

UNIVERSIDAD DEL VALLE

BACHELOR'S DEGREE PROJECT WORK

Design and Construction of a Hand Rehabilitation System Prototype

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*Grade project submitted in fulfilment of the requirements
for the degree of Mechanical Engineering*

in the

Research Group in Production Systems Automation
Department of Mechanical Engineering

Santiago de Cali, August 2015

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Declaration of Authorship

I, Nicolás RAMÍREZ PARRA, declare that this thesis titled, 'Design and Construction of a Hand Rehabilitation System Prototype' and the work presented in it are my own. I confirm that:

- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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Abstract

In spite of the existence of rehabilitation protocols designed to restore the functional capacity of the hands, special unfortunate factors in the Colombian context, whereas geographical, social, political or economical, restrict the access to specialized treatment in health institutions. This situation is specially critical for people with a condition of geographic vulnerability that have suffered an injury in hands, since the access to specialized treatment such as rehabilitation procedures, which take several sessions and demand commitment and consistency from the patient, is even more difficult. For this reason, a novel hand rehabilitation system integrable to teleoperated architectures is proposed, that seeks to overcome the accessibility barriers and widen the reach of the specialist of physical therapy.

The design of the device followed an interdisciplinary methodology specially developed for rehabilitation systems, which was already implemented in previous works such as UMCP¹ and SRH² [1, 2], and has been refined from their experiences.

The first main result from this methodology was the design requirements of the system, which gave the guidelines for the basic design and led later to the prototype. This alone is a notorious characteristic of this design since the interdisciplinary requirements assured not only functional considerations, but perception, ergonomic and security considerations as well. And as a result, a patient centered design is achieved, which promotes the continuous use of the device through visceral design concepts and integrates a visual feedback that would motivate the patient.

The main highlights of the design are the mechanisms to execute passive and active rehabilitation procedures, while registering the movement and force data, which can be sent wirelessly to a User Interface. These data can give the specialist quantitative data regarding the patient progress, making the system as whole not only a rehabilitation assisting device, but a powerful tool to monitor the progress of patients during rehabilitation.

The present work presents a system to assist in the rehabilitation of patients with a condition of geographical vulnerability, which cannot replace the importance of physical therapists or physiotherapists, but rather extend their reach and knowledge to people in need of specialized rehabilitation treatment

¹Unidad de Movimiento Continuo Pasivo

²Sistema de Rehabilitación de Hombro

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Abbreviations

EPS	Entidad P romotora (de) S alud
IPS	Institución P restadora (de) S ervicios
ESE	Empresa S ocial (del) E stado
SGSSS	Sistema G eneral (de) S eguridad S ocial (en) S alud
WCPT	W orld C onfederation (for) P hysical T herapy
DANE	Departamento A dmistrativo N acional (de) E stadística
WHO	W orld H ealth O rganization
ICF	I nternational C lassification (of) F unctioning, (Disability and Health)
MCP	M etacarpophalangeal
IP	I nterphalangeal
PIP	P roximal I nterphalangeal
DIP	D istal I nterphalangeal
TM	T rapeziometacarpophalangeal
ROM	R ange (of) M otion
DOF	D egree (of) F reedom
ADLs	A ctivities (of) D aily L iving
BADLs	B asic A ctivities (of) D aily L iving
IADL	I nstrumental A ctivities (of) D aily L iving

Chapter 1

Introduction

There is no better definition for the human hand, as the one already stated by Aristotle in 350 B.C.: The hand is a tool of tools [4]. And with this tool of tools we have built the world around us, hence the interaction with this world requires extensively the use of the hands. This interaction was catalogued by the WHO in a list of activities under the name of Activities of Daily Living (ADL)[5].

However, any person under any condition has a risk of injury that could restrict or limit the functional capacity of the hands and this would echo in the independence during the development of the ADL, which in turn would decrease the individual's quality of life.

Therefore, re-establish the lost functional capacity must be considered a priority and physical rehabilitation procedures would be the medium to accomplish this goal. Although, specialized treatments in the Colombian context present challenging access barriers, specially for individuals with a condition of geographic vulnerability. This situation has led to inconsistent or even inexistent rehabilitation procedures, which would prolong the disability or even turn it permanent, decrementing the individuals quality of life.

The present work presents a novel design of a hand rehabilitation system integrable to a tele-operated architecture that is expected to serve as a medium to *shorten* the distance between the patient and the specialist, and thus overcoming the accessibility barriers for people with a condition of geographic vulnerability.

This document presents in the following **Chapter 2** a deeper insight on the previously introduced concepts, concluding with the description of the problematic situation. Later, in **Chapter**

3 objectives are presented and from this chapter on ,the structure of the document follows the proposed methodology in **Chapter 4**, where the phases to achieve the objectives are described. The second phase of the methodology is presented in **Chapter 5**, where relevant background regarding hands biomechanics and relevant normative for medical devices is presented, however a more detail development of this theory can be found in Appendices **A** and **B**. Later, in **Chapter 6** details the considerations taken while studying the State of Art and Technique and the Semi-Structured Interviews, and explains how to interpret the results contained in Appendices **E** and **G**. As a result from the first part of the methodology, the design requirements are achieve and a partial table is presented in **Chapter 7**, with a description on how to interpret them. The complete table of Design Requirement is shown in Appendix **H**, with its categories and users. Following this Chapter, the most relevant conceptual proposals and selections are introduced in **Chapter 8**. From the selected basic design, **Chapter 9** describes the proposed system, its subsystem and interrelations. This description would continue in **Chapter 10**, which occupies with some detail design considerations. Finally, the conclusion and future works are presented in **Chapter 12**.

Chapter 2

Contextual Frame

This chapter describes the problem definition, specifically, it identifies a user, a need and a context. Additionally, it gives some data of the problem in the Colombian context. It gives an insight of the motivation and expected impact that this project would have, and defines the user towards which the design is intended. In the first section, the guiding concepts of problem are defined and its interrelationships concludes with the “problematic question”. Additionally, it describes statistics and normative for Colombia regarding disability and physical rehabilitation.

2.1 Problem definition

The problematic situation is identified after discussing four fundamental concepts: geographical vulnerability, transitory disability, rehabilitation and life quality, which are connected by auxiliary concepts as shown in the Figure 2.1. These concepts constitute the backbone of the problematic situation approached, giving as well a clear view over the scope and justification behind this project.

As the Figure 2.1 shows, the discussion begins by wondering, why the context on which a rehabilitation procedure takes place, specifically for hand in this particular case, leads to different results. The World Confederation for Physical Therapy (WCPT), in which the Colombian legislation concerning physical therapy is based on, defines the physical therapy as a profession that restores the maximum functional capacity of individuals[6]. However, the context of the

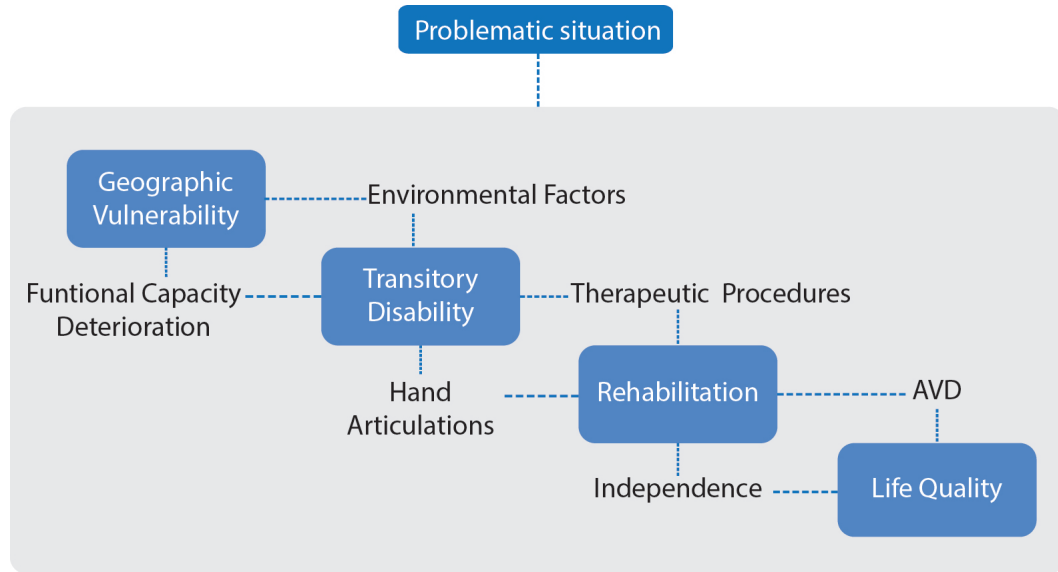


FIGURE 2.1: The governing concepts of the problematic situation defined. Source: Author.

patients in each country is not the same, Thus, in order to characterize these differences, the conceptual backbone begins defining *geographical vulnerability*.

First, the term *vulnerability* is defined as a condition of a person or community, which converges in the risk or probability of being injured or damaged as a result of changes or permanence of situations internal o external to the person or community [7]. Now, stating that these situations are *environmental factors* that limit or even impede the *access* to adequate circumstances for a normal life development, leads to the concept of *geographical vulnerability*.

Furthermore, the *environmental factors* constitute the physical, social and attitudinal context in which the people live [5]. For the Colombian context, these factors depend on the region, as well as the infrastructure that communicate one another and socio-economic conditions; these statistics are shown in detail in the next section.

Following with the concepts shown in Figure 2.1, any person has the risk to suffer an *injury* that can lead to *disability*, which could be permanent or transitory. Focusing the attention on the latter, a person with a condition of *transitory disability*, can restore its ability to a full extend by using different therapeutic methods known as *rehabilitation procedures* and hopefully would then return to its work activities. However, is important to emphasize that a *rehabilitation procedure* is also necessary for permanent disability in order to prevent further degeneration in articulations, but the patient would never recover the lost ability [5].

On the other hand, the *physical rehabilitation procedures* usually take multiple sessions, and as a result, higher commitment of the patient is required. This particularity of therapeutic procedures makes them even more susceptible to failure due to discontinuity along the process. Some of the reasons behind it could be attributed to the person's condition of *geographic vulnerability* described before. Furthermore, if a *disability* is not treated properly with a *therapeutic procedure* or if it is not treated at all, the person would probably depend on a third person to perform *activities of daily living*, as long as the disability continues. The activities of daily living, or ADL, are activities or chores that are performed daily for the normal development of human life, hence a decrement in *independence* while performing ADL would affect negatively the *life quality* of the individual.

Then, **how** a person with a condition of *geographical vulnerability*, that has suffered an *injury* and as a result acquires a *transitional disability*, can overcome the *environmental factors* that limit the access to an effective physical rehabilitation, which is necessary to recover the lost ability and to perform once again *activities of daily living* independently improving its *life quality*.

2.2 Justification

A study of disability in Colombia in 2010 concludes that there is a significant amount of people with geographical vulnerability [8]. According to a census from 2005, a 44.5% of the people that live outside the cities, have a medium-high and high human capital exclusion, in comparison to the situation inside the cities, as is shown in the Figure 2.2. The human capital exclusion is defined as a social exclusion, understood as a negation to the rights' accessibility of health and education, such as the affiliation, the access to medical services, rehabilitation and the educational system [8], in other words, this term is strongly related to geographic vulnerability.

Therefore, these statistics corroborate the importance of people with geographical vulnerability. Even though, there are a several causes behind this phenomena, a centralized distribution of the health centers, known as IPS and ESE, could be one of the leading causes, as shown in the Figure 2.3. This centralized tendency reduces the presence of health centres in Orinoco, Pacific and Amazon regions.

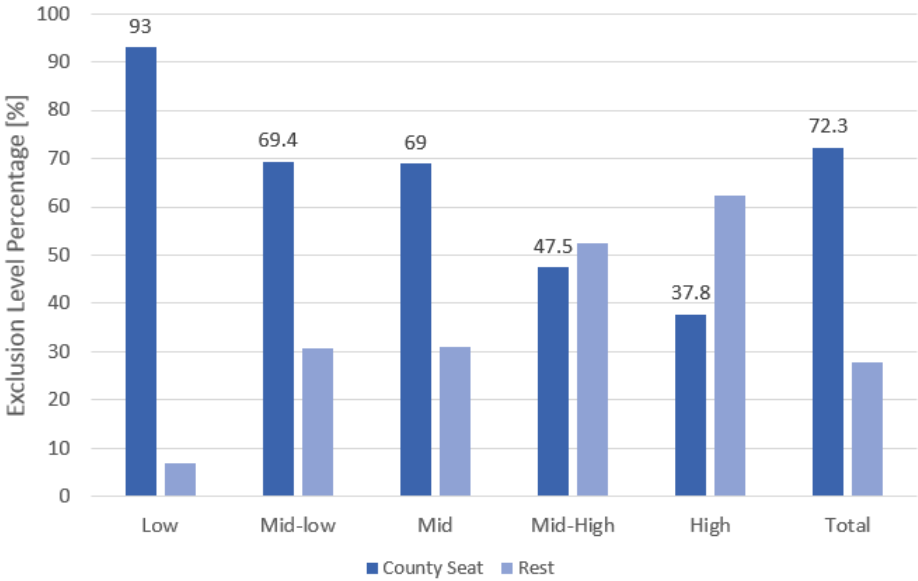


FIGURE 2.2: Percentage of people registered per geographic area according to the level of human capital exclusion. Source: DANE, 2010.

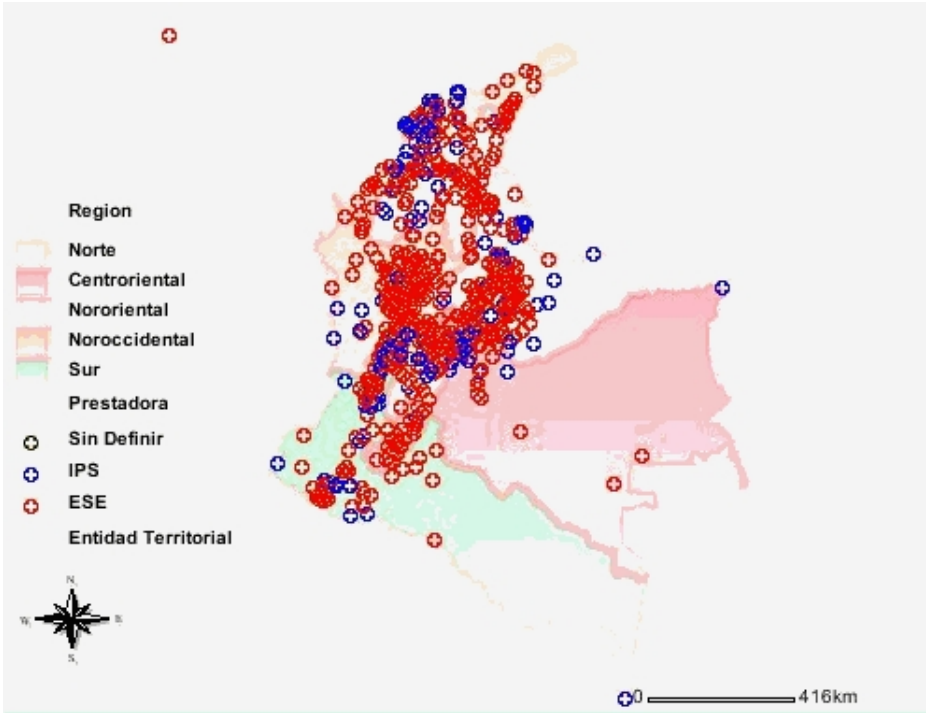


FIGURE 2.3: Regional location of health providing institutions from the subsidiary and contributory regime. Source: Superintendencia Nacional de Salud, 2008.

This situation is even more aggravating if we take a look to the roads' infrastructure in the country, necessary to communicate health centres located in big cities with communities located outside them. Colombia is one of the countries with bigger delays in terms of road infrastructure, occupying the place 97th out of 120 countries in relation to kilometres per inhabitant and density of paved roads, according to the World Bank Economic in 2011 [9]. This deficient infrastructure is presumed to be one of the environmental factors that limits the access to health centres.

Restricted access to health centres and to a therapeutic procedures would prolong the disability condition resulting in a decrease in the life quality. Furthermore, a transitory disability in hands would make the condition even more undesirable, due to the importance of our hands in the activities of daily living (ADL). The report from the World Health Organization (WHO) categorizes the ADL into 56 major categories¹, for example it describes the activities: Use of transport, driving, dressing up, eating, drinking, etc. It is identified that at least 21 of them involve directly the use of hands, as shown in Appendix C.

Even if the extend of the impact in quality of life due to hand injuries appears to be evident, the offer of specialized treatment seems insufficient, as the Figure 2.2 shows.

Even though some articles sustain improvements in the Health System after studying the Colombian Health System since the creation of the law 100 in 1993 [10].²This article explains that in 2009, after 16 years from the creation of law 100, more than 90% of the population is affiliated to the SGSSS, which represents an increment of 60% in comparison to data from 1993. However, it is important to point out the clarification the same report made, regarding the similarities between the definitions of insurance, affiliation and coverage in the law 100 [10]. Thus, having access to a health center, whereas IPS or ESE³, has a wider context than just be affiliated to the SGSSS, because the environmental factors must be taken into account. It can be said that the government is aware of the huge room for improvement, so as an alternative solution in the long term, it encourages the research in technologies such as the *telehealth*, through the law 1419 of 2010.

This law establish the guidelines to the development of *telehealth* in Colombia. Additionally, it encourages the insurance companies and others enterprises that provides services to the SGSSS to offer this modality in their portfolio, as an adequate, effective and rational modality [11].

¹Excluding the "other specified" and "no specified"

²This law creates the General System of Social Security in Health (SGSSS for its name in Spanish).

³IPS and ESE for the contributive and subsidiary regime, respectively.

Thus, the law outline the *telehealth* as a promising support to the Colombian Health System in the near future.

2.3 Chapter Synthesis

In this chapter the problematic question was stated, where a person with a condition of geographic vulnerability and a transitory disability was identified in the Colombian context. Some statistics were also provided to give a quantitative grasp of the problem.

Chapter 3

Objectives

3.1 General Objective

Design and construct a hand rehabilitation system prototype that would serve as a tool that could restore the hand functional capacity in patients with injuries in hand articulations.

3.2 Specific Objectives

- Identify the restrictions and needs of the users that would benefit from using this device.
- Specify the mechatronic architecture that allows hand rehabilitation procedures, such as active assistive and resistive therapy.
- Implement a control system according to the biomechanics parameters that has the possibility to be integrated to teloperated architecture.
- Establish an user interface.
- Construct a hand rehabilitation system prototype.
- Evaluate the mechanical behaviour of the hand rehabilitation prototype using models that resemble the anthropometry of the human hand.

Chapter 4

Methodology

The development of a product for medical applications must take into account the relations between the patient and the specialist's needs, as well as their context. Therefore, this work presents a methodology to develop products for medical applications as described in [1], for the definition of the design requirements.

Initially, the methodology categorizes concepts that are born from a brainstorm and a preliminary research, regarding a chosen topic, for this case: *hand rehabilitation*. After refining and building these concepts through discussions, the governing concepts are defined and then used as the backbone for the problem definition, as was already shown in Figure 2.1. This phase is known as conceptualization phase. Subsequently, the development of the project itself is further divided in four general phases, defined as: Definition of design requirements, conceptual design, establishment of the basic design and construction of the mechatronic architecture, detail design and construction of a prototype to demonstrate its performance. These phases are shown in the general methodology in Figure 4.1.

4.1 Conceptualization

After the brainstorm and the preliminary research, four main concepts are achieved by identifying a *user*, a *need* and a *context* for the problematic situation. In this sense, the discussion starts from the condition of geographic vulnerability, and thus defining a *context* and a condition of a *user*; two auxiliary concepts are used: environmental factors and injury. The latter relates

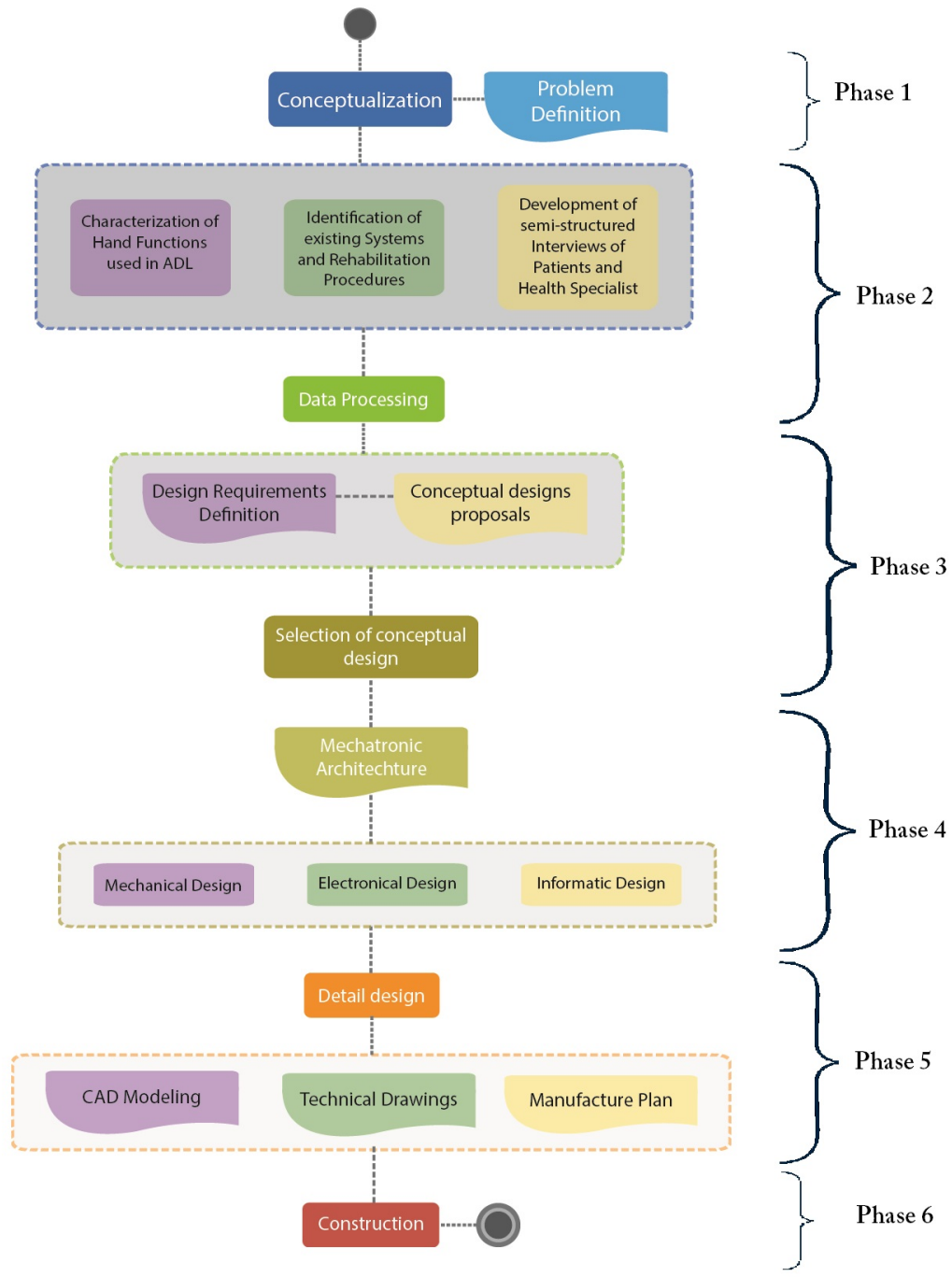


FIGURE 4.1: General scheme for the methodology in the first level of detail. Source: Author.

to disability, which is a condition of the *user*. Although, the context of this work is focused on transitory disability of hand due to its possibility to execute again ADL, is important to note that there are also permanent disabilities of hand which can be benifitiated from therapeutic procedures, in order to prevent further degeneration in articulations.

4.2 Definition of Design Requirements

In this second phase, the articulations and functions of the hand related to ADL are identified. Simultaneously, a detailed study of the systems and rehabilitation procedures (benchmarking) and semi-structured interviews with patients and specialists are made. Several qualitative and quantitative data is collected and then processed to build the design requirements. Each of the processes explained is developed in detail in the following subsections.

