still a draft.

1. Build an electronic diagram for all components.
2. Develop an embedded system programming.
3. Test pressure sensor characterization.
4. Test pressure sensor, proportional and solenoid valves to measure their response time.
5. Obtain transfer function from testing proportional valve, pressure sensor, solenoid valve along with FISAs actuators.
6. Obtain and test a PID and PD controllers to find out the best choice for FISAs operation.
7. Adjust manually the PD controller.

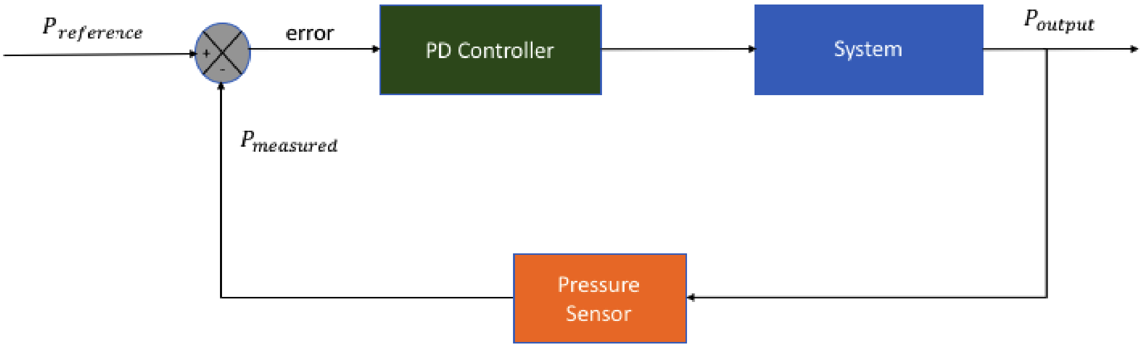


Fig. 4.11 Block diagram of the PD controller for pressure

The experimental results highlight that the control strategy is able to achieve fast response time, fast rise time and steady-state accuracy performance and provides wide range of pressure regulation.

4.5 MOSAR Experimentation & Assessment

Once the FISAs control has been achieved, this last phase will consist to integrate the whole components on the MOSAR system in order to do experimental work on the patient and validate MOSAR performance with different rehabilitation protocols under the supervision of a Therapist. Nevertheless, this part of the project is out of the scope and will be reported separately.

Chapter 5

Results

From the aforementioned research, two articles on the Journal Citation Report were published. Therefore, based on the degree regulations of the Reglamento de Estudios Avanzados (REA), Chapter 8 of the final evaluation and degree evaluation, specifically on the articles 59 and 60, the present degree of PhD to be obtained is through this modality, complying with all the exposed requirements.

5.1 Article 1: Design Criteria of Soft Exogloves for Hand Rehabilitation-Assistance Tasks

By: Juana Mariel Dávila-Vilchis, Juan C. Ávila-Vilchis, Adriana H. Vilchis-González* and LAZ-Avilés.

This article arises from an exhaustive research on the development of a soft exo glove device for hand rehabilitation of patients with hemiplegia or hand disabilities. Since the current case of study was oriented to manipulation tasks at the beginning. Therefore, this article presents a summary of 91 exogloves during the last decade. This paper provides the design guidelines for future developments of SEG systems, as well as, their design parameters of each device with a deep description in order to establish the bases for their design and development.

Journal: Applied Bionics and Biomechanics

DOI: https://doi.org/10.1155/2020/2724783

5.2 Article 2: Design Methodology for Soft Wearable Devices-The MOSAR case

By: Juana Mariel Dávila-Vilchis, LAZ-Avilés, Juan Carlos Ávila Vilchis and Adriana H. Vilchis-González*.

In this second article, a methodological approach is proposed for the design and development of any soft wearable device. This need arises for how to start developing the MOSAR system for upper limb rehabilitation. Therefore, a detailed methodology for soft robots was proposed with 2 stages (A and B) made up of 4 phases: **Phase 1:** identification of the primary need of the patient. **Phase 2:** consists of developing the virtual, mathematical and physical experimental model of the device. **Phase 3:** refers to the control and manufacture of the experimental physical model. Finally in **Phase 4:**, the experimental physical model is validated. The contribution of this article is focused on supporting people who start working on soft robotics and have an overview of the design guideline. In addition, the modularity of this methodology allows it to be applied to any other SWD.

Journal: Applied Sciences

DOI: https://doi.org/10.3390/app9224727

5.3 Article 3: Fabric Inflatable Soft Actuators for Soft Wearable Devices-The MOSAR case

By: Juana Mariel Dávila-Vilchis, Juan M. Jacinto Villegas, Adriana H. Vilchis-González*, Juan Carlos Ávila Vilchis and LAZ-Avilés.