4.2.1 Hand's Biomechanics Characterization

A biomechanical analysis of a system can be categorized into a kinematic and a kinetic analyses. On the one side, the kinematic analysis' goal was to identify the range of motion (ROM) of the hand articulations necessary for ADLs, i.e. the functional range of motion (FROM). This was accomplished following the scheme in Figure 4.2. First, a literature review was initially made on ADLs based on the ICF [5], then, the 21 hand-related ADL identified were compared to the 21 principal grips classified by Kapandji [12], shown in Appendix C, to identify which grips are used during ADL, called ADL grips.

Finally, the angles for each ADL grip were measured with a similar device as shown in Figure 4.3, for flexion-extension around the zero position, that is where all the phalanxes are in the palm's local transversal plane. On the one side, the measurement was made from dorsal using positive angles for extension over zero position and negative angles for flexion under zero position. On the other side, the measurement for abduction-adduction starts from an imaginary line across the metacarpals, where abduction is when the finger moves away from this reference line, and adduction is when the finger moves toward the reference line. Positive and negatives angles are used to describe the rotation towards the ulnar or radial side, respectively.

These measurements gave the quantitative data of the range of motion for the hand functions in activities of daily living, also called functional range of motion or FROM.

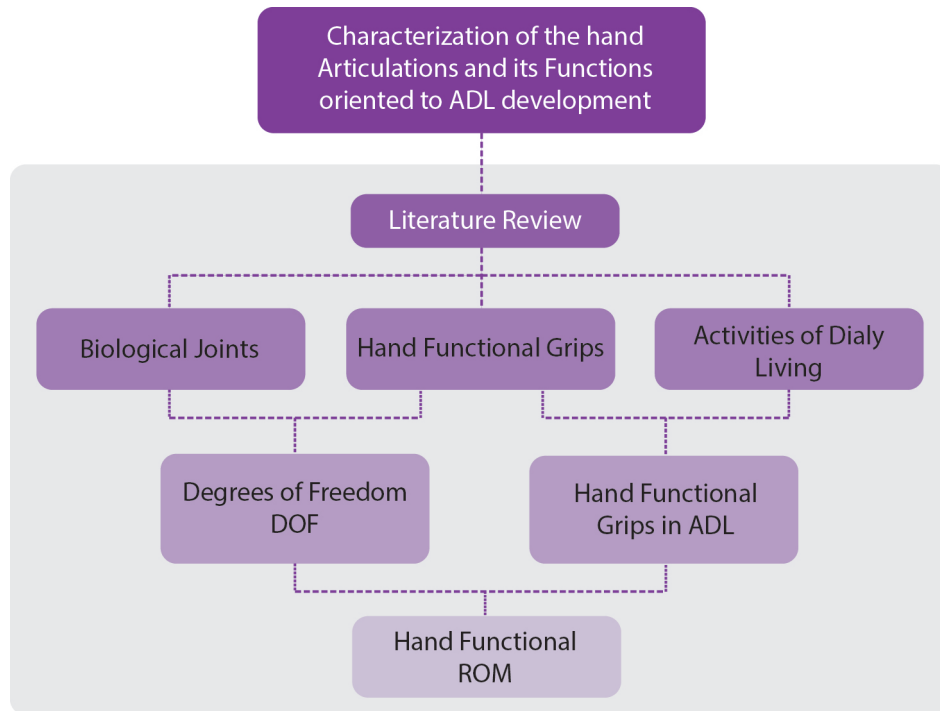


FIGURE 4.2: The hand characterization for ADL was build from the identifications of the degrees of freedom, hand funtions and ADL. Source: Author.



FIGURE 4.3: The goniometer is used to measured the angles in different grips positions. Source: FisioStore.it

On the other side, a kinetic evaluation of the finger motion was made. For this evaluation the normative model proposed by Chao [13] was used to build the biomechanical model. And then, based on the research made by [3], the previously identified range of motion and the anthropometric values the kinetic model was completed.

4.2.2 Benchmarking

The categorization of the State of Art and Technique is crucial to establish a reference point, and then compare the final result with the available (commercial) options. Furthermore, these works presented design concepts that may be considered later on during the design proposals. In order to compare the works from the State of the Art and Technique, some selection criteria is used, as shown in the Figure 4.4.

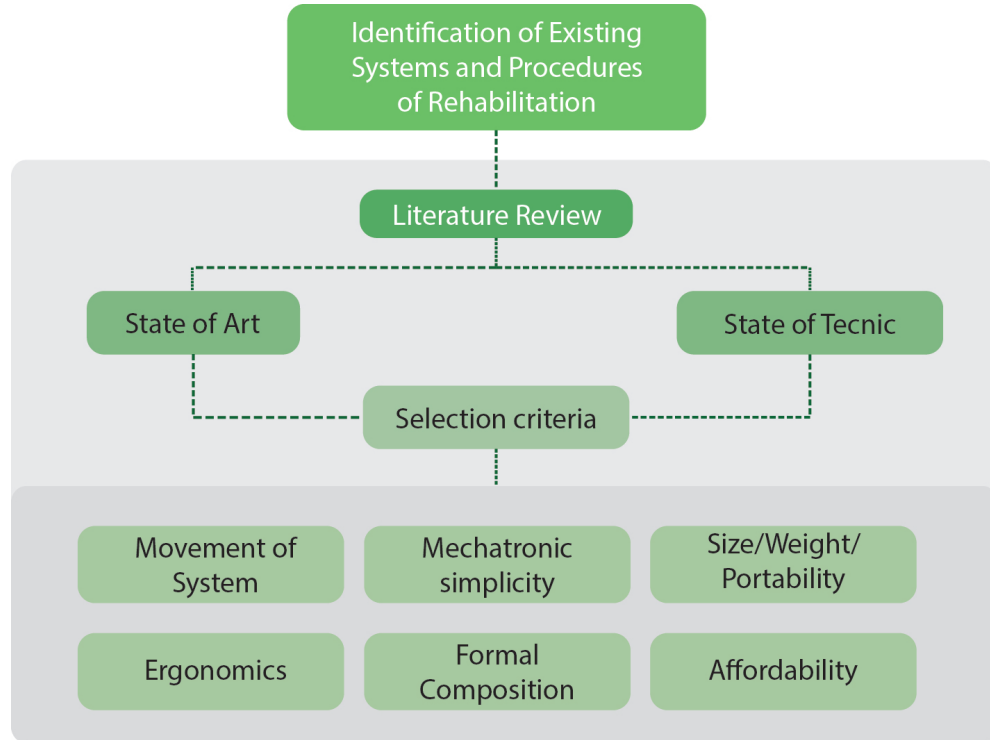


FIGURE 4.4: The identification of the existing systems and rehabilitation procedures was categorized in State of Art and State of Technique, for academic and commercial products, respectively. Source: Author.

Hence, improving the quality of the analysis, the selection criteria parameters were explicitly defined in common agreement with the design team. As follows,

- **Ranges of motion possible:** It accounts for the ranges of motion that the proposed concepts would allow. This criteria also takes into account movement precision. However, there are some wrks that would not applied to this criteria.
- **Simplicity:** It is understood as the number of parts a certain concept may have. The fewer parts a concept involves, the simpler it would be considered.
- **Portability:** It combines weight and dimensional considerations. Would the devise be easy to move from one place to another?
- **Security:** It describes the patient's security considerations that the designer had while designing. They can be mechanical or electronical.
- **Ergonomic criteria:** It concerns with the interaction of user with the device while using it, and how the concept reduces the fatigue or discomfort of the patient. This is not applicable to all concepts and a subjective evaluation was carried out.
- **Perception:** It refers to the emotional interaction between the device and the user, from what the user can "perceive", e.g. sight, textures, security, etc.
- **Affordability:** It includes materials, manufacturability, cost and maintenance.

The prototype developed by this work is compared to these academic and commercial products under the same criteria. With this comparison, one can determine if the performance of the prototype is competitive with the existent state of technique.

4.2.3 Semi-structured interviews

While designing a product for medical applications, the final users of the product must be included during the design process, therefore, patients and specialists were interviewed with the structure show in Figure 4.5. It was a semi-structured interview with the questionnair listed in Appendix D. The questions were oriented to determine whereas the problematic situation identified previously was according to reality, and if that was the case, which parameters must be specially taken into account during the design process.

The results of these interviews widened the perspective of the patient's context, characterized the stages of a rehabilitation procedures and described their principal movements, describe the

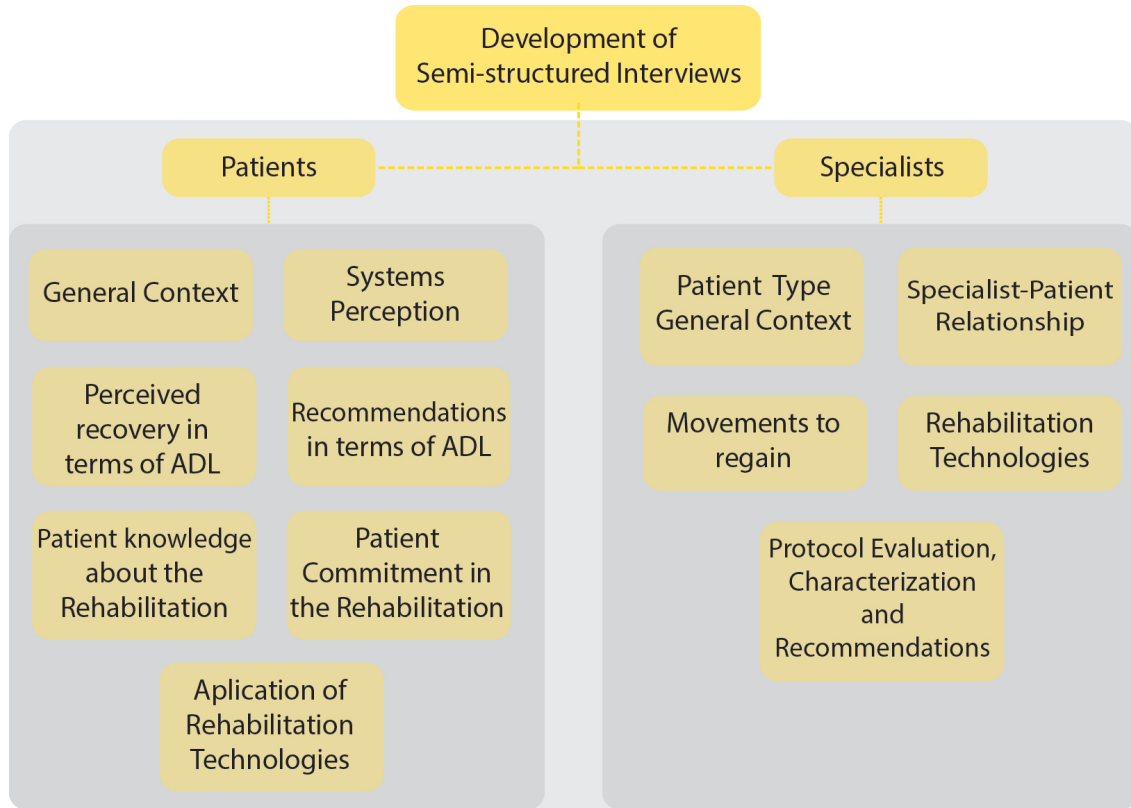


FIGURE 4.5: General scheme for the methodology in the first level of detail. Source: Author.

ergonomic and perceptual considerations needed for a medical product, and gave an insight on the communication between patient and specialist nowadays. Finally, the semi-structured interviews made evident the factors that contribute to an ineffective treatment, which leads to a recurrent injury or a not fully rehabilitated hand.

4.3 Design Requirements and Conceptual Proposals

4.3.1 Establishment of the Conceptual Design

The design requirements from the previous phases are the backbone for selecting individual concepts, which are combined and give form to subsystems, also called modules. A combination of these subsystems and their interrelationships would define the architecture of the basic global design. In other words, the system requirements are envisioned as a guide for all the individual design concepts; whose optimal combination would give form to modules. Consequently, a combination of the modules would give form to basic design proposals.

The selection of the global basic design had different consecutive stages, such as evaluating the concepts from each module separately, then combining the concepts and choosing compatible combinations, comparing the potential performance of each combination and finally selecting the global basic design from global basic design proposals.

The design concepts were chosen by a multi criteria analysis, in which the parameters were the same as for the State of Art and Technique evaluation, e.g. range of motion, simplicity, portability, ergonomic criteria, perception and affordability. To this end, the design team gave the maximum score to the concept that fulfil the parameter better than the other ones. The rest of the concepts would receive an averaged score. The selection fo the electronic concepts was made independendly, using the following criteria.

- **Reliability:** Perform its functions under the stated conditions of operation.
- **Resolution:** The minimum change that the device can detect.
- **Affordability:** Price in the national market
- **Size:** Minimum possible dimensions of the device
- **Assembly:** How the electronic components are assembled on the structure.

4.4 Mechatronic Architecture and Basic Design

The optimal combination an its modules is presented as the basic design, with a list of its constitutive parts. Later, the design team proposes a general *Mechatronic Architecture* using IDEF0 diagrams for the rehabilitation system, the user interface and its interaction with the rehabilitation system, describing its operations, protocols and signal processing. A slight variation from the IDEF0 language convention was used to describe the system, as can be seen in detail in Chapter 9.

4.5 Detail Design

The selected conceptual design must be study from the functional perspectives of a mechatronic design. So, the behaviour under the expected operation conditions must be evaluated from a

mechanical, electronic and informatic perspective, without leaving aside the formal requirements selected in the previous step.

On the one side, the mechanical components of the system were evaluated using kinematic, kinetic, and solid mechanics theory, as described in [14, 15]. Additionally, the mechanical behaviour of key pieces was studied with finite element methods. Critical components such as the principal mechanism, wrist positioner and driven module deserved a more detail explanation. On the other side, the electronic components were selected with the following special criteria derived from the Design Requirements.

The variables of interest for the *local control subsystem* and the *local communication subsystem* were identified and then related with Activity Diagrams, based on the general architecture. Once the architecture was clearly defined and the specific electronic components were selected, the electronic circuit was designed and then simulated by circuit simulation software.

With the results of previous steps, the final dimensions and specifications were determined. The models simulated in previous steps were condensed in 3D detailed models, printable - boards and programming code. As a whole, they would document the actual system and would be helpful as well for some manufacture specifications.

4.6 Demonstration of the expected behaviour

As follows, a prototype¹ of the hand rehabilitation system is constructed with several manufacture techniques. From 3D printers prototyping to industrial machine-tool manufacturing. It is important to emphasized, that this stage depend on how well the design process was built and how well the designers took into account the construction stage during the design process.

4.7 Chapter Synthesis

In this chapter the 6-phased methodology was presented, which is a refinement of the same methodology in previous studies of knee and shoulder rehabilitation systems ???. An special

¹Understood as a sample, model or release of a product built to test a concept or process. It is the step between the formalization and the evaluation of an idea [Advances in usability evaluation, Marcelo M. Soares, 2012, CRC Press p. 482. ISBN 978-1-4398-7025-9.]

emphasis was made on the definition of the design requirements as they would assure the validity of the design as an useful medical device to the intended users. The methodology serves as a guideline for the entire project.

Chapter 5

Characterization of the Hand Biomechanics

The human hand is one of the most marvellous results of evolution. Its principal prehensile function is the most versatile tool human specie had developed and some literature even claim, that specifically the opposable thumb had contributed in a considerable degree to the human brain development [16]. Such a notable structure has been consequently extensively studied, and as a result there are several functional models that describe the human hands.

This chapter summarizes the second phase of the methodology, which is divided in three parts. First, the hand joints and the functional range of motion are described. It is followed by the description of the anthropometric lengths selected to build the biomechanical model. Finally, the biomechanical description of the hand is presented, including the functional range of motion, the kinematics and kinetics of the hand.

5.1 Hand Joints and Axes Convention

The joints of the hand are made of articular cartilage that enables low friction and absorbs vibration in the articulation [17]. The biological joints are simplified to a revolute articulation, with an instant centre of rotation (ICR) as shown in the Figure 5.1.

The main articulations for the fingers 2 to 5 are Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP). For the thumb, the articulations are called

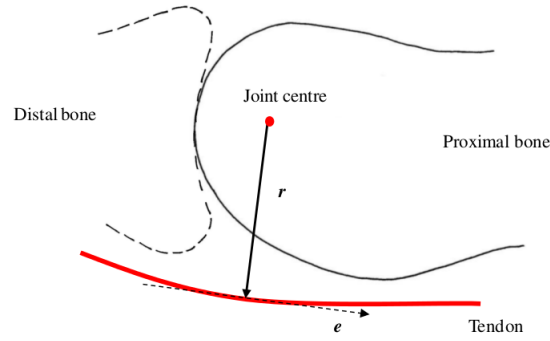


FIGURE 5.1: Hand joint centre approximation. Source: Addapted from Warlow [18]

Trapeziometacarpal (TM), also known as Carpometacarpal (CMC), once again Metacarpophalangeal (MCP) and Interphalangeal (IP). Those are shown schematically as well in Figure 5.2. It is evident that the human hand is a highly articulated object, but it is also a highly constrained one [19]. The most common constrains include the ones within the same finger, such as tissue between joints and fingers, which constrains the maximum range of (finger) motion (ROM). The movement of the articulations is characterized by the relative motions between the distal and proximal segments of the phalanges [20], see Figure 5.1. Therefore, a convention is used to name these articulations as shown schematically in the Figure 5.2.

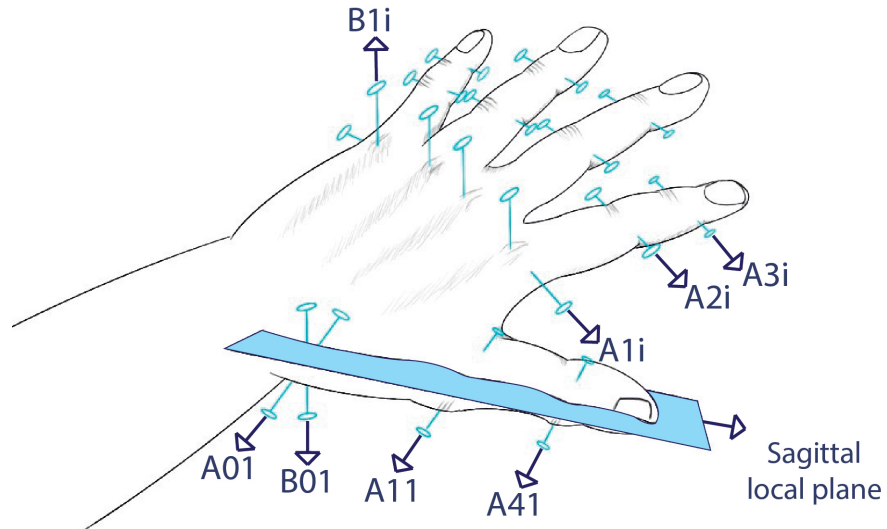


FIGURE 5.2: Descriptive drawing of the hand planes defined for the present study. Source: Author.

For simplicity, a convention for defining the axes is defined as depicted in Figure 5.3. The Table 5.1 lists the axes in each joint, as was also evident in Figure 5.2.

The axes for each degree of freedom (DOF), coincide with the join centre in Figure 5.2. There can be several degrees of freedom on one joint and these are condensed in the Table 5.1. Describing

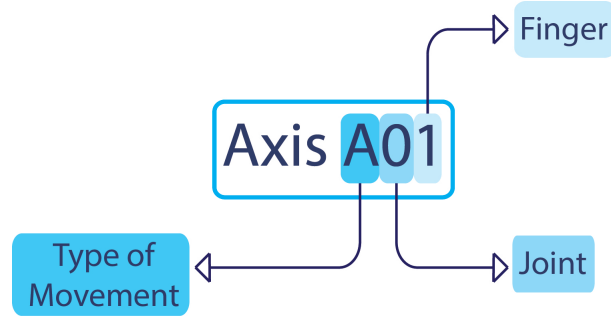


FIGURE 5.3: Axes convention, where the letter stands for the type of movement (“A” for flexion-extension and “B” for abduction-adduction), the first number describe the joint number (TM=0, MCP=1, PIP=2, DIP=3 and IP=4), and the last number is the finger number. Source: Author.

TABLE 5.1: The hand degrees of freedom and functional axes in each articulation.

Finger(s) #	Articulation	# DoF	Axes
Fingers 2 to 5	MCP	2	A1i and B1i, where $i=[2:5]$
	PIP	1	A2i, where $i=[2:5]$
	DIP	1	A3i, where $i=[2:5]$
Finger 1	TM	2*	A01 and B01
	MCP	1	A11
	IP	1	A41

from proximal to distal, for fingers 2 to 5, there is an axis perpendicular to each metacarpal at the MCP joints, which are contained in the local transversal plane of the palm and associated with flexion-extension movements (A1i). Perpendicular to them, but also in the MCP, there are the axes associated with abduction-adduction movements (B1i). Similar axes are contained on local transversal planes for the proximal and medial phalanges and located across the PIP (A2i) and DIP(A3i) articulations. A rotation over each of these axes describe 1 DOF joint for extension-flexion.

As stated before, the thumb must receive a category on its own, by taking special considerations while defining the planes and axes as well. The biological healthy thumb has 3 DOF on the TM joint, and 1 DOF for the MCP and IP joint. From a classical model [21], an axis perpendicular to the palm transversal plane is assumed to be across the TM articulation, defining the rotation around this axis as the abduction-adduction DOF for the thumb. An additional plane is defined as the transversal local plane for the first metacarpal (thumb’s metacarpal), which contains an axis perpendicular to the metacarpal located across the TM joint. Similarly, two more axes contained in local transversal planes in the proximal and distal phalanges, across the MCP and IP joint are defined.

An additional benefit of this convention is that it would allow the description of the digit lengths in the following section.

5.2 Fingers' Functional Range of Motion

As previously noticed, there is a difference between the range of movements (ROM) humans can accomplish by its own will, and the one the articulation can be moved. Consequently, the biological ROM is defined as the passive movement extension to which the articulations listed in Table 5.1 can be moved, constrained by biological connective tissue such as ligaments. However, it is of special interest to correlate the ROM in the hand functions while performing ADLs for each hand articulation. To this goal, a classification of ADL that involve hands is made, and as a result, the hand-related ADL are listed in C.1. Later on, the list of hand functions, as classified by [12] shown in Section C.2, was compared with the hand-related ADL. The resulting matrix in Section C.3 shows the hand function relevancy in ADL and identify the ADL hand functions. Finally, by measuring each hand configuration, the FROM is compiled in Table C.1. The maximum and minimum are condensed in Table 5.2. It describes the expected ROM that the patient should aim after finishing rehabilitation procedure.

TABLE 5.2: The biological range of motion of hand articulations.

Finger	Axis	RoM	Axis	RoM	Axis	RoM	Axis	RoM
1-Thumb	A01	(60,35)	B01	(50,25)	A11	(165,115)	A41	(170,100)
2-Index	A12	(185,100)	B12	(10,-20)	A22	(185,100)	A32	(190,125)
3-Middle	A13	(190,160)	B13	(5,-20)	A23	(170,105)	A33	(180,125)
4-Ring	A14	(200,150)	B14	(25,-10)	A24	(170,100)	A34	(180,125)
5-Little	A15	(185,95)	B15	(35,-5)	A25	(170,100)	A35	(180,125)

5.3 Anthropometry

In order to construct the biomechanical model, a keystone of the device design, the anthropometric values of the phalanges for the Colombian population are needed. As far as the author could verify, neither the lengths nor the masses of the phalanges for Colobian population was available in the literature. Therefore, a series of assumptions were made to approximate values from other studies to the Colombian population as follows.

First, an approximate length of the phalanges was obtained by combining a North American Army report [17] and a Colombian Anthropometric Study with the assumptions explained in Appendix A. In order to list all the measurements, a convention shown in Table 5.3 was employed.

TABLE 5.3: Anthropometric convention for defining lengths

Length Code	Description
di_bh	Length or mass of the phalanx located between the proximal (b) and distal (h) joint in finger i.
w_i	Wide of finger i (Maximum od each finger)
w_H	Hand breadth
c_H	Circumference of the hand (measured in the MCP Joint)
d_P	Palm length
w_W	Wrist wide

The resultant anthropometric data is compiled in the Tables 5.4 and Table 5.5, for length values of women and men.

TABLE 5.4: Anthropometric data for Colombian population (Women 95 Percentil). Modified from ANSUR [17].

Phalanx	Length [mm]	Phalanx	Length [mm]	Phalanx	Length [mm]
d1_01	81	d3_12	53	d5_12	39
d1_14	22	d3_23	28	d5_23	18
d1_4P	32	d3_3P	27	d5_3P	25
w_1	21	w_3	20	w_5	17
d2_12	61	d4_12	50	w_H	105
d2_23	23	d4_23	25	c_H	192
d2_3P	27	d4_3P	27	d_P	101
w_2	20	w_4	19	w_W	60

TABLE 5.5: Anthropometric data for Colombian population (Men 95 Percentil). Modified from ANSUR [17].

Phalanx	Length [mm]	Phalanx	Length [mm]	Phalanx	Length [mm]
d1_01	87	d3_12	58	d5_12	44
d1_14	24	d3_23	29	d5_23	29
d1_4P	36	d3_3P	30	d5_3P	29
w_1	24	w_3	23	w_5	20
d2_12	65	d4_12	55	w_H	105
d2_23	25	d4_23	26	c_H	212
d2_3P	30	d4_3P	31	d_P	113
w_2	24	w_4	22	w_W	60

Secondly, anthropometric data of the masses for each phalanx was not available in the literature, however data regarding the hand as a whole was indeed found in [22]. It was assumed that the

human hand has an uniform density, and so by having the volume and the weight of a human hand and the volume of the phalanges¹, an approximate weight for the phalanges could be obtained. The weight and volume of the hand were taken from [23] as a percent of the total body weight and volume, and the mass for each individual phalanx is listed in Tables 5.6 and 5.7.

TABLE 5.6: Anthropometric data for Latin American population MEN

Phalanx	Value [g]	Phalanx	Value [g]	Phalanx	Value [g]
d1_01	25.3	d2_3P	8.2	d4_23	6.4
d1_14	7.0	d3_12	15.5	d4_3P	7.5
d1_4P	10.5	d3_23	7.7	d5_12	8.4
d2_12	18.1	d3_3P	7.9	d5_23	5.5
d2_23	6.9	d4_12	13.3	d5_3P	5.5

TABLE 5.7: Anthropometric data for Latin American population WOMEN

Phalanx	Value [g]	Phalanx	Value [g]	Phalanx	Value [g]
d1_01	14.9	d2_3P	4.5	d4_23	3.7
d1_14	4.1	d3_12	8.5	d4_3P	4.1
d1_4P	5.9	d3_23	4.5	d5_12	4.7
d2_12	10.3	d3_3P	4.3	d5_23	2.2
d2_23	3.9	d4_12	7.4	d5_3P	3.0

5.4 Kinematic Analysis of the Human Hand

A body kinematic is defined as the the spatial position and orientation of body segments in terms of displacement, velocity and acceleration [18]. The hand kinematic has been extensively studied [19] and several biomechanical models have been proposed to simulate the hand's movements behaviour. The model in Figure 5.4.a. results from modelling the hand articulations with revolute joints at the PIP and DIP joint and a saddle joint at the MCP joint[3]. The saddle joint can be model as two revolute joints, which rotate on different axes.

This particular model consists of 3 linked chains of rigid segments with 4 DoF, for fingers 2 to 5. For the finger 1, the TM articulation is simplified to two DoF, due to its complex measurement.

The two dimensional model of the finger is presented in Figure 5.4.b., which follows the symbol convention in Table 5.8.

The algorithm proposed by Denavit-Hartenberg develops from a "Parameters Matrix" shown below, where θ_i and d_i represent the variable angle and distance, and l_i and α_i are the constant

¹The phalanges are assumed cylindrical

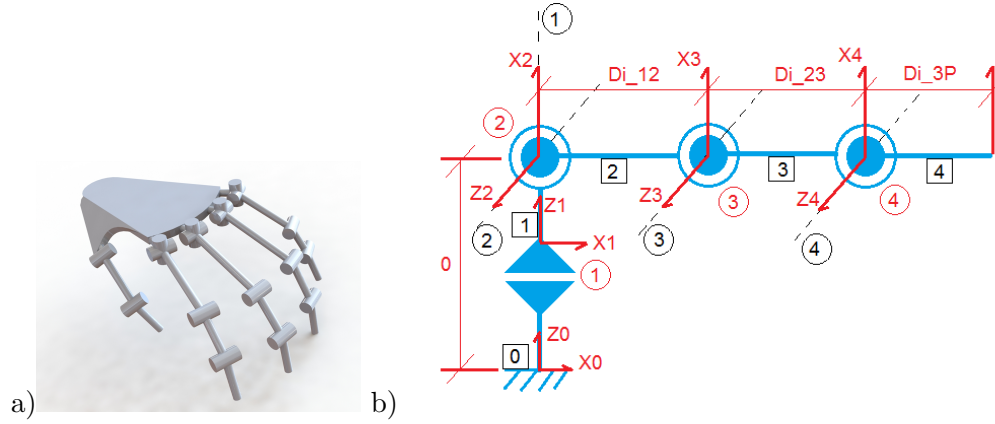


FIGURE 5.4: Simplified robotic model of the human hand in a) 3D and b) 2D, following the Denavit-Hartenberg convention. Source: Author.

TABLE 5.8: Graphical convention for finger joints.

Type of joint	Degrees of Freedom	Representation
Revolute joint with axis leaving the plane	1	
Revolute joint with axis in the plane	1	
Prismatic	1	

lengths and coordinate system rotation that define the system. The parameters for fingers 2 to 5 are summarized in the Table 5.9.

TABLE 5.9: DH Parameters Matrix for Fingers 2 to 5.

Joint	θ_i [$^\circ$]	d_i	l_i	α_i
B1i	θ_{B1i}	0	0	0
A1i	θ_{A1i}	0	0	$\pi/2$
A2i	θ_{A2i}	di_12	0	0
A3i	θ_{A3i}	di_23	0	0
End Effector	θ_{5i}	di_3p	0	0

Note that the coordinate systems S0, S1 and S2 are located in the same point, therefore d1, d2 and d3 = 0. For illustration purposes however these coordinate systems are drawn separately. As a special case, the thumb's parameters are shown in the Table 5.10.

TABLE 5.10: DH Parameters Matrix for Finger 1.

Joint	θ_i [$^\circ$]	d_i	l_i	α_i
B11	θ_{B01}	0	0	0
A01	θ_{A01}	0	0	$\pi/2$
A11	θ_{A11}	d1_01	0	0
A41	θ_{A41}	d1_14	0	0
End Effector	θ_{51}	d1_4p	0	0

The final transformation matrix, from the transform matrix principle, is a combination of the rotational components and the displacement components. The matrices applicable for finger 1 to 5 are shown below.

$$T_4^0 = \begin{bmatrix} T_R & T_P \\ 0 & 1 \end{bmatrix} \quad (5.1)$$

$$(T_4^0)_R = \begin{bmatrix} \cos(\theta_{A1i}) * \cos(\theta_{A2i} + \theta_{A3i} + \theta_{5i}) & -\cos(\theta_{A1i}) * \sin(\theta_{A2i} + \theta_{A3i} + \theta_{5i}) & \sin(\theta_{A1i}) \\ \sin(\theta_{A1i}) * \cos(\theta_{A2i} + \theta_{A3i} + \theta_{5i}) & -\sin(\theta_{A1i}) * \sin(\theta_{A2i} + \theta_{A3i} + \theta_{5i}) & -\cos(\theta_{A1i}) \\ \sin(\theta_{A2i} + \theta_{A3i} + \theta_{5i}) & -\cos(\theta_{A2i} + \theta_{A3i} + \theta_{5i}) & 0 \end{bmatrix} \quad (5.2)$$

$$(T_4^0)_P = \begin{bmatrix} \cos(\theta_{A1i}) * (di_{12} * \cos(\theta_{A2i}) + di_{23} * \cos(\theta_{A2i} + \theta_{A3i}) + di_{3P} * \cos(\theta_{A2i} + \theta_{A3i} + \theta_{A3i})) \\ \sin(\theta_{A1i}) * (di_{12} * \cos(\theta_{A2i}) + di_{23} * \cos(\theta_{A2i} + \theta_{A3i}) + di_{3P} * \cos(\theta_{A2i} + \theta_{A3i} + \theta_{A3i})) \\ di_{12} * \sin(\theta_{A2i}) + di_{23} * \sin(\theta_{A2i} + \theta_{A3i}) + di_{3P} * \sin(\theta_{A2i} + \theta_{A3i} + \theta_{A3i}) \end{bmatrix} \quad (5.3)$$

5.5 Kinetic Analysis of Human hand

Several authors had developed methods to analyse reaction forces and moments in the hand, that a grip can produce on the articulations or even the individual contribution of tendons and muscles in the hand movement [3, 18, 24–27]. However, is Chao et al. in 1978 with the “Normative Model of Human Hand for Biomechanical Analysis” that structured a standardized reference [13]. For this project purposes, the latter model is adopted and a deeper explanation on this can be found in Appendix B.

In order to determine the largest resistance to rotation expected from the patient’ fingers during rehabilitation therapy, several assumptions were made. A stiff hand would be consider as the worst case scenario, although this definition alone is still too vague, because the stiffness have innumerable possible causes [28]. The literature lists some of them: depth scars, poor skin elasticity, neurological problems, ligament sprain, tendon rupture, fibrosis, osteoarthritis, fractures, prolong immobilization, etc. [28].

As was previously established, this project focuses on transitory disability, but permanent conditions benefit as well from therapeutic procedures, however, special considerations should be

taken. For example, injuries or conditions that lead to chronic degenerative pathologies such as arthritis, or damages to central or peripheral nervous system that would affect the hand functional capacity may have highly deformed anatomic features or high sensitivity, are considered out of the scope of the present document. Specially, features such as spasticity which is related to the inhibition of the motor neurons that results into an involuntary and excessive muscle contraction [29]. Then, injuries related only to osteomuscular, tendinous, or ligamentous systems are considered during the design.

On the other hand, the literature lacks of studies regarding biomechanical analysis on injured hands, once again due to the particularities of each condition. Then, it was assumed that the maximum resistance from a stiff hand under the previously listed considerations is *comparable* to the resistance a functional grip would oppose to a force that tries to extend the hand. Several studies agree that the hand exerts the largest tendon force during power-grip[30]. Then, using the results from [3] for the tendon force in power grip configuration, the torques around each joint are calculated using the normative model.

TABLE 5.11: Results from [3] describing the forces in FDP, FDS, RI, UI and LU during Power-Grasp. (Ratio: Tendon force/Grip force)

FDP	FDS	EDC/EIP	RI	UI	LU
1.7	2	0.0	9.0	10.9	0.3

Notice that the biomechanical considerations were made around the flexor tendons since they contribute to cylindrical grips and present the largest forces, in comparison to extensor tendons, in comparison to extensor tendons [24, 30]. Although, various studies also develop biomechanical models and experiments to characterize the extensor mechanism [26] which could be adapted to Chao's normative model.

5.6 Chapter Synthesis

Basic concepts of hand anatomy are described in this chapter, as well as biomechanical considerations to build the hand-model that would be used as basis for constructing the design requirements. Two conventions are described to characterize the FROM and the anthropometric values. These conventions are further extended to the D-H algorithm to name the rotation axes.

Chapter 6

Benchmarking and Semi-Structured Interviews

This chapter begins with an introduction to the normative regarding medical devices. Later on, it describes in detail the State of Art and Technique research, also called benchmarking, which gave some key points to consider while establishing the design requirements and establish a base line with the final design. Additionally, the chapter presents some of the most relevant results obtained from the semi-structured interviews, which provided a better understanding of the specialist-patient relationship.

6.1 Normative

There are several legislations concerning the regulations of medical devices. For the national context, the Decree 4725 of 2005 gives recommendations to reduce risk for patients while using medical devices, while the Agreement 259 of 1983 established parameters to offer optimal working conditions to people with an impairment condition.

On an international context, there are ISO normative such as the UNE-EN ISO 9999:2007 and ISO 9001:1994 which regulates devices to exercise arms, thorax and legs, and dictates quality standards for the design, development, production and installation of a product or service.

These normative served as a guideline while defining the system requirements. However, the scope of the present project does not includes all the regulation contain in the ISO normative.

6.2 Benchmarking

As it was previously seen, there are several regulations regarding hand therapy products, but the market provides quite a large offer of simple devices, mostly to provide resistance to flexion such as therapy balls, torsional springs for strengthening hand grip, or elastic devices for finger extension exercises, as the ones shown in the Figure 6.1.

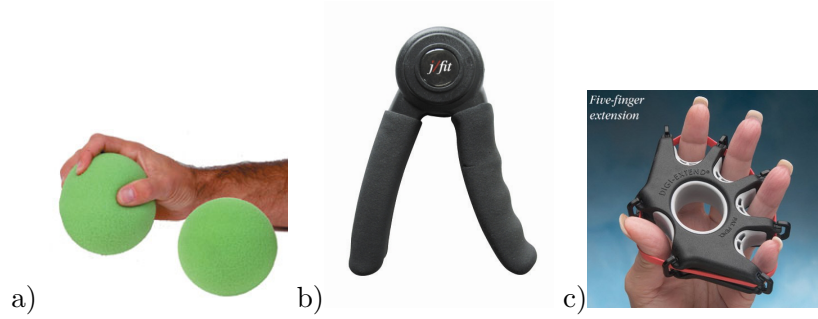


FIGURE 6.1: Traditional hand therapy products. Source: RehabMart.com

However, the present document is oriented to *intelligent devices*, capable of being integrated to a teleoperated architecture. Therefore the design team look for academic initiatives and fully developed products projects with the following key words: *Hand rehabilitation system*, *Hand rehabilitation robot*, *Hand exoskeleton*, *Haptic interfaces*.

Later, the documented projects were catalogue and characterized with the parameters listed in Table 6.1. Although, not all the parameters were applicable for all the devices, because there was a limited technical detail available for some products and academic projects, e.g. electronic prototypes did not show a detailed mechanical description. These parameters are an adaptation for the ones reported by [1].

Then, following the scoring methodology in Chapter 4, the systems were also compared. The results of this scoring are shown below in the Table 6.2.

The best rated projects are reviewed in the following section, however, the complete characterization for all the projects can be found in Appendix G.

TABLE 6.1: Chosen parameters to characterize the State of Art and Technique.

General Parameters	Specific Parameters
Motion	DOF
	Types of rehab. movements
	ROM
	Type of mechanism
	Kinematic
Simplicity	Force
	Torque
	Actuators
	Sensors
	Communication system
Portability	Power supply
	Weight
Security	Dimensions
	Mechanical restrictions
Ergonomic criteria	Electronical /Software restrictions
	Type of contact
	Hand dimensional adjustment
Perception	Noise
	Formal aesthetics
	Design Concept
	Colours
	Textures
	Visual impact
Affordability	Security perception
	Price
	Production processes
	Maintenance
	Materials

6.2.1 Best Rated State of Technique

6.2.1.1 Kinetic Maestra Hand Portable

The rehabilitation system, shown in the Figure 6.2a, focuses on patients with transitory and permanent hand impairments, that would benefit from a continuous passive movement. It has one unique motor that mobilises the fingers simultaneously, except from the thumb. It is produced by the enterprise Patterson Medical. Its ROM varies from 15° in hyper-extension to -90° flexion. Similarly, its range of speeds varies from 27 to 135 seconds per cycle (cycles from 0° – -90° – 0°).

TABLE 6.2: State of Art and Technique Comparison- Weighing

	Weight %	Device 1	Device 2	Device 3	Device 4	Device 5	Device 6	Device 7	Device 8	Device 9
Motion	25	2.5	3.5	2.5	2.5	4.5	4	3.5	2.5	3.5
Simplicity	10	4	2.5	4.5	4	2.5	5	2.5	4	2.5
Portability	10	1.5	3	3	4.5	4.5	3.5	2.5	3	2.5
Ergonomic	20	2	2	3	4	2	2	3	1	3
Perception	25	2	2	3	3	3	3	2	1	2
Affordability	10	4.5	4	4.5	5	4	4	4	5	4
	100	2.525	2.725	3.175	3.525	3.375	3.4	2.875	2.275	2.875

	Weight %	Device 10	Device 11	Device 12	Device 13	Device 14	Device 15	Device 16	Device 17
Motion	25	3.5	3.5	2	3	3	5	3	4.5
Simplicity	10	2.5	2.5	2.5	3.5	3.5	2.5	3.5	2.5
Portability	10	2.5	4	1.5	5	5	2	5	2.5
Ergonomic	20	3	1	3	5	5	4	4	4
Perception	25	2	1	3	5	5	5	4	3
Affordability	10	4	5	4	4.5	4.5	4	4.5	4.5
	100	2.875	2.475	2.65	4.3	4.3	4.15	3.85	3.625

6.2.1.2 WaveFlex

These devices specialises in post-operative treatment of post-traumatic stiffness on the MCP and PIP articulations, Flexor Tenolysis¹, surgically attached hands or phalanges, burn injuries and stable fractures or crushed hands. It also has one unique motor found in dorsal that moves the fingers simultaneously. It is notable that the fingers are attached by flexible bars and it is produced by the Canadian enterprise Remington Medical.

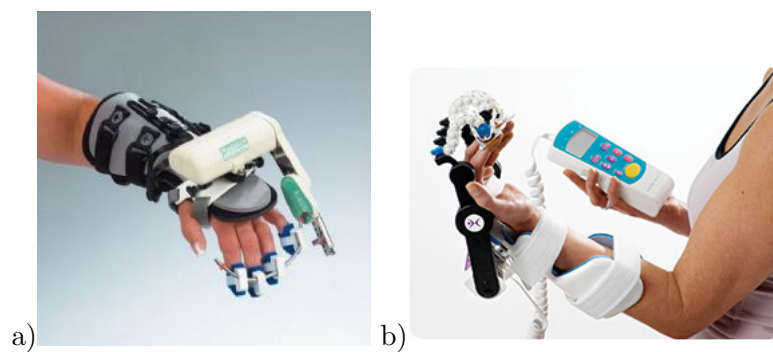


FIGURE 6.2: Best rated devices of the State of Technique. a) Kinetic Maestra Hand Portable and b) WaveFlex.

¹It is a surgical procedure used to remove adhesions that inhibit flexion of digits. Source: emedicine.medscape.com/article/1238950-overview

TABLE 6.3: The colour convention for the Interviews is shown.

Colours	Categories
	Perception of the Devices and Protocols
	Perception of recovery after rehabilitation ADL (functional and psychological)
	Recommendations for stages after the rehabilitation in ADL grips
	Knowledge of patient about rehabilitation (protocols and devices)
	Patient commitment and appropriation with the rehabilitation (before, during rehab and after)

6.3 Semi-Structured Interviews

The interaction with the specialist and patients was particularly important to guarantee an useful medical device design. Although, the scope of this project is not to develop a product², several considerations regarding the rehabilitation procedures were highlighted during the semi-structured interviews with specialists and patients, such as therapy stages, patient and specialist interaction, patient injuries classification, etc.

The complete questionnaire can be found in Appendix D, as well as the complete “Interview-Results Matrix” in Appendix G, where the answers from patients and specialist were recorded. Notice that the matrix was classified with the colour convention in Table 6.3.

Some of the main conclusions are summarized nonetheless in the following section.

- The main reason a patient begins a rehabilitation procedure is due to pain, followed by the lost of function.
- Most of the patients do not complete a rehabilitation procedure. The causes are diverse, but lack of time, lack of motivation and disinformation are frequent causes.

²A product is the item offered for sale. A product can be a service or an item. It can be physical or in virtual or cyber form. Source: The Economic Times. <http://economictimes.indiatimes.com/definition/product>

- Most of the patients do not know about specialized rehabilitation systems for hands. The specialists do know rehabilitation devices, but most of them are rudimentary (not instrumented³).
- The service in rehabilitation centres is not personalized (due to limitations in infrastructure).
- Most of the evaluating criteria is subjective and based on the specialist experience.
- The specialist gives an initial diagnose and then a series of test are executed by the patient to measure the extend of its disability condition, an action plan is elaborated, then executed and finally the patient is re-evaluated.
- The therapeutic procedures can be classify in three major stages, edema reduction stage, arc of movement retrieval, and finally the strengthening stage. However, these stages are not necessary consecutive and the specialist may execute all of them in a single session⁴.
- The success in the rehabilitation procedure lies on the patient's discipline. For example, exercise at home as indicated in the therapy and its motivation to continue the rehabilitation are fundamental.

These conclusions were then translated to requirements, mostly from the ergonomics and perception category.

6.4 Chapter Synthesis

In this chapter, a general overview of the relevant normative for medical devices and the results achieved from the State of Art and Technique study and Semi-Structured Interviews were shown. It describes how to interpret the complete *State of Art and Technique Matrix* in Appendix F and under which parameters would the design presented in this document be compared to similar products in the market. Additionally, it presents a summary of the most relevant results achieved by the semi-structured interviews, whose complete results and investigation instrument can be found in Appendix D and E.

³It refers to devices that use sensors

⁴Further information regarding the hand rehabilitation is summarized in Appendix A

Chapter 7

Design Requirements

The design requirements are the result of the second phase of the methodology which intends to fulfil the general objective. This chapter is divided in three parts. First, a classification of the design requirements is introduced and in a similar manner, a classification of “user” relevance. Both classifications make easier to discriminate the intended design goal and propose corresponded conceptual design proposals. Then, section 2 describes some of the most relevant design proposals, its advantages and disadvantages. Notice that the requirements take as a base the Teleoperated architecture shown in Figure 7.1 below, already implemented by [1, 2]. This architecture defines 3 users and two places, which are communicated by internet protocols.

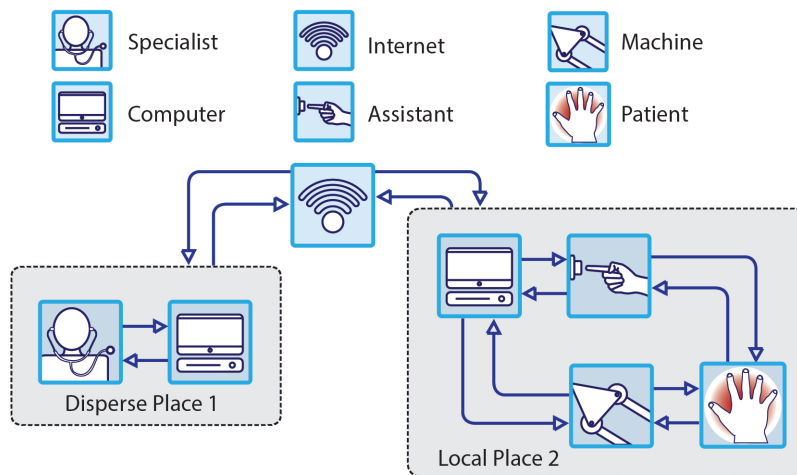


FIGURE 7.1: Proposed architecture of a Teleoperated Rehabilitation defining the local and disperse geographical places

7.1 Design Requirements Categories

The design team proposed a classification of the requirements in the following categories,

- **Safety:** Which precautions should be taken for the patient sake (patient oriented design)?
- **Functional:** How should the system work without interfering with the last category?
- **Ergonomics and Perception:** How can the system be more appealing to the user without interfering with the last two categories?
- **Maintenance:** How can the system prolong its lifetime without interfering with the last three categories?

This categorization allows the design team to approach the design in a interdisciplinary manner, where the functional considerations must coexist with safety and aesthetics requirements.

7.2 Users Categories

Additionally, the design team realized that some requirements are oriented specifically to certain users or several users simultaneously, but with different priorities. Therefore, a second classification was made, but in this case describing each user of the architecture in Figure 7.1.