This article presents the manufacturing process of the soft pneumatic actuators that mobilize the MOSAR system. In this paper, a PD law control for the soft actuators inflation is also proposed through the characterization of a pressure sensor, a solenoid valve and a proportional valve to regulate the air flow in the pneumatic chambers that make up the actuator. Finally, the results of the performance of the soft actuator are evaluated. The angles to perform elbow flexion-extension with variable weights are measured in order to be able to implement those soft actuators on the MOSAR or in another soft wearable device. However, the article is still in draft form.

Target Journal: Soft Robotics

5.4 Patents Applications

From the MOSAR development, this research allows the application of two patents that have been submitted and granted to the Instituto Mexicano de la Propiedad Industrial (IMPI). More details can be found at the end of this document on Appendix A.

1. Industrial design (industrial model, MX_f_2019_002547): this patent refers to the MOSAR system configuration along all its components.
2. Industrial design (industrial model, MX_f_2019_002561): this patent is related to the development of a dummy limb made of silicon that was taken from the case of study. This device will work as a test bench to validate MOSAR performance.

Chapter 6

Conclusion and Future Work

This dissertation proposes the design and development of a soft pneumatic mobilizer called MOSAR for upper limb rehabilitation of a child of 11 years old with right paretic side. This system is designed to perform four independent movements in order to achieve elbow (flexion-extension), forearm (pronation-supination) and wrist (flexion-extension and ulnar-radial deviations). All these movements are critical to increase the upper limb range of motion of the patient.

One of the contributions of this work is a methodology for the design of soft wearable devices that is reported in [2]. It is worth to mention that this methodology encompasses not only an engineering assessment, but also a clinical evaluation from Neurologist and Therapist advises, as well as EMG test. According to this methodology, the following tasks were developed during this research and are highlighted as critical aspects of the project.

- The primary need of the patient is identified.
- The design criteria and constrains for the MOSAR system are defined.
- Based on reverse engineering tool, the MOSAR concept design is generated through the development of several models (casting, silicon and virtual).
- The research is mainly focused on FISAs fabrication and control, since they represent the most challenging components to achieve a successful MOSAR operation.
- FISAs closed-loop control for inflation-deflation is validated at different pressures using diverse weights to evaluate their payload capacity and ROM.
- The MOSAR system was developed for upper limb rehabilitation. Thus, hemiplegic and monoplegic patients could be benefited.

It is noted that the MOSAR research offer an alternative solution to overcome upper limb rehabilitation. It represents a parameterized reference frame for researchers, engineers, therapists and patients since it provides conception, manufacturing, experimentation and successful assessment to reach flexion-extension and pronation-supination motions using FISAs actuators which can be used in other SWD systems.

The MOSAR custom design is created for a particular solution (an 11 years old patient). Nevertheless, it can be generalized for different anatomical dimensions due its modular design. Then, any people with hemiplegia or upper limb disabilities could be benefited with the proposed system. For new patients, only the number of pneumatic chambers must be modified to adapt them to the size of the target limb.

The two published articles, products of this work, establish basic knowledge to immerse in Soft Robotics field and offer an overview of the benefits of this approach in hand rehabilitation or assistance tasks [3]. The proposed design methodology [2] can be used as a basis for the development of a new soft wearable device to tackle different physician disabilities or adapt to another problem that can be solved using Soft Robotics.

The main products and activities of this research are:

- An experimental physical model for the MOSAR device.
- The present dissertation to obtain the pursued of PhD degree.
- Two articles published in indexed journals.
- Three accomplished research stays: 1) at the Prototyping Laboratory of the Unidad de Santiago Tianguistenco (UAEM), 2) at the Reverse Engineering Laboratory (Tecnólogico de Jocotitlán) and 3) at the Robotics and Intelligent Systems Laboratory (University of Arizona State).
- Two industrial design applications to the Instituto Mexicano de la Propiedad Industrial (IMPI). See Appendix A for detailed information.
- Although, it is outside of the scope of this work, hand 3D digitalization of the case of study has been done for future work.

As future work, the validation of the MOSAR system in order to monitor the patient's progress is considered. Moreover, during rehabilitation protocols, therapist and users can make changes to the design of the MOSAR device to improve its performance. It could be convenient to develop a Soft Exo-glove system for the patient in order to achieve also hand rehabilitation and manipulation tasks with his right hand. In this way, a complete rehabilitation of the upper limb could be reached. Additionally, new strategies could be explored including virtual reality environments during rehabilitation protocols. Regarding MOSAR control, the inflation-deflation process could be improved by using vacuum ejectors.