- **Main Specialist:** It is the person with specialized knowledge in charge of the initial diagnose and the plan of action. Its main responsibility is the elaboration of the therapy's protocol and supervises the remote therapy.
- **Assistant:** It serves as a communication bridge between the main specialist and the patient. Its main activities include receiving and preparing the patient for the therapy, installing the system on the patient, and executing the stages of the rehabilitation therapy as notified by the specialist.
- **Patient:** It is the main user and its context was already described in Chapter 2. It should follow the instructions given by the assistant and communicate any discomfort during the therapy.

- **Machine:** It refers to the system software and hardware. Its interface allows the user to operate the device. Its main function is to execute rehabilitation protocols defined by the specialist and record the patient progress during the therapy session.

7.3 Design Requirements(partial)

Both classifications are shown in the list of Design Requirements, which can be seen partially in the Figure 7.2 below. The complete list of design requirements can be found in Appendix H.

		Requirements	Description	Principal Actor			
				Specialist	Auxiliar	Patient	Machine
1		Have a work volume inside the functional range of motion.	If there are positions outside the FROM, there is a chance that device might injuty the patient.			1	2
2		Stops the position of the device in case of a eventuality.	The specialist decides if the therapy procedure should be stopped in case of any eventuality.	1			2
3		Return to rest position after a eventuality takes place.	Understanding eventuality as external factors such as: patient uneasiness, low electric fluid, loss in connection or binding. Or internal factors such as: failure of the mechanical, electronic components.			1	2

FIGURE 7.2: List of design requirements (partial) with categories.

The design requirements served as a check list for the basic designs and ensured the validity of the design as a possible solution to the stated problem.

7.4 Chapter Synthesis

This chapter summarizes the methodology main results for defining the Design Requirements, as well as its internal classification and user's perspective. Additionally, it shows the partial list of design requiments and its categories.

Chapter 8

Conceptual Proposals

Following the design requirements shown in the previous chapter, the conceptual proposals are described. Some of the most remarkable concepts involve the mechanisms and electronic components to execute and register passive movements, control and quantify the opposing resistance in active movement, maintain a defined posture of the wrist ¹ and control several DOF simultaneously. Each of these concepts would be the principal concept for each module of the device and by the end of the chapter, a selection of the possible concept-combinations is made to determine the basic design. It is important to note however, that the selection of the electronic concepts was made independently but still follows the listed design requirements.

At the same time, the concepts of simplicity and ergonomic assure perceptions and comfort requirements, which are fundamental in medical devices. These requirements promote the use of curves and smooth surfaces and demand the use of aseptic materials in the mechanical and electronic conceptual designs as well.

As the literature and the semi-structured interviews showed, in the first stage of the rehabilitation the specialist would define if the patient's wound has healed enough and/or the edema has reduced to an acceptable size to begin the passive and active exercises. The specialists agree that both therapeutic procedures are necessary for a complete rehabilitation [28].

¹The wrist angle would depend on the patient condition and should be established by the specialist

8.1 Passive Movement

In this first section the proposed passive movement mechanisms are presented, as well as the sensors required to register and control angular motion. The Design requirements stated the need to accomplish the FROM, which includes flexion-extension and abduction-adduction movements at the MCP joint. However, from the State of Technique it could be appreciated that any device actuates passive movement in B1i. Additionally, from the Semi-structured Interviews, it could be appreciated that the traditional therapeutic devices are strongly focused in flexion-extension. However, the importance of positioning the MCP articulations is fundamental for an integral rehabilitation. Hence the design team propose to control passive flexion-extension movements, but leave the abduction-adduction DOF to positionate the fingers.

Before the selection of the main mechanism of passive movement, two preselections were made. First, it was decided whether the mechanism should be dorsal or volnar. The following table compares the advantages and disadvantages of each.

	Dorsal mechanism	Volnar mechanism
Advantages	Anatomical congruency enables access to complete ROM	Mechanical advantage and minimum load on articulation
Disadvantages	Mechanical advantage	Interference with flexion ROM

8.1.1 Mechanical Proposals

Due to the FROM specified in Section 5.6, volnar mechanisms are not suitable to this application. The second pre-selection was made to select between exoskeleton-like systems and "desktop" systems. The latter was chosen, mainly after realising the complexity in force transmission in dorsal desktop devices. In other words, dorsal mechanisms are more suitable to exoskeletons, while volnar mechanisms work better in desktop devices. Additionally, a dorsal mechanism comes with the space restriction, since the surface in the hand is limited, as well as ergonomic limitations due to the weight in the hand. Therefore, indirect transmission of force is linked with the dorsal mechanisms concept.

In this sense, dorsal mechanisms were proposed and brief descriptions, their advantages and disadvantages are summarized in the following sections.

8.1.1.1 Four-bar

A variation of the four-bar mechanism was proposed, taking advantage of the 1-revolute joint property of the fingers' joints. The third bar of the mechanism would be the patient's phalanx and this would assure minimal reaction force at the biological joints while allowing acceptable transmission of torque.

The indirect transmission mechanism could be accomplished with a system of discs and Bowden-cables. Additionally, this mechanism could work as well with pneumatic or hydraulic systems, but due to the increment in price and complexity, this systems were discarded.

Advantages: Simplicity, easy manufacture, direct kinematic analysis possible, light weight.

Disadvantages: Poor power transmission, undesirable accelerations may appear, complex control.

8.1.1.2 Pinion-rack mechanism

The mechanism guarantees an optimum power transmission due to the property of pure rotation. The mechanism transforms rotation motion into linear displacement, which would make the fingers rotate around its axis. The initial rotation of the pinion is driven once again by a pulley and Bowden cables. No other transmission mechanism is applicable in this case.

Advantages: Optimum power transmission and precise control of rotation.

Disadvantages: Complex control to coordinate the input and output rotation, complex manufacturability and weight.

8.1.2 Sensors to Register Angular Motion

The market offers several types of sensors to register angular motion, but some of the most popular sensors are potentiometers² and transducers encoders³. However, non-conventional sensors such as *flat resistors* (also called Flex Sensors) may be appealing for the application in terms of assembly options.

²It is a voltage divider device that can behave as a variable resistor as it rotates

³It is an encoder device that would translate the information of a rotatory (or linear) position to an analogue or digital electronic signal and there are numerous types, such as optical or magnetic

TABLE 8.1: Selection of the angular motion sensor

	Weight	Potentiometer	Optical transducer encoder	Magnetic transducer encoder	Flat resistor
Reliability	20%	5	5	5	5
Resolution	20%	5	5	5	5
Affordability	10%	5	5	4	3
Size	25%	5	3	3	4
Assembly	25%	3	3	3	5
	100%	4.5	4.0	3.9	4.6

With the criteria in Section 4.3.1, the design team made the selection of the sensor as can be seen in Table 8.1.

The flat sensor was selected by a close margin from the potentiometer. The main differences between them were the affordability and the assembly. Although the miniature-sized potentiometers are less expensive, they are more difficult to assemble to the device structure.

8.2 Active Movement

The active movement is necessary to regain strength and control over the muscles. As described in Appendix A, there are several types of active exercises, however the device would focus on isotonic and isometric exercises, because of their relevance in hand rehabilitation procedures, as has been evident during the interviews with the patients. Additionally, several traditional hand therapy products can complement fairly well the home exercises, as the ones presented in the State of Art and Technique.

From the mechanical point of view, two design concepts are proposed: the use of brakes and the use of springs. The following sections describe their advantages and disadvantages.

8.2.1 Mechanical Proposals

8.2.1.1 Brakes

On the one side, the use of brakes restricts the movement of the pulleys by friction, as can be seen in an elevator brake mechanism. On the other side, the number of parts involved and the size that it should have for this application, increase the complexity of the mechanism.

Advantages: High reliability for isometric active therapy.

Disadvantages: Not ideal for isotonic active therapy, because the friction restriction can not be easily controlled. Increment in costs and complexity is expected.

8.2.1.2 Springs

Springs attached at the end of the Bowden cables provide an opposite force that would restrict the patient movement. According to the therapy level, different stiffness can be used.

Advantages: Allows different levels in the isotonic therapy. Isometric therapy can be executed using springs with large stiffness⁴.

Disadvantages: The springs' resistances are discrete. An increment in therapy's duration is expected as the springs must be changed. Additionally, this change must be made by the assistant.

8.2.2 Sensors to Register Exerted Force

To give the specialist a quantitative notion of the progress of the active hand therapy, the design requirements stated the need for a force sensor. Similarly to the angular sensors, there are several types of force sensors. On the one side, the load cells, which are commonly used in industry, create an electrical signal proportional to an applied force. There are several types, for example strain gauges or piezoelectric load cells. Additionally, special types of force sensors called *flexi-force* sensors are used in several application which includes robotics and medical devices[31]. On the other side, there are devices that measure force indirectly, taking advantage of the Hooke's Law. These devices are usually encoders that measure linear displacement of an elastic media with known stiffness.

As can be seen in Table 8.2, the flexi-force sensor had a clear advantage over the other devices. The main differences are the resolution and the assembly of these sensors. As for the resolution, the strain-gauges and piezo-electric load cells are designed for large-scale applications, so its resolution and ranges are not required in the device. Additionally, the assembly of such components is more complex in comparison to the Flexiforce.

⁴The stiffness of the spring must be higher than the expected force of the hand in power-grip

TABLE 8.2: Selection of the force sensor.

	Weight	Strain-gage	Piezoelectric	Flexiforce	Indirect measurement
Reliability	20%	5	5	5	3
Resolution	20%	3	3	5	4
Affordability	10%	3	4	4	5
Size	25%	5	3	5	4
Assembly	25%	3	3	5	4
	100%	3.9	3.5	4.9	3.9

8.3 Fix Wrist Posture

The design requirements stated the need to immobilize the wrist posture in order to execute therapy in the fingers. Interfering with the wrist articulation itself and eminences such as ulnar head of the extensor tendons are the main challenges. Additionally, the mechanism should allow a position between 20 degrees extension and 30 degrees flexion. Several mechanism were proposed to provide this fixed posture.

8.3.1 Short Four-Bar mechanism

A traditional four-bar mechanism is proposed with the driven bar (second bar) would be as close as possible to the wrist and the fourth bar would be the dorsal surface of the device, where all the other mechanisms would reside. A ratchet-like mechanism is necessary as well to secure the desire position.

Advantages: It is simple and easy to manufacture.

Disadvantages: Force transmission angles are poor. In order to provide the necessary ROM without interfering with biological eminences, prominent curves in the third bar are needed.

8.3.2 Long Four-Bar mechanism

It is also a four-bar mechanism, however the driven bar (second bar) would be farther from the wrist articulation.

Advantages: It is simple and easy to manufacture. Better aesthetics.

Disadvantages: Larger input torque is necessary and poor force transmission angles. The size is also incremented in order to provide the necessary 30 degrees in flexion.

8.3.3 Push n' Roll Mechanism

The mechanism has basically two stages. On the first stage, there are pins that will not allow the rotation of the mechanism core. Springs would constantly try to maintain the core in this position. Once the user “push” the mechanism, the core would move to the second stage where the pins no longer constrain its rotation.

Advantages: Compact size, increased control over the ROM.

Disadvantages: High complexity and cost.

8.4 Control Several DOF

8.4.1 Mechanics Proposals

One of the major challenges of this design is the number of degrees of freedom that the device should accomplish in passive therapy. Additionally, as stated before, indirectly force transmission is necessary due to space limitations on the dorsal surface of the hand.

8.4.2 One Motor One DOF

The most straightforward approach would be to use one motor for each degrees of freedom.

Advantages: Simultaneous control of the DOF.

Disadvantages: High cost. Complex control design. Heavy weight.

8.4.2.1 Interchangeable Bowden Cables

From the semi-structured interviews, the specialist found no limitation in making the therapy “one finger at a time”. Although it clearly would increase the duration of the therapy, there are not medical restrictions. Therefore, a second mechanism is proposed with interchangeable

Bowden cables with a unique motor. The assistant would be in charge of changing the position of the Bowden cable for each articulation.

Advantages: Does not require an extra mechanism. Light weight and low price.

Disadvantages: Increased responsibility for the assistant. High increment in the therapy duration is also expected.

8.4.2.2 Gearbox

Evolving from the previous concept, a gearbox is proposed to change between each pulley. The term “Gearbox” can be misleading since it is immediately related to a device to increase torque. However, in this case the property of interest is the possibility to transmit torque selectively to other shafts, with a unique torque input.

Advantages: The complete DOF range can be achieved and can be actuated remotely.

Disadvantages: High cost. Increment in the therapy duration because the therapy must be “one finger at a time”.

8.4.3 Electronic Proposals

Similarly to the previous requirement, the electronic control must receive and send signals to and from several sensors with limited number of ports. One possibility is to use several microprocessors in master-slave configuration, but this would increment not only the cost but the complexity. Instead, a multiplexer (or mux) is proposed to select one of several analogue or digital inputs, and a demultiplexer (or demux) is used in the opposite direction, thus taking a single input and selecting from several outputs.

8.5 Materials

From the design requirements it is established that due to ergonomic restrictions the device must be as light as possible, while guaranteeing a minimal deflection, thus materials with low-density and good weight/resistance ratio are ideal. Manufacturability of the pieces should be considered as well.

Additionally, the materials should be aseptic, in the sense that they must be easy to clean and resistant to corrosion. And from the *Perception Requirements* it was established that the surfaces must be as smooth as possible to transmit a sensation of security.

There are two types of materials and manufacture procedures that one must take into account. On the one side, the materials for the final product that would involve the manufacture procedures associated with production lines such as the use of dies, and on the other side, the use of materials associated with prototyping.

For the prototype construction, the material proposed is ABS, a synthetic thermoplastic. And for the final device, aluminium is selected. Further information of its mechanical behaviour can be seen in Section 10.1.2.3.

8.6 Selection and Basic Design

The following Table 8.3 compares the selection for every possible combination of conceptual proposals, using the same criteria defined in Chapter 'refChapter4 for the Benchmarking, i.e. simplicity, portability, security, ergonomic criteria, perception and affordability. In order to identify all the possible combinations, a letter is assigned for each of the previous categories, and a number for each possible concept. For example, C3 corresponds to the category C: "Fix Wrist Posture" and the concept 3, which is the 3: "Push n' Roll Mechanism". It is important to point out that the concepts for the "Control Several DOF" category are reduced to one, "the Gearbox", since the other two can not fulfil the design requirements. Additionally, the electronic components were also selected independently.

8.7 Chapter Synthesis

This chapter presents the conceptual proposals according to the design requirements. A combination of the concepts from each module give a total of 12 possible basic designs. The mechanism to control several DOF and the electronic devices were selected independently.

The chosen basic design is a combination of concept A1, B2 and C3, from the passive, active and wrist modules. In other words, the device would have a four bar mechanism to control passive

TABLE 8.3: Selection of the basic design from the combination of the design concepts

	Weight	A1-B1- C1-D3	A1-B1- C2-D3	A1-B1- C3-D3	A1-B2- C1-D3	A1-B2- C2-D3	A1-B2- C3-D3	A2-B1- C1-D3	A2-B1- C2-D3	A2-B1- C3-D3	A2-B2- C1-D3	A2-B2- C2-D3	A2-B2- C3-D3
Simplicity	20%	5	5	4	5	5	4	3	3	2	3	3	2
Portability	10%	5	5	5	5	5	5	4	4	4	4	4	4
Security	30%	3	3	5	3	3	5	3	3	5	3	3	5
Ergonomic	20%	3	4	4	3	4	4	4	5	5	4	5	5
Perception	10%	4	4	5	4	4	5	4	4	5	4	4	5
Affordability	10%	3	3	3	4	4	4	2	2	2	3	3	3
	100%	3.7	3.9	4.4	3.8	4.0	4.5	3.3	3.5	4.0	3.4	3.6	4.1

movement, which is controlled by Bowden Cables attached to a driven module called “Gear-Box”. As for the active therapy, it uses spring modules that allow different levels of therapy with different spring stiffness. Finally, a mechanism called “Push n’ Roll”, would be used for positioning the wrist flexion and extension position. The selected sensors for measuring angles and force are the flex resistor called “Flex Sensor” and the force resistor called “FlexiForce”, respectively.

Chapter 9

Hand Rehabilitation System Architecture

From the scoring in previous Chapter, the basic design is achieved. It is explained in the first part of this chapter followed by a description of the mechatronic architecture, i.e. the systems, subsystems and their interrelationships were explicitly described by IDEF0 diagrams. A variation of the IDEF0 language convention is used for describing the system, where each system and subsystem is understood as a function that transforms *Inputs* into *Outputs*, while there are certain external parameters and instructions that would *Control* the system. Additionally, each system would require certain *Mechanisms*, which includes components, tools and personnel. The system would be shown in this chapter in a top-down fashion, from general to specific. After the general architecture, the global Activity Diagram of the rehabilitation session is shown. It describes the expected activities of users during an actual session, with the teleoperated architecture. Once again, the assuming that this architecture is already implemented. More detailed Activity diagrams are shown in [Appendix J](#).

9.1 Basic Design

The basic design, shown in [Figure 9.1](#) consists of four-bar mechanisms and spring modules with indirect power transmission, that register the flexion and extension angles of the fingers during passive therapy and the indirect force of the fingers flexion during active therapy. It employs a Gear Box and a multiplexer to select individual fingers and execute the rehabilitation protocols

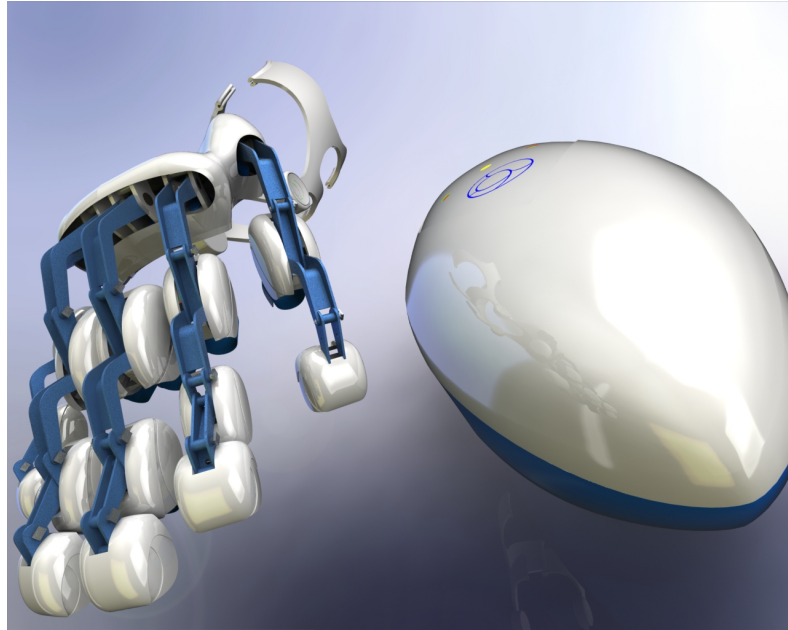


FIGURE 9.1: Hand module and gear box complete design

“One Finger at a Time”. Additional features include a Wrist Positioner and the possibility to separate the Finger modules from the orthosis.

According to the design requirements and the conceptual proposals, a basic design is achieved. It is divided in six modules for its description, beginning from proximal to distal, and from the hand to external modules.

9.1.1 Hand Orthosis and Push n’ Roll Mechanism

Initially, the Forearm and Wrist modules would make the hand orthosis and the main structure for the hand device, as can be appreciated in Figure 9.2. It has elastic-textile parts that enables different dimensions of forearm and wrists. Additionally, the material used for its construction was ABS plastic.

Continuing with the dorsal module, it has several levels. In the first level, strategically positioned pads are found to avoid hand particularities and pressure points. In the second level there is an electronic board, which contains the electronic components that would serve as intermediaries between the sensors and the main electronic board, which can be found in the GearBox. In the following level, the bowden cables are distributed at the dorsal surface and then driven to the Gear Box. On the top level, the abduction and adductions modules serve to position the fingers passively. Finally, a dorsal surface covers all the mechanisms.

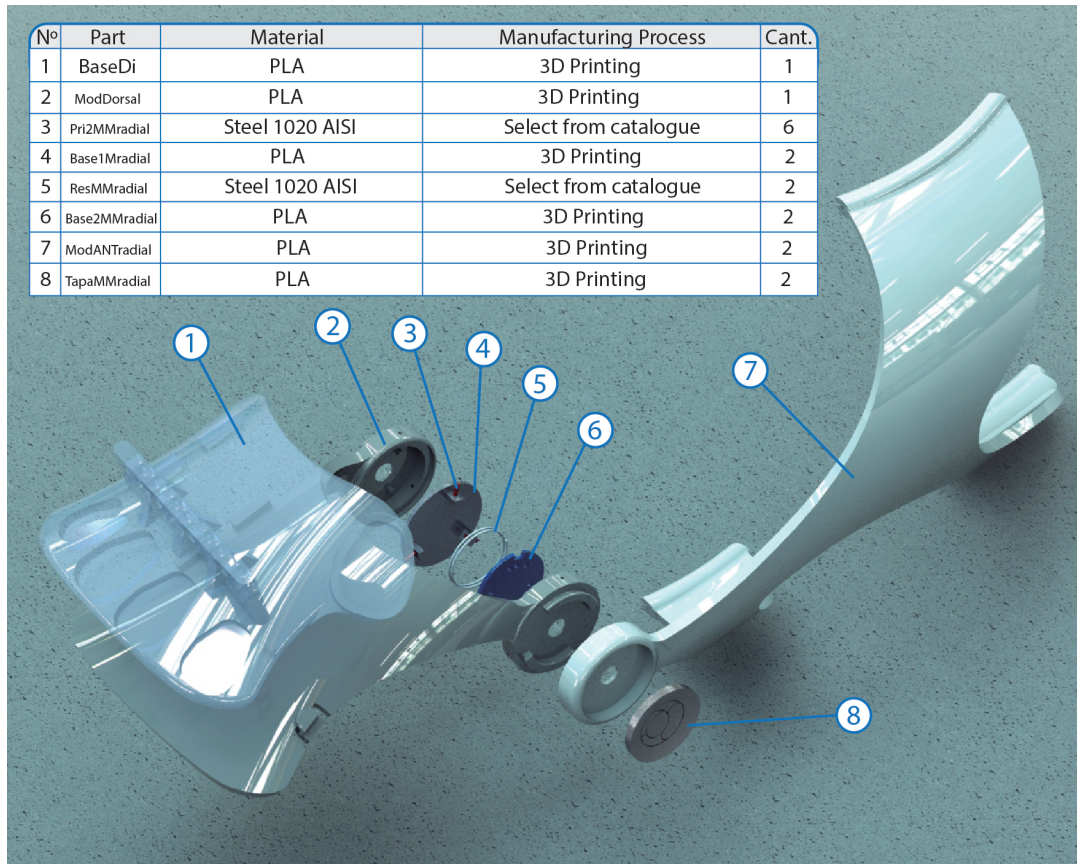


FIGURE 9.2: Orthesis module with the forearm and wrist mechanism

9.1.2 Passive Mechanism: Four Bars

The previous Figure Figure 9.3 shows as well the abduction-adduction modules, which serve two functions. First, they serve as support for the Four Bar mechanism and second, they enable passive abduction-adduction positioning of the fingers. As for the Four bar mechanism, it consists on curve shaped bars with U profiles, which uses the biological phalanx as the third bar. The unusual shape allows to conduct electronic and Bowden Cables, and to avoid the heads of the metacarpals during passive therapy. A pulley system can be found at the base of the second bar for the proximal and distal four bar mechanism. This is connected to the Gear Box via Bowden Cables, as depicted in Figure 9.4.

9.1.3 Active Mechanism: Spring Modules

The active therapy is accomplished through a 5th Bowden Cable that is fix to the distal support. It is designed for active exercises which are resistive in flexion and assistive in extension. During

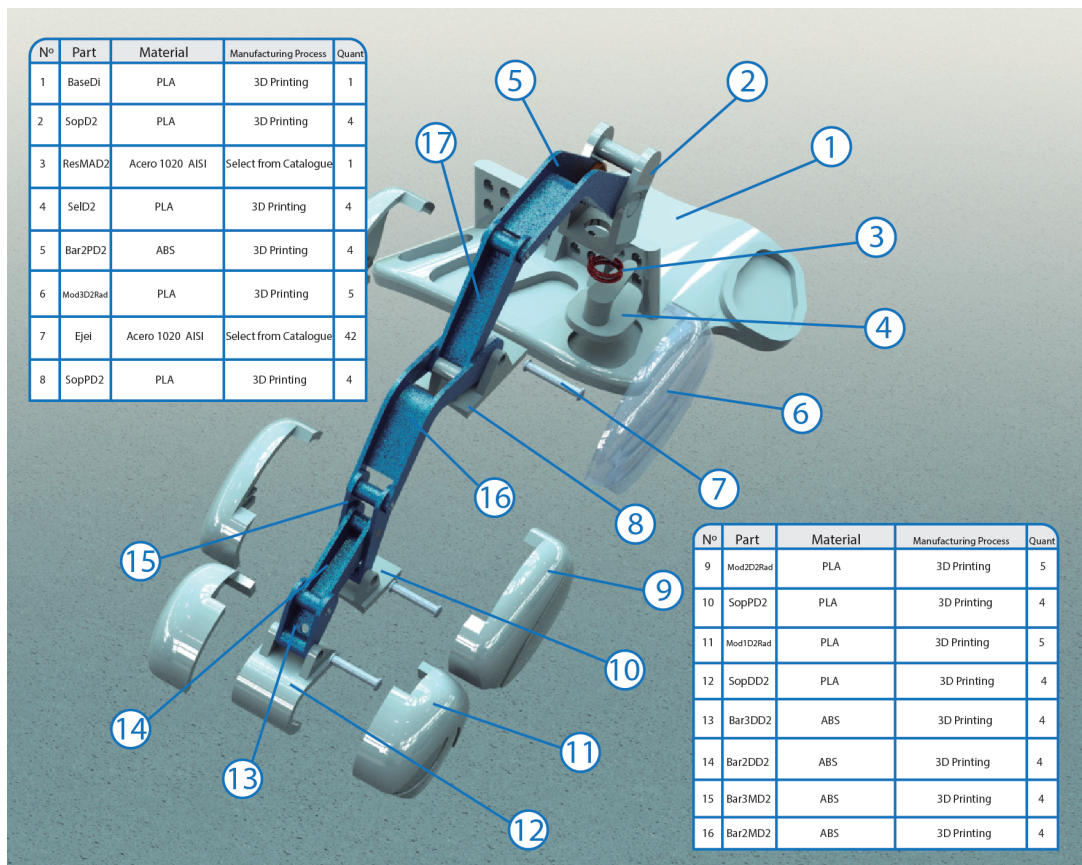


FIGURE 9.3: An exploded view of a finger module is shown

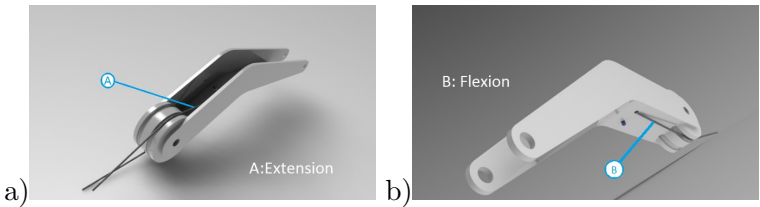


FIGURE 9.4: It shows a detail for the connection with the second bar of the proximal mechanism for Finger 2.

active therapy, the specialist must choose a stiffness depending on the individual conditions of the patient and the assitant should *install* the corresponding spring in the device. Each spring module has a integrated force sensor that enables recording the forces during the therapy. On the one side, as was the case for the actuators, the spring modules must be positionated at the GearBor, and are connected with Bowden Cables to the distal phalanx of the fingers. The Figure 9.5 below show its components and external estruture. One part of the mechanism remains static, while the other concentric part moves along its axis when the user begin with its therapy. This contraction generates that the inner spring opposes a resistance, which can be measured with the sensor at its end.

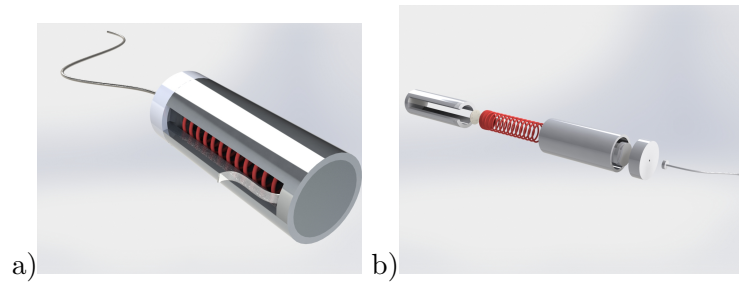


FIGURE 9.5: Spring capsule configuration for active therapy. The Figure a) shows an external view of the mechanism and b) a exploded view of the module.

9.1.4 Power module: GearBox

A normal Gear-box would allow the change of gear relations to increment or decrement torque. However, this particular Gear-Box is intended to “guide” the torque from the main motor to several adjacent shafts to the different finger modules.

The Gear-Box has two indential modules, for the MCP and PIP articulations. Each of them has 5 auxiliar shafts for each finger, and additionally, 5 spring modules, which were already discussed in the previous sections. This configuration would allows passive and active therapy procedures.

The 9.6 presents an exploded view of the main components.

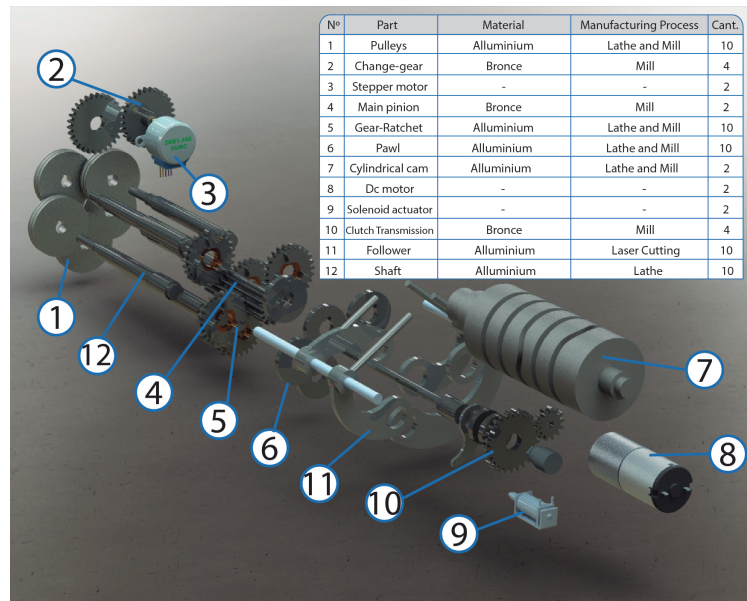


FIGURE 9.6: Functional view of the Gear Box with a list of parts.

The main motor transmits torque to the main shaft through a clutch mechanism, controlled by a linear actuator. The main shaft contains a gear that would move 5 adjacent pinions, which corresponds to each finger of the device. All the pinions are not connected to their shafts, but rather transmit torque with special designed pins that would attach to discs. These discs are solidary to the auxiliary shafts. A cylindrical cam is used to control the displacement of the pinions and by doing so, controlling which auxiliary shaft to move. An additional stepper motor is required to move the cam.

9.2 General Architecture

The variation in the IDEF0 language convention lies in the use of a colour convention to show the interrelationships between the systems. The colour of the *Inputs*, *Outputs*, *Controls* and *Mechanisms* indicate the origin or the destiny of the signal.

The first diagram, depicted in Figure 9.7, shows the General Architecture of the system, where its inputs and outputs are colourless, because they come outside the system boundaries. Inside the diagram, the subsystems are depicted with the colour convention listed in the Figure 9.8.

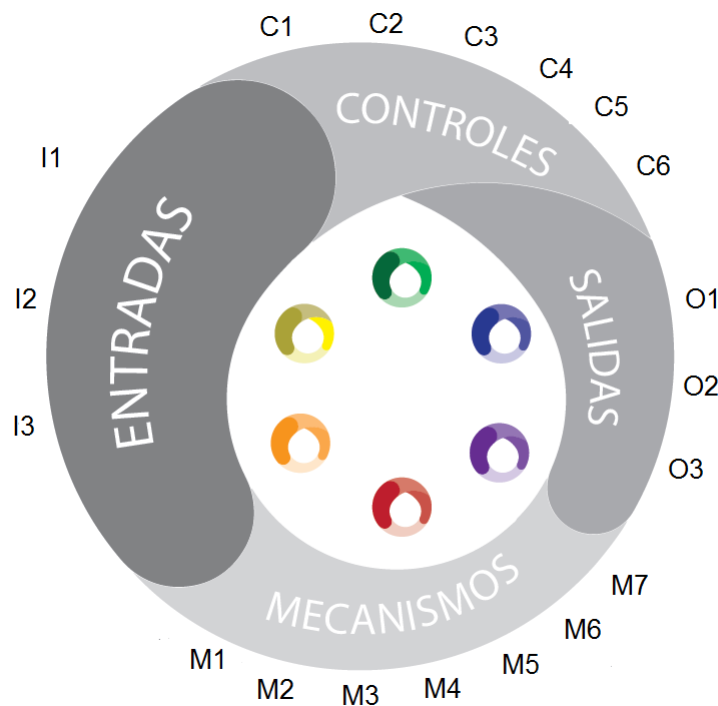


FIGURE 9.7: General architecture for the hand rehabilitation system

Convention	Description
C1	Change phase protocol
C2	Rehabilitation protocol
C3	Quality in communication signal
C4	Failure protocol
C5	Patient review
C6	Cleaning protocol
I1	Active movement
I2	Users ID
I3	Initial position
O1	Passive movement
O2	Notifications
O3	Movement and force data
M1	Energy
M2	Internet
M3	Computer
M4	Specialist
M5	Patient
M6	Assistant
M7	Wireless communication

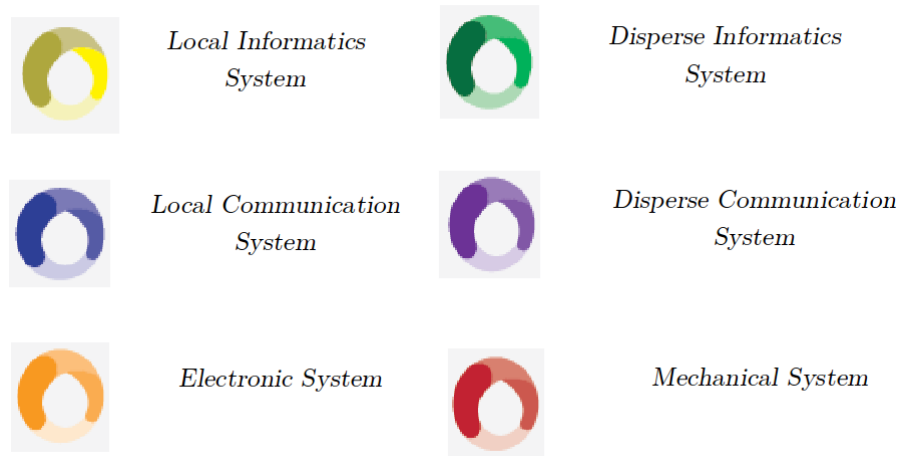


FIGURE 9.8: Colour convention for the subsystems

The *Inputs* of the system are *Users ID's*, *Initial Position* and *Active Movement*. There are three *Users ID's*: the *Specialist ID*, the *Assistant ID* and the *Patient ID*. The first two would allow each user to access the Disperse and the Local Software Interfaces, designed for the Specialist and the Assistant, respectively. The *Patient ID* is necessary to approve the therapy session itself and later to assign the appropriate therapy protocol, according to the patient history and the specialist's criteria.

The *Initial Position* would be a parameter given by the patient condition. When the patient

ROM is limited and the hand is very stiff, the device must be adapted to the patient ROM and then define that position as the “Home” or *Initial Position*. Around this position the *Passive Therapy* would be executed. On the other hand, the system would receive an *Active Movement* from the patient as the *Active Therapy* is executed. As for *Outputs*, the system would “mobilize” the phalanges as the *Passive Therapy* is executed. Additionally, the system would “notify” to the users the state of the device and the stage of the therapy through the software and hardware interface. There are several types of “Notifications” that would be explained in detail in the following subsystems. Additionally, one of the most remarkable characteristics of the system is its ability to register and then compile the data recorded during the passive and active therapy. This is the output called *Movement and Force Data*. In the *Controls* there are several protocols:

- **Rehabilitation Protocol:** It is a matrix of angles specifying the ROM that the phalanges should rotate using the device during passive therapy. This matrix is designed by the specialist according to the patient diagnosis, patient evolution and its own criteria. The Disperse Informatics System describes the input method (User Interface) of this protocol.
- **Change of Stage Protocol:** The therapy has different stages, therefore the device has different modes of behaviour accordingly. From the device point of view, there are five modes: *Test mode*, *Demo mode*, *Passive movement mode*, *Active movement mode* and *Stand-by mode*. These modes correlates to the *Preparing device and Patient stage*, *Explanation and Demonstration Stage*, *Passive therapy stage* and *Active therapy stage*. The device is on Stand-by mode when a *Failure* is detected and is waiting for further instructions, or when is waiting for a Protocol. The Activity Diagram in Appendix J describes this behaviour in detail.
- **Failure Protocol:** It is a set of instructions specially designed to “fix” the failure reported by the device or the Assistant. There is a list of specific Failures that can be fixed by the Assistant, but in some cases the Protocol indicate that the therapy session must be cancelled and the device sent to technical service. Several failures protocols for a similar application were already described by [2].
- **Cleaning Protocol:** It is part of the preventive maintenance and necessary to fulfil the aseptic requirements. It should be executed after each therapy session.

Finally, the mechanisms include the three main users, which are the Specialist, the Assistant and the Patient. It also requires a Computer for the disperse and local software interface, as

well as the communication medium such as internet and wireless connection between the device and the Assistant computer.

As complementary description of the general architecture, the Figure ?? describes rehabilitation session from the specialist(red) and the assistant (blue) point of view. Additionally, the Figure 9.10 shows the internal processing of the device, during a rehabilitation session.

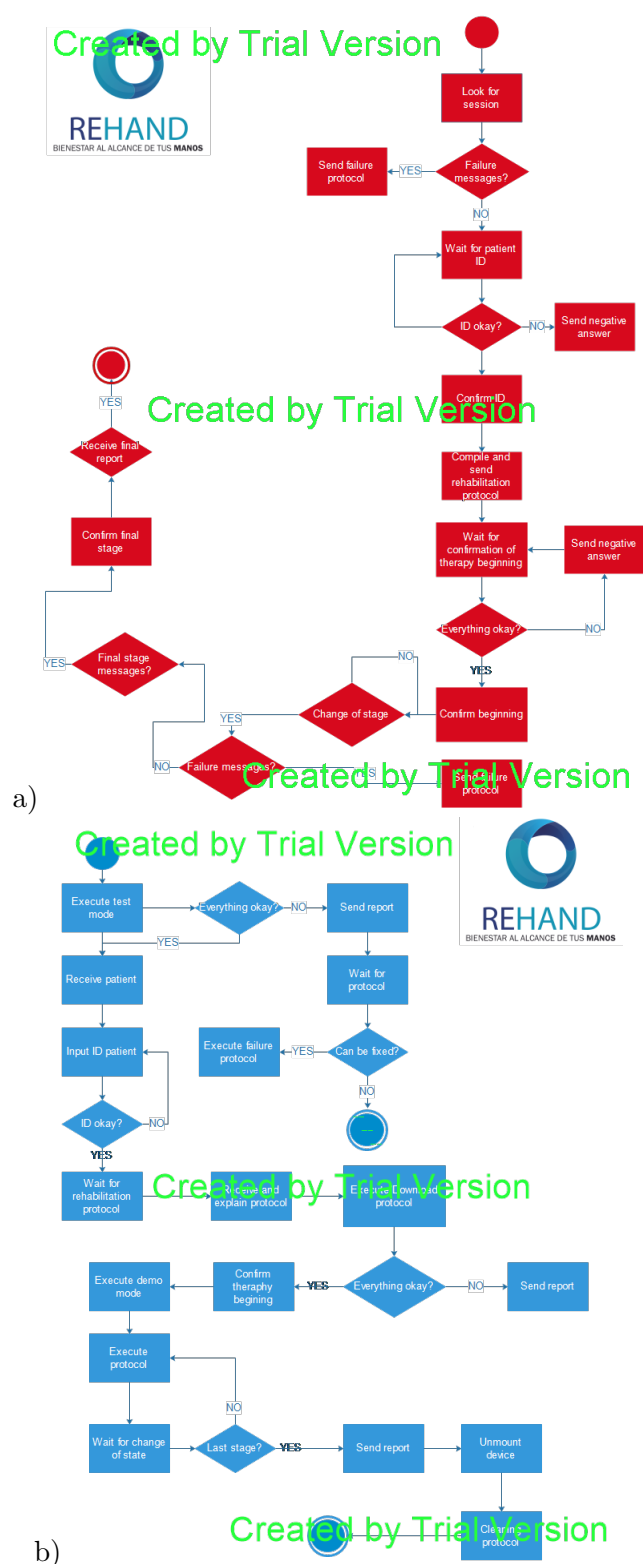
9.3 Disperse Communication System

Although the architecture of Teleoperated Rehabilitation should include the considerations of Internet communication, such as security or bandwidth, it is not in the scope of the present project to give a detail insight. However, the PhD work of Chamorro et al [PENDING] explains in detail this architecture. Then, the disperse communication system is seen as a “black-box” with the *Inputs* and *Outputs* shown in Appendix I. The architecture already showed in Figure Figure 7.1 defining the disperse and local *geographical places*.

The disperse communication system receives the *Rehabilitation Protocol* from the *Disperse Software Interface System* and transmits it to the *Local Software Interface*. The information of *Initial Position* and *Movement and Force Data* travels the other way around, it goes from the *Local Software Interface System* to the *Disperse Software Interface System*. The controls include *Quality in the Communication Signal* since it is an external factor that would have an effect in the communication.

9.4 Local Communication System

This system communicates the Assistant’s computer with the device or in other words, it communicates the *Local Software Interface System* with the *Electronic System*. It allows, for example, transfers of *Movement and Force Data*, gathered by the sensors in the *Electronic System*, to the *Local Software Interface System* or sent the *Rehabilitation Protocol* matrix in the opposite direction. Additionally, it allows the *Electronic System* to report *Encountered Failure Signals* and the *Initial Position* of the patient.



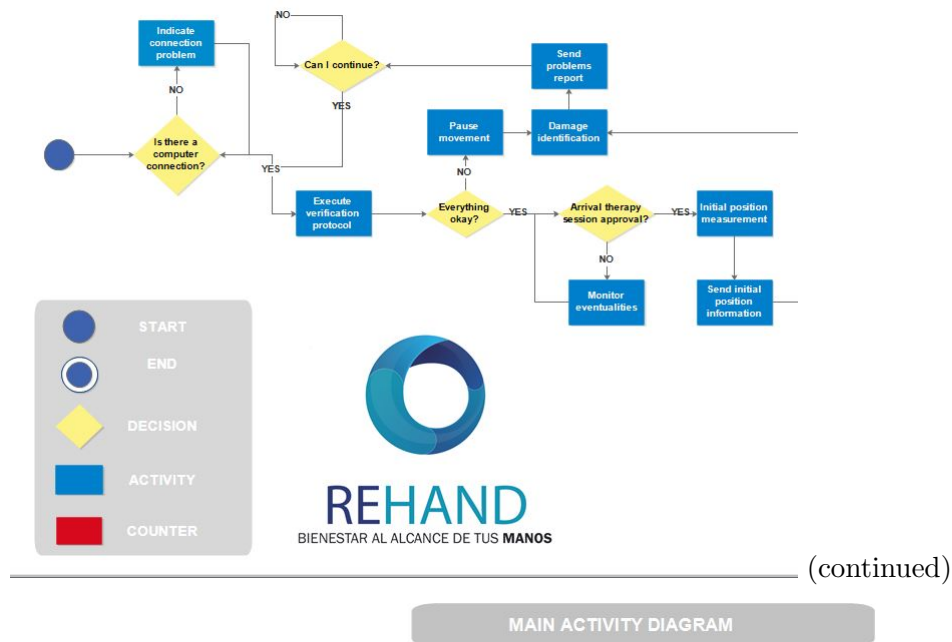


FIGURE 9.10: Main activity diagram for the hand rehabilitation system

9.5 Disperse Software Interface System

This interface is designed for the user *Specialist* and it has four main functions: Check on the status of connected *Sessions*, analyse the historical data of the each registered patient, construct a rehabilitation protocol and, of course, supervise an active *Session*. This diagram can be found in Appendix I.

This system receives and hand over signals to and from the *Disperse Communication System* and to and from outside the boundaries of the system.

9.6 Local Software Interface System

On the other hand, the diagram in Appendix I describes a system that transforms the signals to and from the *Local Communication System* to the Assistant or hand them over to the *Disperse Communication System*. The detail architecture of this interface, as well as the interface of the Disperse Software Interface can be seen in Section 10.3.2. But in comparison to the disperse interface, the local has a very simple architecture, since the Design Requirements defined that the assistant should have the least decision power possible.

9.7 Electronic System

The *Electronic System* receives two signals from the *Mechanical System*, which are *Movement* and *Force data*, which refers to the actual position of the bars registered by the flex-sensor and the signal measured by the force sensor during active therapy. As the therapy begins, the *Electronic System* must make internal calculations to determine the *Initial Position* of the patient with the data given. This initial position would be useful to set the “Home Position” in the internal control program and for the Specialist, so it must be stored and sent through the *Local Communication System*.

The general architecture of the electronic system is shown in the Figure 9.11 and it is complemented with the circuit presented in Appendix .

The *Rehabilitation Protocol* received as Control must be interpreted and transformed by the internal control subsystem. The algorithm should translate the desired biological ROM into rotation of the motor. The electronic system is subdivided in 7 subsystems: Control, communication, power, sensors, actuators(drivers), indicators and security.

9.8 Mechanical System

The IDEF0 diagram for this system is the simplest of all. Its two *Inputs* are the *Actuators Pulse Movement* for controlling the motors and the *Active Movement* made by the patient during active therapy. It has two *Outputs*: The *Passive Movement* and the physical *Notifications*. This last outputs includes light emitted from LEDs in the device and sound alarms. The *Mechanical*

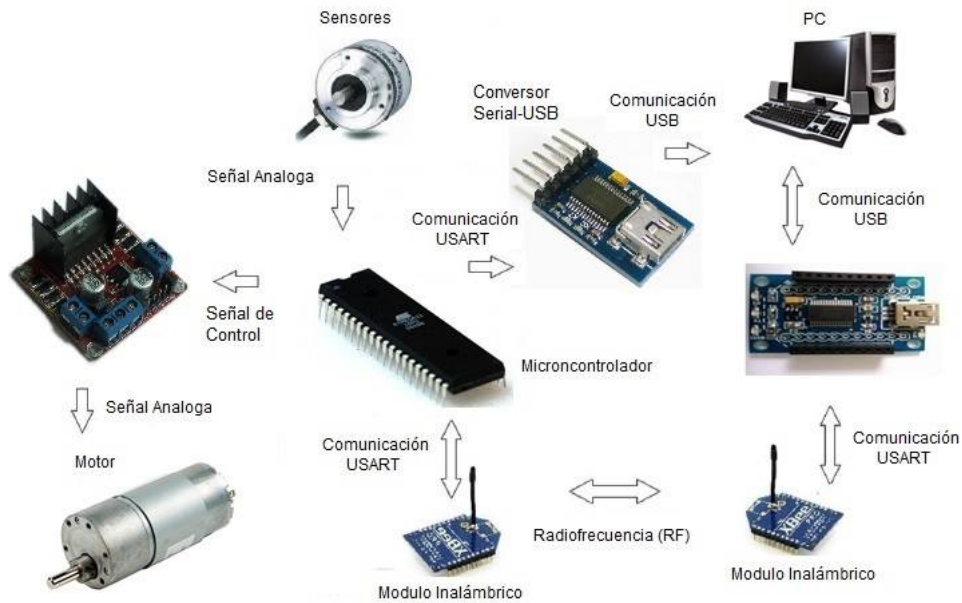


FIGURE 9.11: General electronic architecture with the main components.