It is expected that the MOSAR system will help to stop the patient's spasticity and joint stiffness at his elbow, forearm and wrist. Based on the work reported in this document, the MOSAR system will serve as a reference for the future upper rehabilitation of the patient since the aforementioned joints will increase their range of motion.

Research never ends!

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Appendix A

Patents

A.1 Patent MX_f_2019_002547

DIRECCIÓN DIVISIONAL DE PATENTES
SUBDIRECCION DIVISIONAL DE EXAMEN DE FONDO DE PATENTES AREAS MECANICA, ELECTRICA Y DE REGISTROS DE DISEÑOS INDUSTRIALES Y MODELOS DE UTILIDAD
COORDINACION DEPARTAMENTAL DE EXAMEN AREA DISEÑOS INDUSTRIALES Y MODELOS DE UTILIDAD

Expediente de Registro de Diseño Industrial Modelo MX/f/2019/002547

Asunto: Procede el otorgamiento.

Ciudad de México, a 25 de agosto de 2020.
No. Folio: 58078

Rogerio RAMIREZ GIL
Apoderado de
UNIVERSIDAD AUTÓNOMA DEL ESTADO DE MÉXICO
INSTITUTO LITERARIO OTE. 100
CENTRO
50000, TOLUCA, Estado de México, México

REF: Su solicitud No. MX/f/2019/002547 de Registro de Diseño Industrial presentada el 17 de septiembre de 2019.

En relación con la solicitud mencionada al rubro, comunico a usted que una vez satisfecho lo dispuesto en los artículos 38 y 50 de la Ley de la Propiedad Industrial, se ha efectuado el examen de fondo previsto por el artículo 53 de la citada Ley y se cumplen los requisitos establecidos por los artículos 31, 37 y demás relativos de dicha Ley y su Reglamento, por lo que es procedente el otorgamiento del Registro de Diseño Industrial respectivo. En consecuencia, con fundamento en los artículos 36 y 57 de la Ley de la Propiedad Industrial, se le requiere para que efectúe el pago por la expedición del título y sus primeros cinco años de vigencia y exhiba el comprobante de pago correspondiente ante este Instituto relativo al artículo 9g de la Tarifa vigente.

Para cumplir lo anterior, se le concede un plazo de dos meses, contado a partir del día hábil siguiente a la fecha en que se le notifique el presente oficio en términos de lo dispuesto por el artículo 184 de la LPI, mismo que podrá extenderse por un plazo adicional de dos meses conforme lo señala el artículo 58 de la LPI, comprobando el pago del artículo 31 de la tarifa vigente por cada mes adicional, apercibido que de no hacerlo dentro del plazo inicial o adicional antes precisados, su solicitud se considerará abandonada.

El suscrito firma el presente oficio con fundamento en los artículos 6° fracciones III y XI y 7° bis 2 de la Ley de la Propiedad Industrial; artículos 1°, 3° fracción V inciso a) sub inciso iii) tercer guión, 4° y 12° fracciones I, II, III, IV y VI del Reglamento del Instituto Mexicano de la Propiedad Industrial; artículos 1°, 3°, 5° fracción V inciso a) sub inciso iii) tercer guión, 16 fracciones I, II, III, IV y VI y 30 del Estatuto

Orgánico del Instituto Mexicano de la Propiedad Industrial; 1°, 3° y 5° incisos e) e i) y penúltimo párrafo del Acuerdo que delega facultades en los Directores Generales Adjuntos, Coordinador, Directores Divisionales, Titulares de las Oficinas Regionales, Subdirectores Divisionales, Coordinadores Departamentales y otros subalternos del Instituto Mexicano de la Propiedad Industrial.

El presente documento electrónico ha sido firmado mediante el uso de la firma electrónica avanzada por el servidor público competente, amparada por un certificado digital vigente a la fecha de su elaboración, y es válido de conformidad con lo dispuesto en los artículos 7 y 9 fracción I de la Ley de Firma Electrónica Avanzada y artículo 12 de su Reglamento.

El presente documento electrónico, su integridad y autoría, se podrá comprobar en www.gob.mx/impi.

Asimismo, se emitió conforme lo previsto por los artículos 1° fracción III; 2° fracción VI;37, 38 y 39 del Acuerdo por el que se establecen los Lineamientos en materia de Servicios Electrónicos del Instituto Mexicano de la Propiedad Industrial, en los trámites que se indican.