System is also divided in four main subsystems: Four-bar mechanism, abduction-adduction mechanism, indirect force transmission, push n' roll mechanism and the gearbox.

9.9 Chapter Synthesis

This chapter present the basic design derived from the scoring in Chapter 8. To describe this system, IDEF0 diagrams were used and the General diagram is presented. However, the rest IDEF0 diagrams can be found in Appendix J. As noted, a new colour convention is introduced as a modification to the original IDEF0 modelling language. In summary, the system consists of 6 main systems, which follows the proposed architecture by Chamorro et al. [Pending]. The electronical and mechanical systems have 7 and 5 subsystems, respectively.

Chapter 10

Detail Design

This chapter covers the considerations and methodologies employed during the detail design of several modules of the hand rehabilitation system. It begins with an explanation of the biomechanical model, which is presented in deeper detail in Appendix X. Then, the design of the four-bar module, the indirect transmission and the Gear-Box is described, as well as the considerations while designing the “Abduction-Adduction” and “Push n’ Roll” mechanisms. Additionally, it describes the circuit design and control architecture design criteria, as well as, the architecture for the user-machine interface.

10.1 Mechanical Design

The previously defined functional design requirements establish the parameters that must be achieved by the device, including kinematic and kinetic values derived from the first stages of the methodology. Consequently, the mechanical design of the modules begins with the construction of the biomechanical model, which uses this values.

Following this model, the mechanical design continues with the four-bar mechanism, where the optimal geometry is selected guaranteeing the achievement of the FROM and *adequate* transmission angles; that is transmission angles around $90^\circ \pm 40^\circ$. Additionally, a dynamic model is constructed to evaluate the driving torque required by the motors, using the Lagrange Formulation. Finally, the material selection and the geometry for the four-bars is evaluated

using the results from the previous analysis. As a failure criteria, the Von Mises stress are used to determine the static safety factor.

Later, details regarding the indirect transmission mechanism, as well as a general overview of the Gear Box are shown briefly. However, further considerations of particular parts can be found in Appendix X.

Finally, considerations regarding the wrist Push n' Roll mechanism are also presented.

10.1.1 Biomechanical Model Considerations

From the biomechanical characterization in Chapter 5, the finger is understood as an open kinematic chain with revolute joints. Appendix A describes the complex system of tendons which allows the hand movement, where each tendon contributes to the movement of several phalanges simultaneously through a system of ligament pulleys. In order to design the rehabilitation system and its mechanisms, the expected kinematics and kinetics of the fingers during rehabilitation is required. Once again, Chapter 5 has condensed the FROM for the fingers in Table 5.5 and described the selected kinetic model. From these results, the following additional considerations were taken.

First, the position, direction and contribution of each tendon was taken from [13] while the forces for each tendon are taken from [3] and condensed in Table 5.10. Notice however that results in Table 5.10 are only applicable to finger 2, however this was acceptable because the forces for this finger would be the most conservative design scenario, i.e. the index finger has developed the largest tendon force among all the fingers, as reported by various authors [24, 30].

On the other hand, from the hand rehabilitation point of view, the physiotherapist will not only encounter inertial and passive rotation resistances, such as the ones of the ligaments and the skin found in healthy patients [28], but as well higher rotation resistance from stiff hands. As previously stated in Chapter 5, the causes behind stiff hands are very diverse, but it was assumed for this design that tendon forces achieved during power grip position are *comparable* to a stiffness condition in the hand.

Following the methodology proposed by [13] in the Normative Model ¹ the expected torques for each joint of the index finger are presented in the following matrix. On the one side, the angles

¹See the complete description and adaptation in Appendix B.

$\Theta = [\phi_{A12}, \phi_{A22}, \phi_{A32}]$ used for the model were estimated from a hand in power-grip holding a 50mm-diameter bar². On the other side, the normative model is normalized using the length of the medial phalanx, therefore the lengths are multiplied by 23 mm³

$$\tau = \begin{bmatrix} Mx_{DIP} & My_{DIP} & Mz_{DIP} \\ Mx_{PIP} & My_{PIP} & Mz_{PIP} \\ Mx_{MCP} & My_{MCP} & Mz_{MCP} \end{bmatrix} = \begin{bmatrix} 0 & 0.1 & 0.5 \\ -0.1 & 0.1 & 2.4 \\ -1.4 & 0.7 & 13.9 \end{bmatrix} [N - m] \quad (10.1)$$

From the previous matrix it can be inferred that the largest torque is found on the MCP articulation, as expected [24]. Additionally, the matrix shows that there are moments on all the coordinate axes (See Figure 5.4), which was also expected since the tendons' positions were defined in a 3D fashion in the Normative model [13]. Nonetheless, the predominant values are around the z-axis.

On the other hand, from the semi-structured interviews, a quantitative velocity of rotation for each therapy could not be determined, however it should be a “low velocity”. For designing purposes a minimum and maximal rotational velocity of $1^\circ/s$ and $10^\circ/s$ were assumed. Once the design could be tested during rehabilitation procedures, these values could be adjusted.

10.1.2 Four-Bar Mechanism Design

From Chapter 8, the four-bar mechanism is selected as the principal mechanism for passive motion. Additional design requirements complemented this concept and influenced its geometry, such as anatomical and ergonomic restrictions. So, a curve four-bar mechanism with a U-profile is proposed.

10.1.2.1 Kinematics

For the kinematic analyses, the bars of the mechanism would be assumed lineal and the convention for the mechanism's components is shown in the Figure 10.1. Notice that this mechanism uses the phalanx as the third bar of the mechanism (output link), however, due to ergonomic

²It was concluded from [3] that the most suitable diameter for a power grip would be around 34mm, i.e. the human hand would produce the largest force with the minimal tendon forces. However, since it is of interested to establish the largest force in tendons, a 50mm diameter bar is used selected instead.

³Value taken from the anthropometric analysis.

conditions the *mechanical joint* can not be located on the *biological joint* exactly. Therefore, the joint is located at $2/3$ of the total phalanx length, for the proximal and the middle phalanx. Consequently, a triangle-like bar was used, instead of the traditional bar, since the axis of rotation must be above the finger as well.

It is important to point out that the motion of the distal phalanx will not be controlled during passive therapy, since its movement is connected with the PIP rotation through tendon restrictions (See Appendix A).

The four-bar configuration is shown as well in the Figure 10.1 below, where the lengths are l_{0ij} , l_{1ij} , l_{2ij} and l_{3ij} and the angles of the four bar are θ_{ij} , α_{ij} , ϕ_{ij} and β_{ij} . The sub-index i represents the finger, the $i = 1, 2, 3, 4$ or 5 , and j represents the position of the mechanism, whereas $j = p$ (proximal) or m (medial).

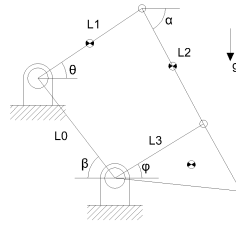


FIGURE 10.1: Four-Bar mechanism configuration

Using the anthropometric data and the FROM matrix, a correlation between the angles is established for the proximal and medial four-bar mechanism for finger 2 following the derivation in Appendix ???. It is of particular interest to model $\theta(\phi)$ and $\alpha(\phi)$. The Figure 10.2 below presents these relations and a linear fit for proximal and medial four-bar mechanisms.

The equations below represent the relationship between the angles of the mechanism for the index finger.

$$\begin{aligned}\theta_{2p} &= 0.65\phi_{2p} + 41.3 \\ \theta_{2m} &= 0.67\phi_{2m} + 34.2\end{aligned}\tag{10.2}$$

$$\begin{aligned}\alpha_{2p} &= -0.29\phi_{2p} + 74.3 \\ \alpha_{2m} &= -0.15\phi_{2m} + 65.7\end{aligned}\tag{10.3}$$

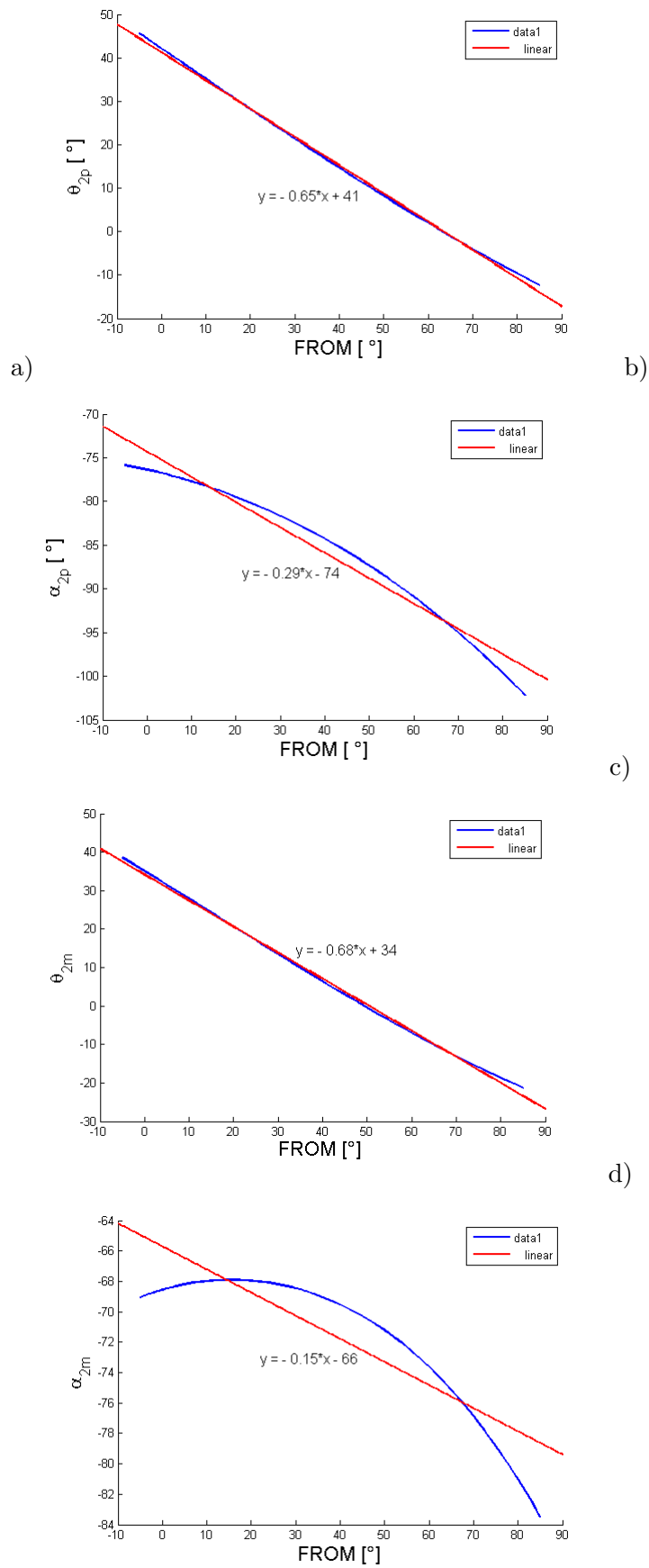


FIGURE 10.2: Four-bar mechanism angles functions taking the FROM as the independent variable, where a) and b) corresponds to the proximal mechanism and c) and d) to the medial mechanism.

The previous equations are valid for the final geometry, although iterative design procedure was necessary to achieve these values. As previously stated, the transmission angles would be the design criteria. First, the *Dead-Centre Positions* were determined looking for the singularities from the angular velocity in Equation 10.4, derived in Appendix ??.

$$\dot{\theta} = \frac{l_3 * \sin(\phi_{ij} - \alpha_{ij})}{l_3 * \sin(\alpha_{ij} - \theta_{ij})} * \dot{\phi} \quad (10.4)$$

In order words, the *Dead-Centre Positions* are determined by looking for positions that give $\theta = \alpha$ or $\alpha = \phi$. This could be easily appreciated in the following Figure 10.3, which shows the ratio of θ/α and α/ϕ along the FROM. The nearer to $|1|$ the closer to the dead centre positions.

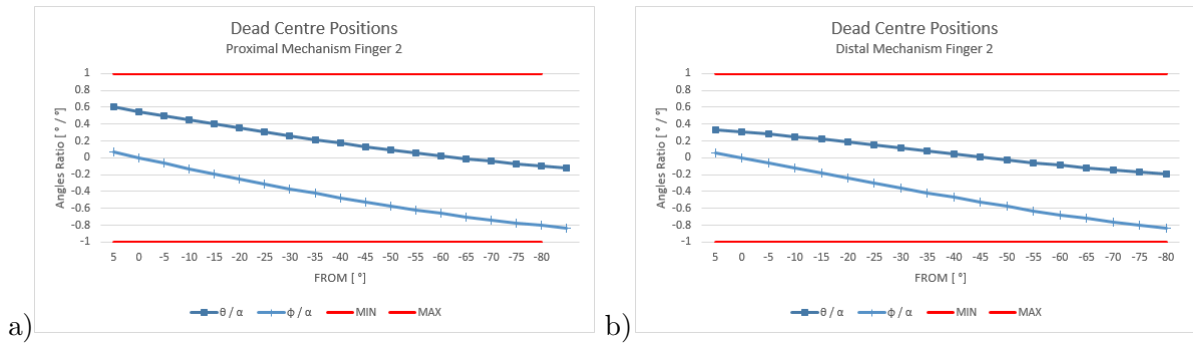


FIGURE 10.3: Ratio of the Four-Bar angles to identify dead centre positions. Where a) is the ratio of θ/α and b) is the ratio of α/ϕ

Since the reliability is an important characteristic of the device, it must avoid the dead centre position between the limits of the FROM, as could be seen in the previous Figure 10.3. Then, the lengths of the bars were adjusted until this condition was achieved.

Following the dead centres, the transmission angle μ variation along the FROM was also calculated, with the methodology in Appendix ??. An optimal transmission angle should be 90° , however this value oscillates as the mechanism move, then a maximum deviation for μ of 40° is delimited for this application. The geometry is once again adjusted to fulfil this requirement and the bars final lengths were determined.

The Figure 10.4 shows the deviation of the transmission angles for joint C in proximal and medial mechanism for index finger. Identical procedures can be extended to fingers 1, 3, 4 and 5.

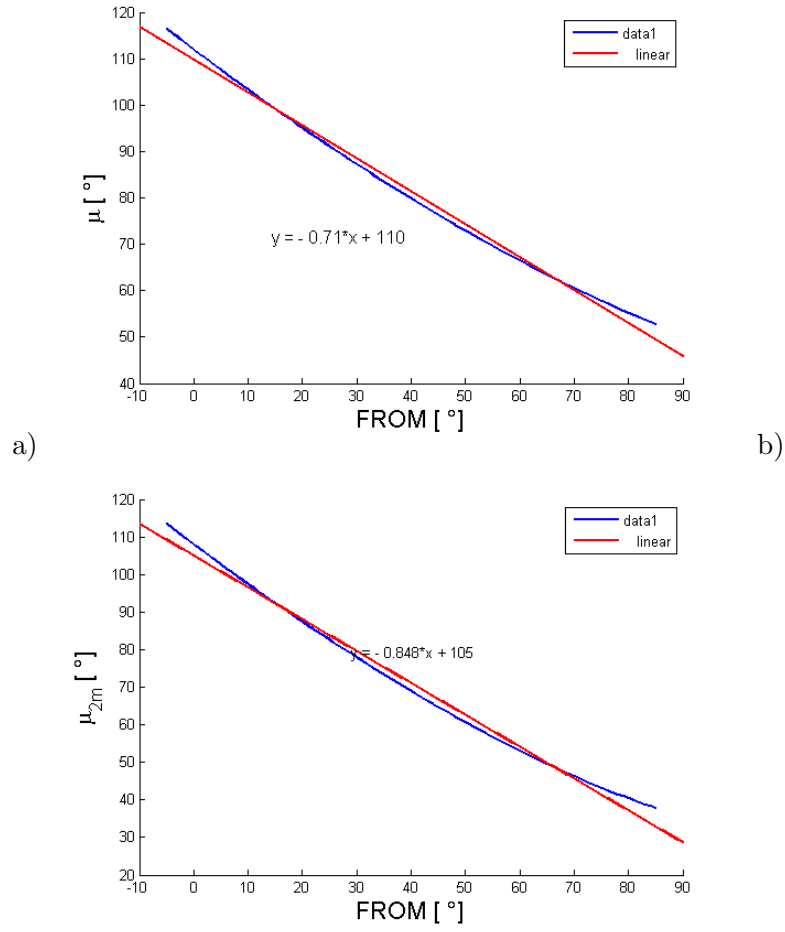


FIGURE 10.4: Transmission angles for the Four bars mechanism in the established FROM for the proximal and the medial mechanism

The mechanical advantage (R), or the ratio between the Input $\dot{\theta}$ and the Output $\dot{\phi}$, can be extracted from derivative of the function $\theta(\phi)$ repeated below,

$$\theta_{2p} = 0.65 * \phi_{2p} + 41.33 \quad (10.5)$$

$$\frac{d\theta_{2p}}{d\phi_{2p}} = 0.65 \quad (10.6)$$

As expected from the linear relation between ϕ and θ , R would be constant as the ratio of the angular velocities as well. Consequently,

$$R = \frac{\dot{\theta}}{\dot{\phi}} = 0.65 \quad (10.7)$$

Finally, for the kinetic analysis is important to derive the accelerations for each bar, specifically at the centre of masses. This was accomplished using kinematics of rigid bodies as shown in detail in Appendix C. First, the angular accelerations $\ddot{\theta}$, $\ddot{\gamma}$ and $\ddot{\phi}$ for the linear bars were derived using the Equation E.15. A system of 6x6 linear equations was obtained, assuming that the angular velocity $\dot{\phi}$ is constant, and so, its acceleration is zero.

$$\vec{a}_A = \vec{a}_B + \ddot{\theta} \times r_{A/B} - \dot{\theta}^2 r_{A/B} \quad (10.8)$$

Note that at joint B, the angular acceleration is not expressed as $\ddot{\alpha}$, since the second bar (the coupler) has a complex translation and rotation movement, so a new angular velocity $\dot{\gamma}$ and acceleration $\ddot{\gamma}$ is introduced, which are with respect to the instantaneous centre of rotation (IC) of bar 2.

The result of this analysis are the graphics describing the accelerations of the CM for each bar. The 10.5 shows the accelerations for all the bars, where the blue color represents the third one. The other accelerations are negligible in comparison to this acceleration and therefore are represented as a linear function near zero.

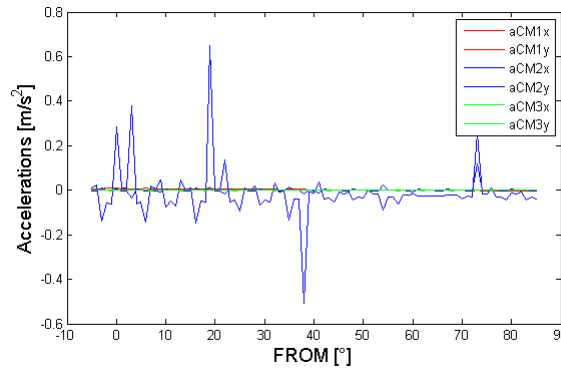


FIGURE 10.5: Accelerations in m/s^2 for $\dot{\phi} = 10(deg/s)$

10.1.2.2 Kinetic Model

A dynamic model is constructed using the Lagrangian Formulation of Classical Mechanics, in order to determine the driving torque. Recalling the Lagrangian as the difference of kinetic and potential energies, as depicted in Equation 10.9.

$$L = T - V \quad (10.9)$$

One can rewrite the equations of motion using the Lagrangian, resulting in the so-called Euler-Lagrange formulation in Equation 10.10.

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = F_i \quad (10.10)$$

This was made for the four-mechanism, obtaining after some mathematical manipulation the Equation 10.11 below, which relates the torque given by biological conditions, that is T_{bio} derived from the Normative model, and the driving torque that the motors should provide, T_{ext} .

$$\begin{aligned} T_{ext} = & 2 * (J_1 S_1^2 + J_2 S_2^2 + J_3 + P_1 C_1 S_1 S_2) \ddot{\phi} + \left[P_1 C_1 \left(S_1 \left(\frac{\partial S_2}{\partial \phi} + S_1 \frac{\partial S_2}{\partial \theta} + S_2 \frac{\partial S_2}{\partial \alpha} \right) + \right. \right. \\ & S_2 \left(\frac{\partial S_1}{\partial \phi} + S_1 \frac{\partial S_1}{\partial \theta} + S_2 \frac{\partial S_1}{\partial \alpha} \right) \left. \right) + 2J_1 S_1 \left(\frac{\partial S_1}{\partial \phi} + S_1 \frac{\partial S_1}{\partial \theta} + S_2 \frac{\partial S_1}{\partial \alpha} \right) + \\ & \left. 2J_2 S_2 \left(\frac{\partial S_2}{\partial \phi} + S_1 \frac{\partial S_2}{\partial \theta} + S_2 \frac{\partial S_2}{\partial \alpha} \right) \right] \dot{\phi}^2 - \frac{\partial G}{\partial \phi} + S_1 \frac{\partial G}{\partial \theta} + S_2 \frac{\partial G}{\partial \alpha} - T_{bio} \frac{\dot{\phi}}{\dot{\theta}} \end{aligned} \quad (10.11)$$

In comparison to the stiff-hand-torque obtained from the biomechanical model, the inertial contributions of the biological phalanges are very small, but are taken into consideration using the results from Tables 5.4 and 5.5.

As the main result, the torque expected along the FROM can be seen in Figure 10.6.

10.1.2.3 Statics Analysis

Let us begin with the Static Kinetic Case for the Four-Bar module. First, the free body diagrams (FBD) are depicted in the figure below,

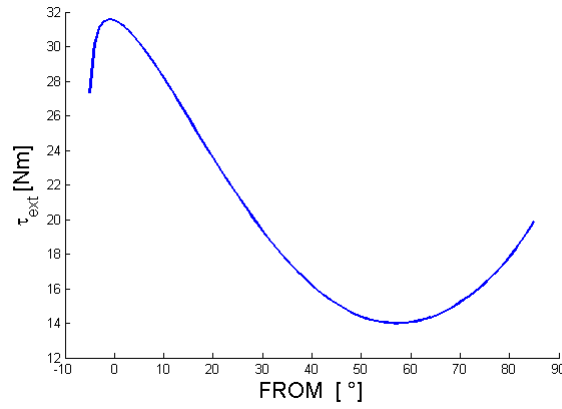


FIGURE 10.6: Expected behaviour of the input torque for moving the mechanism along FROM

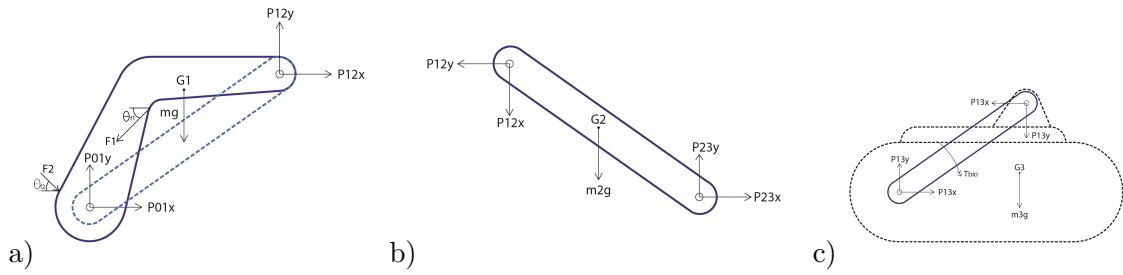


FIGURE 10.7: Free body diagram for each individual bar.

In order to drive the bars, an indirect transmission is proposed, using cables attached to the Power Module. The cables are pinned to the bars as was previously shown in Figure 10.7, where F_1 and F_2 are forces exerted by the cable on the bar. From the kinetic model, it was concluded that the maximum torque expected would be around 0 degrees, therefore using Newton's Second Law once again, the equations of motion are depicted for that specific angle and as a result, a set of 9x9 of linear equations is obtained.

With these results, a FEM model is constructed for the bar that would determine its mechanical behaviour when loaded at $\theta_{2p} = 0^\circ$ and assuming a simple supported beam configuration. It is of interest to determine the deflection of the bar and the safety factor, assuming plastic deformation as failure. Two materials were tested: ABS and aluminum, whose mechanical properties are showed in Tables 10.1 and 10.2.

The results for the proximal mechanism of finger 2 is shown below for both materials. Since the model uses the result from the static analysis, punctual forces are used and the results near them are not accurate, therefore, the maximum deflection is not expected on the upper part of the proximal disc, but rather below the bar where the cable is attached and pulls the bar. This

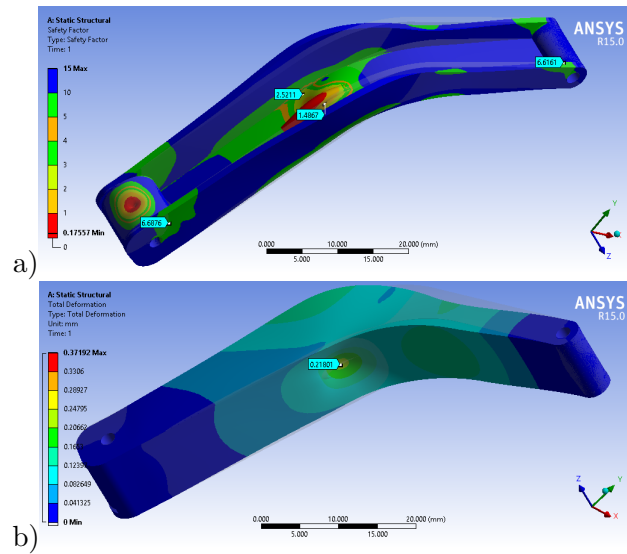
TABLE 10.1: ABS plastic mechanical properties. Source: Matbase.

Property	Value	Unit
Compressive Strength	60	MPa
Density	1060	kg/m^3
Fatigue Failure	22	MPa
Shear Modulus	700	MPa
Ultimate Tensile Strength	40	MPa
Young Modulus	2275	MPa

TABLE 10.2: Aluminium mechanical properties. Source: Matbase.

Property	Value	Unit
Density	2705	kg/m^3
Fatigue Failure	20.7	MPa
Shear Modulus	26.0	GPa
Ultimate Tensile Strength	69	MPa
Young Modulus	68	GPa

reasoning holds for both materials. In first place, the ABS bar had a maximum deflection of 0.25mm and a minimum static safety factor of approx. 1.5. On the other hand, the aluminium bar had a maximum deflection of 3.6×10^{-3} mm and a static safety factor of 15. These results led the design team to select ABS as an acceptable material for prototyping due to its speed and economy, although aluminium proved to be more reliable and better behaved, and should be used in the final device.

FIGURE 10.8: FEM simulation for the selected geometry in Bar l_{2p} . Material: ABS

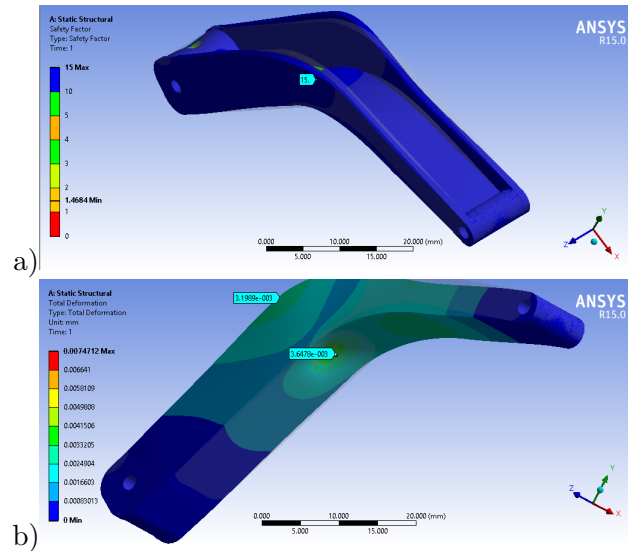


FIGURE 10.9: FEM simulation for the selected geometry in Bar l_{2p} . Material: Aluminium 1060.

10.1.3 Discs and Bowden Cables

Due to ergonomic restrictions, the indirect transmission of forces was necessary to separate the power module from the user hand. To this end, a transmission with wires selected in Chapter 8. Size limitations and optimal power transmission were the principal challenges for this design.

From the static analysis of the Four bar modules, a tension load of 90 N is estimated for the peak torque required. Assuring a safety factor of 2, the design load would be 180 N.

To this end, a cable is pre-selected with the configuration shown in 10.10, which allows more flexibility than configurations with fewer but thicker strands. It has the characteristics in Table 10.3.

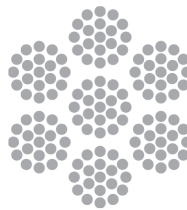


FIGURE 10.10: Wire configuration Type-C (7x19).Source: Ashai Products.

With the values in Table 10.3 for the stainless steel cable, the deformation expected during operation with a rope of 1.5m length would be,

TABLE 10.3: Characterists of the preselected wire for the indirect transmission. Source: Ashai Products

Type No.	Wire Outer (mm)	Rope dia.	Breaking load (N)	Weight (kg / 1,000m)
C-60	0.60		269.5	1.44

$$\epsilon = \frac{wL}{EA} = \frac{4 * 180[N] * 1.5[m]}{1993[GPa] * 0.6\pi[mm^2]} \simeq 0.48[mm] \quad (10.12)$$

While the deformation is acceptable, this cable would allow a static safety factor of 1.5. An additional coating can be selected for this cable, in order to protect it from wear or oxide.

The fatigue due to bending is the parameter that would define the overall safety factor of the cable, however literature and catalogues from manufactures of cables of this caliber did not share fatigue charts. Therefore, weariness due to fatigue should be evaluated experimentally.

10.1.4 Springs capsules

Equivalent to the passive module, the active module plays a key role during hand rehabilitation therapy. Although, in comparison to the passive module, the spring capsules have a simpler behaviour as they are basically a spring attached to a cable, which is being monitored by a force sensor.

There are two design parameters to be taken into account while designing the spring modules. One is the force the cable would inflict over the structure and over the cable it self, and the other is the stroke of the capsule when the patient fully flexion its hand in power-grip.

For this design, the human finger is modeled as shown in the Figure below, where each of the triangles represent the base at the phalanges where the bars are fixed. Two configurations are shown, one in fully extended position, where the cable length is unstretched, and the other one, in fully flexed position. The difference in the cable length would account as the stroke the spring module has for each grip exercise. A stroke of 44 mm is obtained for the lengths at hand.

From the previous configurations, a FBD is elaborated as depicted in Figure [10.12](#).

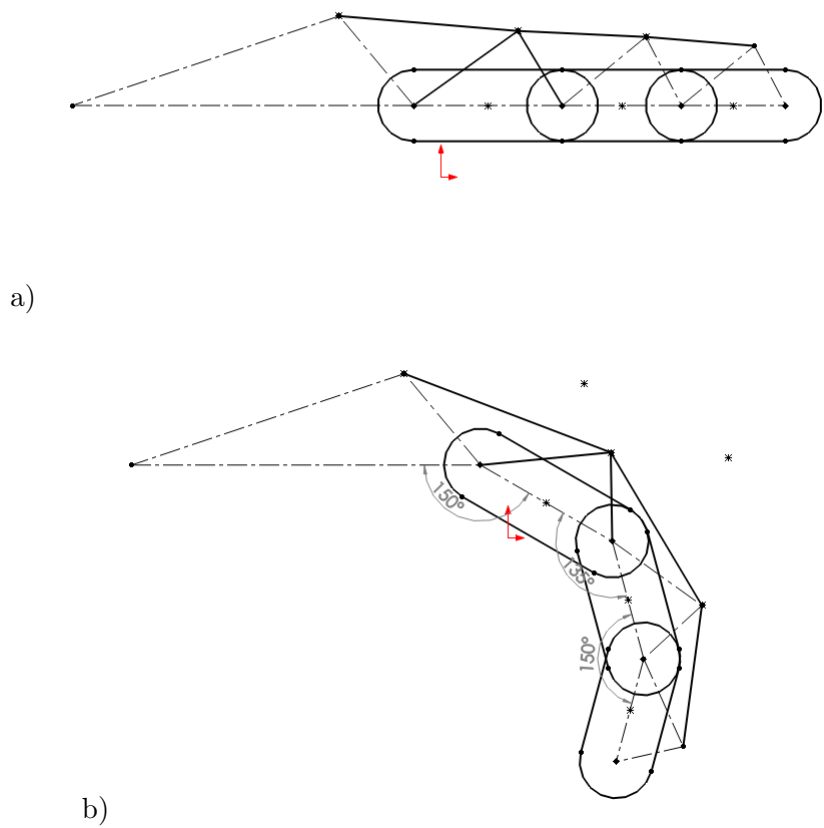


FIGURE 10.11: Model for stretch and unstrech configuration during active therapy

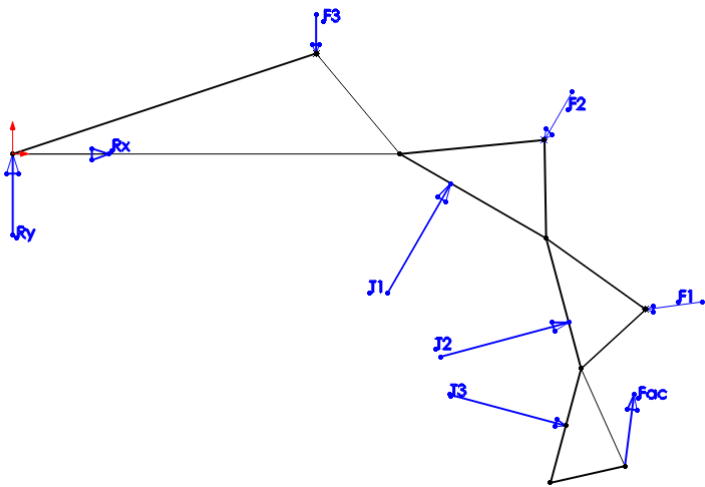


FIGURE 10.12: Free body diagram for active therapy

TABLE 10.4: Characterists of the preselected cable for active therapy. Source: Ashai Products

Type No.	Wire Outer (mm)	Rope dia.	Breaking load (N)	Weight (kg / 1,000m)
C-105	1.05		833	4.40

Where F_{ac} is the cable force acting on the bar, as well as F_1 , F_2 and F_3 are reactions produced when the cable leans on the bars structure. The latter are a function F_{ac} and the direction of the cables.

From the study by [3], the values of T_1 , T_2 and T_3 are known for various grip's spam, and for a 50 mm diameter, $T_1 = 30$ N, $T_2 = 10$ N, $T_3 = 50$ N. With this, the equations of motion derive a $F_{ac} = 333$ N.

This value is higher than the load for passive therapy, an thus another cable must be selected. The strands configuration would be the same, although the cable would be thicker. The properties for the cable for the spring module can be seen in the Table 10.4. The design value is taken as the 670 N.

A previously made for the passive therapy cable, the deformation is calculated, with $\epsilon = 0.23[mm]$, which is within the acceptable margin. A static design factor of 1.2 is obtained.

10.1.5 Abduction / Adduction Modules

The Abduction/adduction modules serve two properties. First, they enable passive abduction and adduction movements of the finger, and second, they provide support for the proximal bars of the Four-bar module.

Using the results from the static analysis of the bars, and having the Reactions as the inputs of the model, the geometry of the Abduction and adduction modules was optimized to withstand the load that it would support. A FEM model is constructed, assuming a fixed support in the bottom of the module, an the loads from the Reactions of the proximal bar derived previously. The results can be seen in the Figure 10.13.

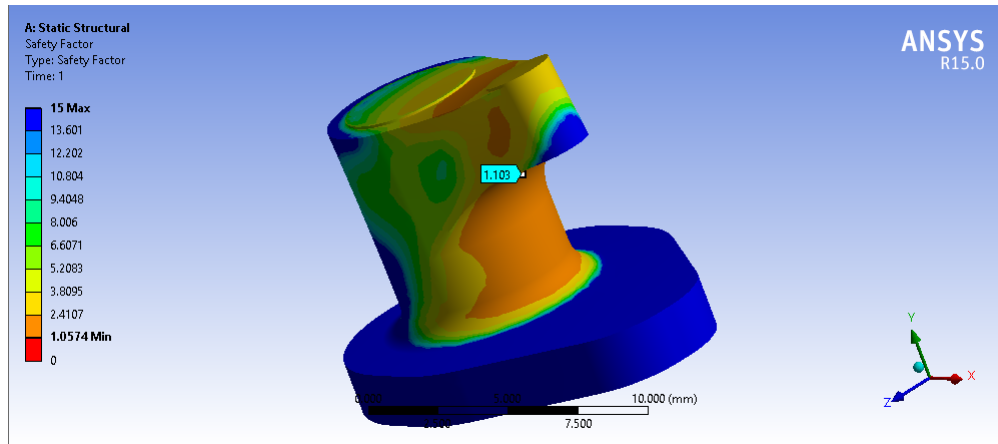


FIGURE 10.13: Results of the simulation for the Abduction/adduction module of Finger 2. The minimum safety factor of 1.1 can be seen in the picture.

10.2 Electronic Design

As part of a mechatronics design, the electronic system plays a key roll in order to instrumentalize the *Hand Rehabilitation System*. This allows to quantify the progress of the passive and active rehabilitation, and control with the passive rehabilitation according to the specialist criteria. The following sections describe the electronical main subsystems with some of the *components* selected from Chapter 8.

10.2.1 General Considerations

The electronic design of the device is composed of seven subsystems as was already shown in Chapter 9. Its main function is to adquire and register the position of the fingers in order to control the device and construct a database of angles for the specialist to study. The seven subsystems are: Power, Actuators, Sensors, Control, Communication, Physical Indicators and Security.

10.2.2 Sensors Selection

From Chapter 8, the flex sensor was selected to measure the bending angle of the patient during rehabilitation. The specific sensor was selected based on the space requirement of the the Four-bar mechanism and the phalanges themselves. The data-sheet for the selected sensor can be found in Appendix K. Some of its especifications are,

- Life Cycle: > 1 million
- Height: 0.43mm (0.017")
- -Temperature Range: $-35^{\circ}C$ to $+80^{\circ}C$
- Flat Resistance: 25K Ohms
- Resistance Tolerance: $\pm 30\%$
- Bend Resistance Range: 45K to 125K Ohms (depending on bend radius)
- Power Rating : 0.50 Watts continuous. 1 Watt Peak

In order to implement this sensors to the device, a analogue to digital conversor circuit must be designed. To this purpose a test with an ADC in pulling mode was made: using a busy waiting configuration a value from the conversation can be obtained when the conversation is enabled. This method was selected because it is simple and requires to execute the conversation only on specific moments of the rehabilitation session, when the activity is focused on data adquisition to execute a determined action. Additionally, this would avoid conflicts with the other interruptions that would be implemented.

10.2.3 Actuators Selection

10.2.3.1 Main Motor

From the kinetic analysis of the human hand and the four bar mechanism, the tension needed in cable to enable flexion of the MCP articulation was derived to be 350 N, and for designing purposes this would be assumed doubled, then $F = 700N$. Since the prototype will not have the Gear-Box, the cable would be directly connected to motor for running tests. The motor will behave as a winch, winding the cable in its axis, pulling th cable, and therfore, in order to achieve the force, the axis must be as thin as possible, while still withstand the load without deformation. A diameter of 5 [mm] is preselected, which would require a motor with a peak Torque of 1.75 N-m.

Therefore, a relative high torque motor must be used, but it must maintain the proportions of the device. From catalogues, the motor with the Torque-Velocity relationship shown in Figure 10.14 is selected.

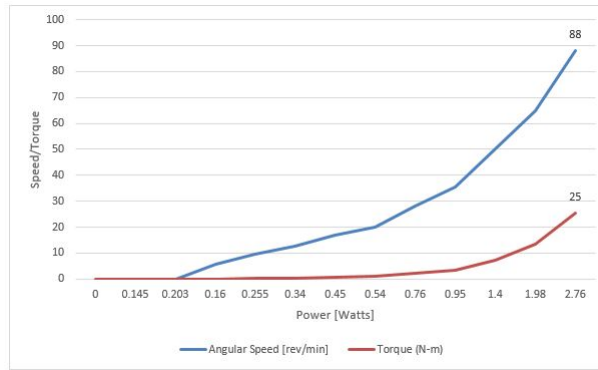


FIGURE 10.14: Results on the experimental characterization of the motor. It shows the relation of torque and speed.

10.2.4 Communication Protocol Selection

This refers to the local communication system, between the electronic and local software system. From the design requirements, the communication must be reliable, fast and must not interfere with the comfort of the patient. Therefore a wireless communication system was adopted using Xbee Pro, which uses a inalambric protocol based on Zigbee (Wireless communication standard IEEE802.15.4). Previous prototypes of teleoperated knee rehabilitation has successfully made use of this protocol[2]. Advantages: bandwidth 2.4 Ghz, and do not use FHSS (Frequency hopping), rather uses a unique frequency. As for the range, it would depend on the power transmission and the material of the antenna, but the normal range for a dipole antenna is 100 m aproximately, and 30 m in inner spaces [2].

- The transmission speed is up to 256 kbps
- Low cost
- Very-low power consumption
- Use of free radio bands and without license requirements.
- Simple and cheap assembly
- Flexible and extensible nets.
- The use of Zigbee replaces a serial communication with a cable.

10.2.5 Processor Selection

In order to select a controller, several characteristics should be taken into account. An Atmega32 microprocessor was selected, since it fulfills the requirements and has a strong bond to this area.

- 32 inputs and outputs port.
- 8 channels ADC of 10 bit.
- 32 Kbytes of programmable flash memory
- 2 timers of 8 bit and 1 of 16 bit.
- 4 channels of PWM.
- USART Serial Programmable.
- Serial interface SPI Master/Slave Interface Serial SPI Maestro/Esclavo.
- External clock external.

10.3 User-Machine Interface

The User-Machine Interface is divided into two categories, one the hardware and the software. In the Hardware description, a list of features such as LED indicators and sound alarms can be found. Later, the software interfaces for the specialist and the assistant are described.

10.3.1 Hardware

The device would have two types of LEDs. Some of them can be found in the GearBox, while the others are on the dorsal surface of the hand device.

In the first place, the LEDs in the GearBox would give a visual feedback for the assistant and the patient, indicating a state of the session, as follows:

- **Running:** The device is executing the corresponding stage of the rehabilitation session⁴.
Associated with the Green LED.

⁴These stages were previously described in Section 10.3 (The Control Design)

- **Waiting:** The device has sent an information or is waiting for an information to be sent from the Local Software Interface. Associated with the Yellow LED.
- **Warning:** The device has detected malfunction in any of its components, e.g. elevated voltage, lost of connection. This state will indicate as well that a change of stage is going to take place, e.g. the movement of the passive therapy is going to begin. Associated with the Red LED.

On the second place, the other LEDs can be found in the dorsal surface and would indicate to the patient how much more must he/she execute the exercise. For example, if it is a passive therapy protocol exercise, the lower red level indicates that the movement has just begun and the upper green level indicates that the movement has arrived to its goal. The same goes for active therapy protocol.

10.3.2 Software

As previously stated, the device would have two types of *Software Interface*, a *Local* and a *Disperse*. They correspond to the software interface for the Assistant in the local location and for the Specialist in the disperse location.

Both interfaces begin with a Login window as the shown in Appendix K. Depending of the user nature (Specialist or Assistant) a series of windows could be displayed.

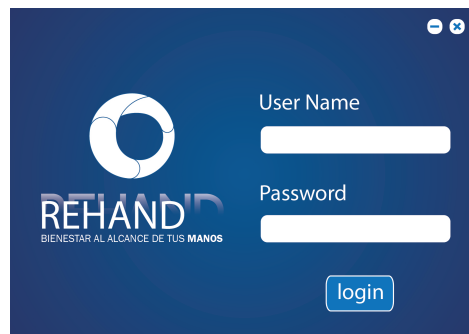


FIGURE 10.15: Login for both users

10.3.2.1 Specialist Interface

The first window after the *Login* would be one with several Tabs, where the *Connections Tab* is initially shown, as depicted in the Figure 10.16a. In this Tab, the specialist would be able to

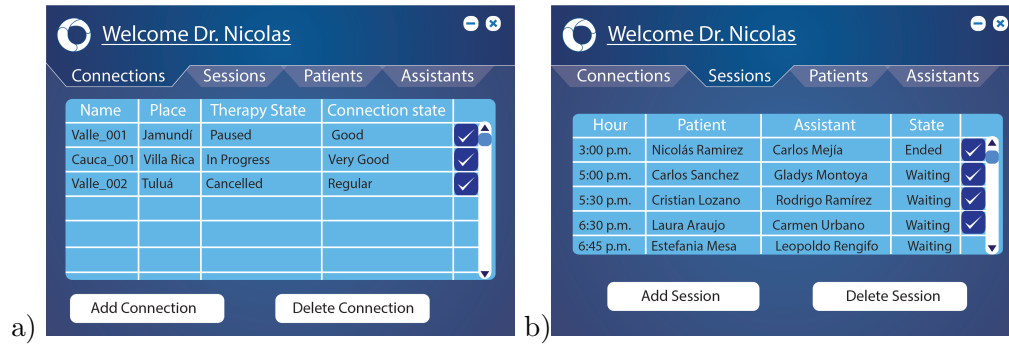


FIGURE 10.16: Principal window with multiple tabs. a)Connection tab and b) Session Tab.

see all the available Connections and their states. The user can add or eliminate a Connection in this Tab.

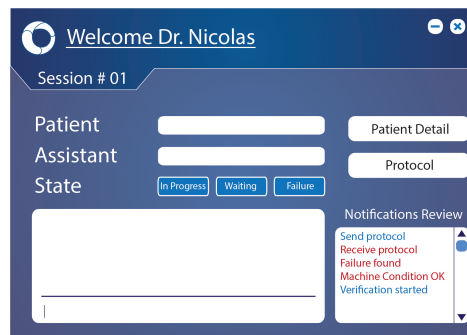


FIGURE 10.17: Session Information pop up window

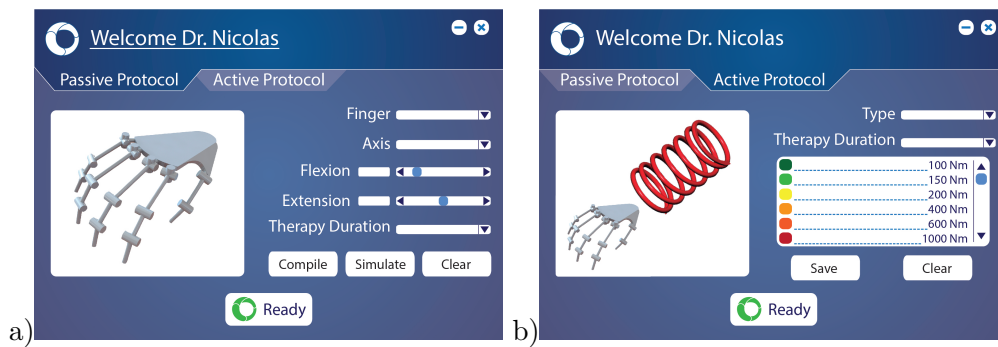


FIGURE 10.18: Pop-up window to edit the protocol

In the second tab called *Sessions*, the user can find all the sessions that had been arranged, its date and state (in progress, waiting, cancelled or finished). Additionally, the user would be capable of adding or eliminating a session. This tab is shown in Figure 10.17.

If the user select any of the sessions listed on the *Sessions Tab*, an additional window shown in Figure 10.17 would be displayed. In this window, called *Session Information*, the specialist would be able to see the Patient and Assistant basic information, the state of the session, a chat

First Name	Last Name	Place	Code	
Nicolás	Ramirez	Jamundi	00042	☒
Carlos	Sanchez	Palmira	00043	☐
Cristian	Lozano	Stder. Quilichao	00044	☐
				☐
				☐

FIGURE 10.19: Patient tab with all the registered patients

a)

b)

FIGURE 10.20: Patient information pop up window. a) Patient Detail and b) Patient History

box and a notification box. The last two items are key to ensure a communication between the Specialist and the Assistant, because they would communicate only via plain text, due to band wide restrictions⁵. The *Notification Box* in the specialist *Session Information* would show a history of all the information received and sent between the Disperse Communication System. It differs from the assistant's *Notification box*, because there the notifications would come to and from the Local and Disperse Communication System.