ATENTAMENTE
COORDINADOR DEPARTAMENTAL DE EXAMEN ÁREA
DISEÑOS INDUSTRIALES Y MODELOS DE UTILIDAD
LUIS SILVERIO PÉREZ ALTAMIRANO
LSPA/MPSJ/2020

Cadena Original
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fracción III; 2° fracción VI; 37, 38 y 39 del Acuerdo por el que se establecen los Lineamientos en materia de Servicios Electrónicos del Instituto Mexicano de la Propiedad Industrial, en los trámites que se indican; en caso de no contar con lector QR o en su defecto no pueda ser leído por su dispositivo, digitar en la página antes referida el siguiente código: ChhhmWYP7+s4QuuHCivZqBweBBw=

A.2 Patent MX_f_2019_002561

DIRECCIÓN DIVISIONAL DE PATENTES
SUBDIRECCION DIVISIONAL DE EXAMEN DE FONDO DE PATENTES AREAS MECANICA, ELECTRICA Y DE REGISTROS DE DISEÑOS INDUSTRIALES Y MODELOS DE UTILIDAD
COORDINACION DEPARTAMENTAL DE EXAMEN AREA DISEÑOS INDUSTRIALES Y MODELOS DE UTILIDAD

Expediente de Registro de Diseño Industrial Modelo MX/f/2019/002561

Asunto: Procede el otorgamiento.

Ciudad de México, a 25 de agosto de 2020.
No. Folio: 58087

Rogerio RAMIREZ GIL
Apoderado de
UNIVERSIDAD AUTÓNOMA DEL ESTADO DE MÉXICO
INSTITUTO LITERARIO OTE. 100
CENTRO
50000, TOLUCA, Estado de México, México

REF: Su solicitud No. MX/f/2019/002561 de Registro de Diseño Industrial presentada el 18 de septiembre de 2019.

En relación con la solicitud mencionada al rubro, comunico a usted que una vez satisfecho lo dispuesto en los artículos 38 y 50 de la Ley de la Propiedad Industrial, se ha efectuado el examen de fondo previsto por el artículo 53 de la citada Ley y se cumplen los requisitos establecidos por los artículos 31, 37 y demás relativos de dicha Ley y su Reglamento, por lo que es procedente el otorgamiento del Registro de Diseño Industrial respectivo. En consecuencia, con fundamento en los artículos 36 y 57 de la Ley de la Propiedad Industrial, se le requiere para que efectúe el pago por la expedición del título y sus primeros cinco años de vigencia y exhiba el comprobante de pago correspondiente ante este Instituto relativo al artículo 9g de la Tarifa vigente.

Para cumplir lo anterior, se le concede un plazo de dos meses, contado a partir del día hábil siguiente a la fecha en que se le notifique el presente oficio en términos de lo dispuesto por el artículo 184 de la LPI, mismo que podrá extenderse por un plazo adicional de dos meses conforme lo señala el artículo 58 de la LPI, comprobando el pago del artículo 31 de la tarifa vigente por cada mes adicional, apercibido que de no hacerlo dentro del plazo inicial o adicional antes precisados, su solicitud se considerará abandonada.

El suscrito firma el presente oficio con fundamento en los artículos 6° fracciones III y XI y 7° bis 2 de la Ley de la Propiedad Industrial; artículos 1°, 3° fracción V inciso a) sub inciso iii) tercer guión, 4° y 12° fracciones I, II, III, IV y VI del Reglamento del Instituto Mexicano de la Propiedad Industrial; artículos 1°, 3°, 5° fracción V inciso a) sub inciso iii) tercer guión, 16 fracciones I, II, III, IV y VI y 30 del Estatuto

MX/2020/58087

Orgánico del Instituto Mexicano de la Propiedad Industrial; 1°, 3° y 5° incisos e) e i) y penúltimo párrafo del Acuerdo que delega facultades en los Directores Generales Adjuntos, Coordinador, Directores Divisionales, Titulares de las Oficinas Regionales, Subdirectores Divisionales, Coordinadores Departamentales y otros subalternos del Instituto Mexicano de la Propiedad Industrial.

El presente documento electrónico ha sido firmado mediante el uso de la firma electrónica avanzada por el servidor público competente, amparada por un certificado digital vigente a la fecha de su elaboración, y es válido de conformidad con lo dispuesto en los artículos 7 y 9 fracción I de la Ley de Firma Electrónica Avanzada y artículo 12 de su Reglamento.

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Asimismo, se emitió conforme lo previsto por los artículos 1° fracción III; 2° fracción VI;37, 38 y 39 del Acuerdo por el que se establecen los Lineamientos en materia de Servicios Electrónicos del Instituto Mexicano de la Propiedad Industrial, en los trámites que se indican.

ATENTAMENTE
COORDINADOR DEPARTAMENTAL DE EXAMEN ÁREA
DISEÑOS INDUSTRIALES Y MODELOS DE UTILIDAD
LUIS SILVERIO PÉREZ ALTAMIRANO
LSPA/MPSJ/2020

Cadena Original
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