The *Session Information* window also has two buttons: Patient Detail and Protocol. Both open additional pop up windows as shown in Figure 10.19 and Figure 10.18. Focusing the attention first on the latter, there would be four types of protocols: Cleaning, Failure, Passive and Active Protocols. The first two are a series of instructions to be executed by the assistant as a preventive maintenance for the device, to maintain the aseptic conditions for the patients and/or to execute countermeasures for failures in the device. Although it depending on the failure, the assistant should be instructed to fix the immediate problem or send the device to specialized maintenance. The specialist must choose the preloaded cleaning and failure protocols, and then, send them to the assistant.

⁵See Design Requirements

When the passive or active protocol is selected, a new pop-up window is opened, where several tools to construct the passive and active rehabilitation protocols are displayed. The passive protocol is composed of a matrix of angles with some additional information, such as therapy duration, while the active protocol would be a series of instructions specifying the therapy duration and level of resistance.

As for the *Patient Detail* button, the pop-up window in Figure 10.20 is opened. The specialist will be able to access all the detail information of the patient for the current therapy in the tab *Patient Information*. In the next tab called *Patient History*, the specialist can compile and visualize all the information regarding previous rehabilitation procedures for a certain patient. Two graphics are introduced for showing the progress of the FROM and force for the affected hand. The radar charts were selected because they are ideal to show multivariate data.

Returning to the main window, the two last tabs concern themselves with the registered patients and the assistants, as shown in Figure 10.19. When selecting any of the patients, the pop-up window *Patient Information*, which was previously described, is opened. The specialist would be able to register or delete a patient or an assistant from these lists.

10.3.2.2 Assistant Interface

The assistant interface would be a much simpler interface, where there are only two windows. Immediately after logging in, the assistant would encounter the window in Figure 10.21a, where the ID of the patient must be introduced. Once the specialist has confirmed that the patient ID matches with the programmed session, then the session is allowed to begin and a second window is displayed. In the second window, depicted in Figure 10.21b, the assistant can communicate with the specialist, receive and send notifications from the local and disperse communications systems, report failures or download protocol. The latter button would only be available when the specialist has sent a rehabilitation protocol and has instructed the assistant to download it to the device.

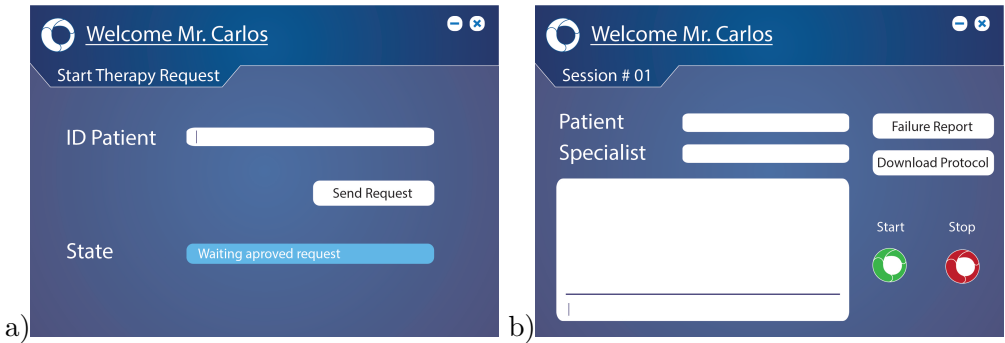


FIGURE 10.21: Assistant Interface. a) Patient ID confirmation and b) main window during therapy

Chapter 11

Prototype and Discussion

One of the main results of this project was the construction of the Hand Rehabilitation System prototype. To this end, several manufacture procedures were implemented. For one side, the structural main components, such as the dorsal and forearm modules, as well as the bars and its cases were manufactured with additive manufacture, that is a 3D printing. On the other side, the electronic circuit was first developed in Protoboard, and later printed in a the final board. Discussion regaring the materials and results from the construction phase are summarized in this chapter. Additionally, the interface used to prove the electronic circuit and comments regarding future works are presented by the end of the chapter.

11.1 Hand Module

The final design consists of four-bar mechanisms and spring modules with indirect power transmission. With the help of sensors, the flexion and extension angles of the fingers are registered during passive therapy and the indirect force of the fingers flexion during active therapy. It employs a Gear Box and a multiplexer to select indivual fingers and exectute the rehabilitation protocols “One Finger at a Time”. Additional features include a wrist positioner and the posibility to separate the finger modules from the orthosis.

Most of the parts have curve geometries that imply a more challeging manufacture. Additionally, ergonomics and perception of the device are important design requirements that should be

satisfied by the prototype to some degree. Due to its speed and precision, the additive manufacture was selected for most of the parts of the hand module, and therefore, ABS was selected as the material.

After the 3d printing, the parts were immersed in acrylic wax to give them better mechanical properties. The parts after printing are presented in Figure 11.1 below, where the a) shows the forearm module with wax and b) shows the same part without.

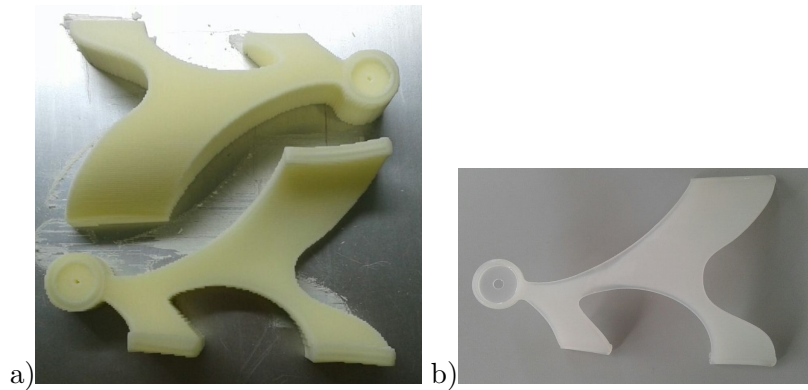


FIGURE 11.1: Forearm part by additive manufacture a) with and b) without wax after 3d Printing.

Once the parts were polished and covered with polyster resin to enhance even more its mechanical properties, the finger and dorsal module were assembled as shown in the figure below.



FIGURE 11.2: Assembled prototype (without transmission).

One of the first observation during this initial test was the evident instability of the bars on the phalanges, as a consequence of two design flaws. First, there was a low precision in mechanical articulations which allow some roominess; partially because the pins at the joints were made of

steel and would deformate the plastic bars when loaded. And second, the lengths of the bars, although necessary to have good transmission angles, incremented the inertial component in the longitudinal direction, causing stress on the mechanical articulation. This would lead to misbehaviour of the mechanism, such as poor force transmission or failure at the mechanical articulations. The abduction/adduction mechanism was specially sensible to changes in the finger rotation and proves to be inadequate for the device.

As consequence of this first trial, the design team proposed the use of a glove that would serve as a base for the mechanism, providing more stability. The use of gloves was discarded during the design requirements' definition since they exclude the users with stiff hand in flexed positions, and as a result the fisiotherapists and occupational therapists oppose to the use of gloves for hand devices. However, this was necessary for the prototype to further prove the device and its function.

Blue and white were the colors chosen in the concept selection stage, then they were implemented in the prototype. The figure below shows the complete assembly for the hand module of the Hand Rehabilitation System, including the finger module, dorsal module, wrist positioner and forearm module.



FIGURE 11.3: Assembled prototype with bar's cases, glove and colors (without transmission).

The indirect transmission system was implemented directly, that is, without the use of the Gear-Box but directly connected to the DC motor. This arrangement reduced the available torque, the output speed increases and the system would be able to control the movement of one finger. This was nonetheless sufficient to prove the concept of the indirect transmission.

In order to control the motors, the electronic circuit explained in the previous chapter was used. It implements a pwm to control the speed of the motor, having a range between 1 to 500 [$^{\circ}/s$], from where only the range between 1 to 10 [$^{\circ}/s$] would be used.

11.2 Tests

Two basic tests were done on the prototype, in order to determine its functionality.

11.2.1 Work Volume

First, the work volume of the device was tested while pulling the bars to the most extended position for every biological articulation of the test finger. The exercise was repeated for the flexion.

The results from these tests can be seen in Figure 11.4.

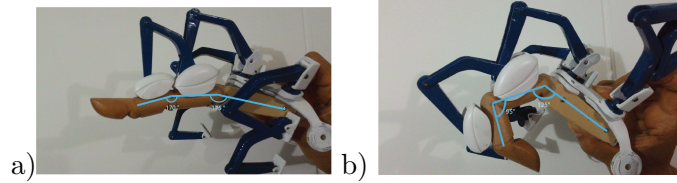


FIGURE 11.4: Prototype Work Volume validation

As can be seen above, the bars did not accomplished the intended FROM, as the angles expected in extension was 185° for MCP and PIP, and they only achieved 175° and 170° , respectively. On the other hand, the MCP joint in flexion achieved an angle of 125° while the PIP had an angle of 95° , which are not the intended angle, having a that the “functional” flexion is 100° .

The FROM for the MCP and PIP joint in Finger 2 covers 85° , from where a deviation of 1° implies a a deviation of 1.2 %. Therefore, the values obtained were out of the tolerance margin.

There were different reasons behind the difference. First, maintaining the dorsal module in place was not possible all the time. The position of this module would determine the length of the bar l_0 of the mechanism, and therefore, changing its value would alter the kinematic behaviour.

Second, the tolerance between the bars was lower than anticipating due to the additional layers of wax, resin and paint. Although necessary, the additional layers should have been taking into account to enable free rotation of the bars.

11.2.2 Torque

The second test was the evaluation of the torque that the device had available at the MCP joint, necessary to lift the phalanx. The configuration used for this test can be seen in the Figure 11.5.

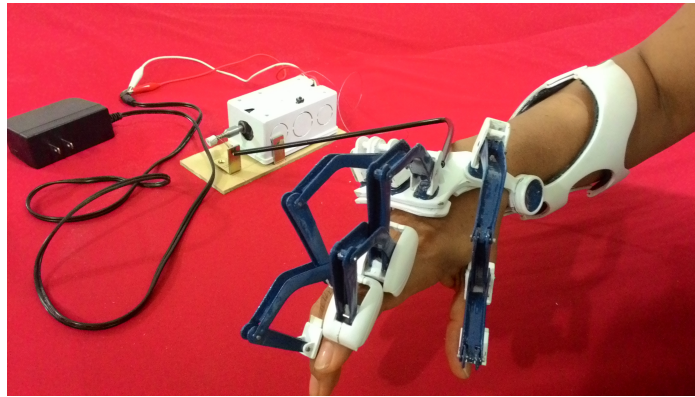


FIGURE 11.5: Prototype Work Volume validation

The device tried to lift the finger of the subject, while it did not exert any resistance to the movement. The mechanism was able to pull the proximal phalanx approximately 10° , but the Abduction and Adduction mechanism failed, repeatedly. As it did not have the optimized geometry presented in Section 10.1.5. nor the material (aluminium), it behaved as expected.

However, some conclusions were drawn from the test. First, the winch mechanism lack of an idle pulley. It was needed not only with the direct configuration of the prototype, but in the Gear-Box design. Additionally, the Abduction/adduction mechanism made of ABS, proved to be insufficient even without rotational resistance from the subject. Once again, keeping the dorsal module in a fixed position was challenging and altered the results of the test.

11.3 Electronic Board and Interface

The functional test of the electronic module began with the interface, which was a modified part of the most general GUI in Chapter 10. It was modified to be a *functional* version and includes both active and passive therapy protocols. The Figure 11.6 presents the modified interface that

allows the user to input passive and active therapy parameters. The passive therapy protocol is composed by the minimum and maximum degrees to move for each articulation, the speed of the movement and the duration of the therapy. On the other hand, the parameters for the active therapy protocol are the stiffness of the spring and the duration of the therapy.

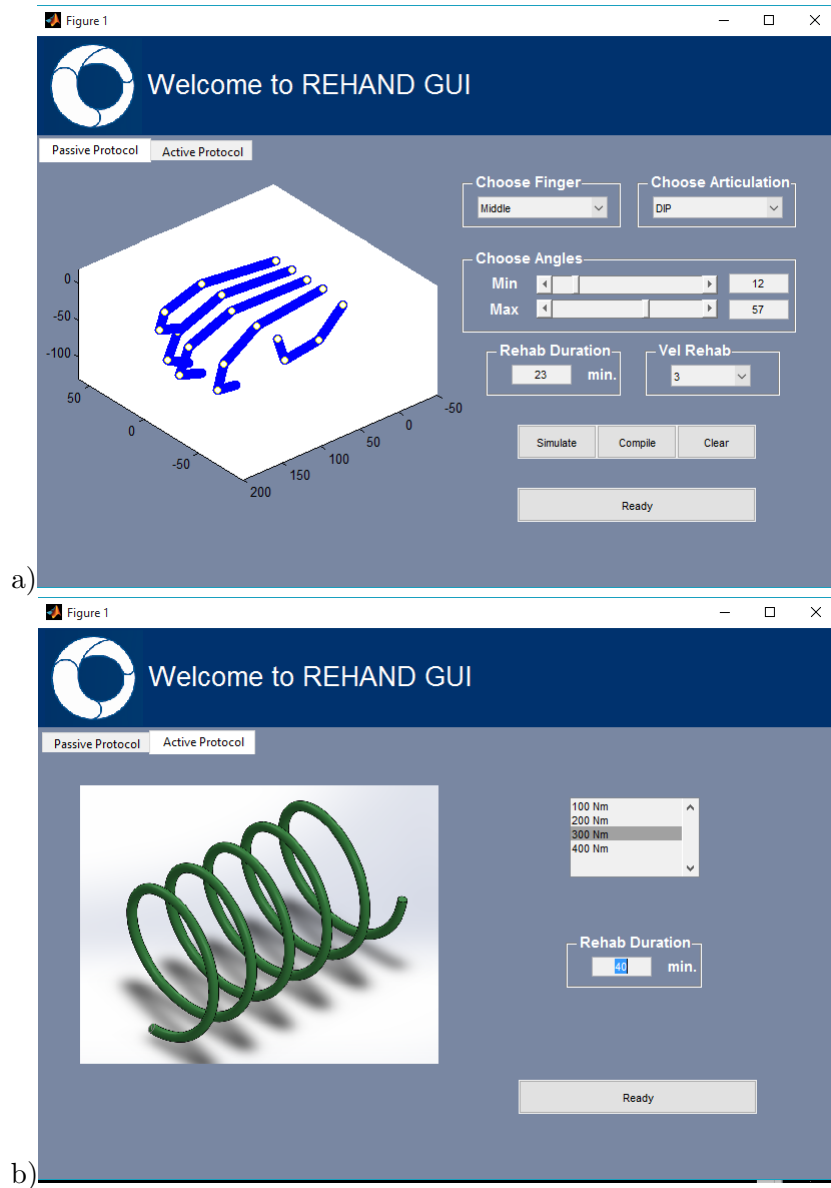


FIGURE 11.6: Modified test GUI for functional test

When the “Ready” button is pushed, the data is compiled in a text file and sent to the device using the Xbee modules and XCTU ®program. The implemented GUI, see code in Appendix X, compiled successfully the text file and the Xbee communication module as able to sent this data over 30 mm distance.

As for the electronic module, the circuit in Chapter 10 was reduced in a electronic board as depicted in Figure 11.7.

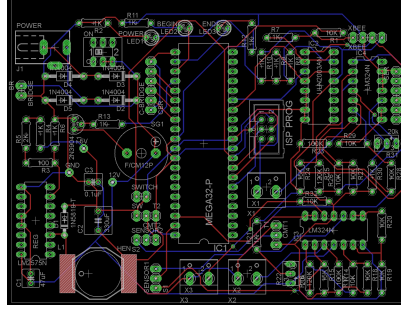


FIGURE 11.7: Electronic board from the circuit presented in Chapter 10

The periferial components, that is the sensors to measure rotation and force, presented huge variation during operation. For one side, the Flex sensors had different operation curves, i.e. two sensors presented different resistance value at the angle. This property made its characterization more difficult and introduced variation during angle measurement. Additionally, after some use, the flex-sensor hardware itself presented a curvature, which alter its characteristic parameters.

The final tests showed a tolerance over 5 [°], which is not acceptable for teleoperation. Its shape was convenient for assembly purposes, however its accuracy was lower than expected and therefore it should not be used.

11.4 REHAND as a Brand

The Hand Rehabilitation System is named *REHAND* and is given the slogan, “Wellness to Reach of Your Hands”. The logo in Figure 11.8 represents a modular crab claw, which indicates two of the design concepts which were the claws, as a symbol of grips, and modularity.

11.5 Future Work

The manufacture of the prototype proved to be one of the most effective ways to discover design flaws. Some of the key results of the construction phase were oriented to the poor stability discovered in the finger modules, specially at the most proximal articulation, which coincides with the Abduction and Adduction mechanism. Future proposals should be oriented to sturdier connections, materials and shapes that enhance the overall stability. Additionally,



FIGURE 11.8: Hand Rehabilitation System Logo and Slogan

different abduction/adduction mechanisms should be proposed, allowing a rigid base for the finger modules while keeping their functionality.

As for the electronic development, the proposed circuit and board has the potential to decrease in size, with SMD components. Additionally, further security circuits such as watch are to be implemented in the device to enhance the reliability of the system.

On the other hand, the GUI is yet to be completed, with the completed architecture showed in the previous Chapter. It should be presented to the involved users to evaluate its usability, effectiveness and reliability.

Much work is left, in order to make REHAND a fully fleshed product. After a series redesign and prototyping, it should enter a more rigorous testing phase, with non-humans and then human hands.

Chapter 12

Conclusions

From the first stage of the project, the following question rose as the identified problematic situation: how a person with a condition of geographic vulnerability and a transitory disability, that needs access to specialist treatment can overcome the factors that limits its access. Some statistics were also provided to give a quantitative grasp of the problem and give a more solid background on this problematic in the Colombian context. Even though, some of the data was outdated, the situation does not seem to have improve. However, the search for more recent data must be made continuously.

Later in the document, a 5-phased methodology was presented and an special emphasis was made on the definition of the design requirements. The methodology allowed a structured design process and make easier the integration of interdisciplinary context on the same device.

With respect to the General Objective, the methodology proves to be an excellent tool to approach the problem from several disciplines simultaneously, which is a requirement when designing medical devices. Although, the presence of a health specialist during the development of the project was seen as an external consultant, and a dedicated attenttion in future interdisciplinary works could lead to better results.

On the one side, the first stage of the methodology succeeded in describing the biomechanics of the hand throughly, using extensively previous studies like [13]. On the other side, the semi-structured interviews allowed the characterization of the therapeutic procedures, and furthermore, allowed the design team to expierence first hand the reality of the patients.

However, the literature lacks of information regarding non-permanent conditions that affect hand functional capacity. This situation lead to assume that maximum possible stiffness of the hand is equivalent to the joints resistance to move when it is in power-grip position. Therefore, initial assumption behind the biomechanical model implemented should be study in further detail, as the present project reach fails to proves the validity of the model while representing osteomuscular and ligamentous injuries that would generate a transitory disability.

In a similar sense, although the mechanical design was focused on transitory disability, the system may be applicable to certain permanent disabilities, whose rehabilitation procedures contain similar passive and active exercises. Nonetheless extensive clinical studies must be carry out to assure the safety for the patient, due to special limiting conditions, such as spasticity, usually related to neurological patients.

IDEF0 diagrams were used to show the mechatronic architecture and relations between the subsystems. A colour convention was employed to help visualize the signals from one system to another. Additionally, complemetary Activity Diagrams for the Rehabilitation Session were also presented. These diagrams illustrate in a more detail fashion the commands and signals inside the electronic subsystem.

Finally, the construction of the prototype was made mainly with 3D printers due to complex surfaces. However, different plastics and resolutions were used for different pieces. For example, the bars were printed with ABS plastic, while housing surfaces such as the dorsal surface was printed with PLA. The construction of the Gear Box was not possible due to budget restrictions, but the function of the device was proved with the index finger and two dc motors connected *directly*.

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Appendix A

Appendix A. Hand Anatomy

This appendix summarizes some concepts related to hand anatomy. Additionally, it presents the anthropometric considerations taken, while establishing the anthropometric lengths for the biomechanical model in Chapter 4. A short description of the “Activities of Daily Living” and the hand functions during this activities are described in sections 4 and 5. These are followed by the biomechanical description of the hand, including the function range of motion, the kinematics and kinetics of the hand. Finally, some concepts regarding the hand rehabilitation itself are summarized by the end of the Appendix.

A.1 Basic Concepts

The human hand has five fingers, which are shown in the Figure [A.1](#), and receive the names of thumb, index, middle (or long), ring and small, enumerated as fingers 1 to 5, respectively. From a functional perspective, the fingers 2 to 5 can be classified under one category, but the finger 1 has a functional category on its own. The fingers in general can make 2 movements, flexion-extension and abduction-adduction, as shown also in Figure [A.1](#).

In order to provide movement, the hand has five major types of biological structures which are: the bones, for structure, the muscles, for driving the movement, the ligaments, for stability, the tendons, for connection between bones and muscles, and neurons grouped in nerves, for sending movement signals. Although, it is important to remember, that the human hand is also a major

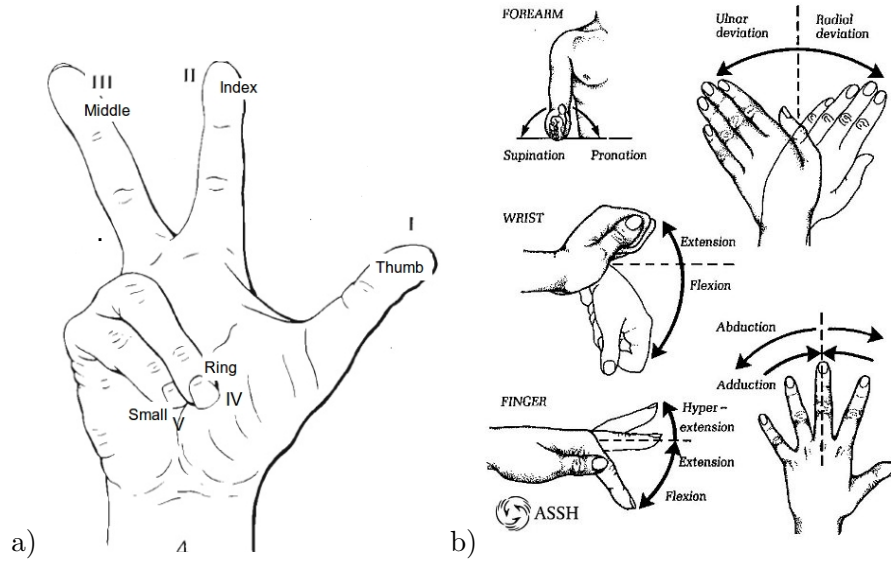


FIGURE A.1: Descriptive drawing of basic hand anatomy and hand movements. Source: Kaspandji, ASSH

sensory receptor, therefore, there are several sensory neurons sending constant feedback to the brain.

Damaging the function of any of these biological structures would result in a hand injury; understanding that the structures within the hand can depend from other external structures. Hence, injuries in the nervous system, circulatory system or previous structures in the forearm, arm and/or shoulder could damage as well the hand functionality [28].

These structures give rise to several eminences and particularities in human hands, which must be taken into account while designing. The most relevant particularities are shown in the Figure A.2 below and the Table A.1, but a complete description can be found in [12].

TABLE A.1: List of hand particularities for Figure A.2.

Number	Name
4	Thenar eminence
6	Scaphoid tubercle
7	Hypothenar eminence
8	Pisiform
19	Interdigital cleft
22	Pulp
24	Extensor Tendons
25	Heads of the metacarpals
27	Ulnar aspect of the hand
34	Ulnar head

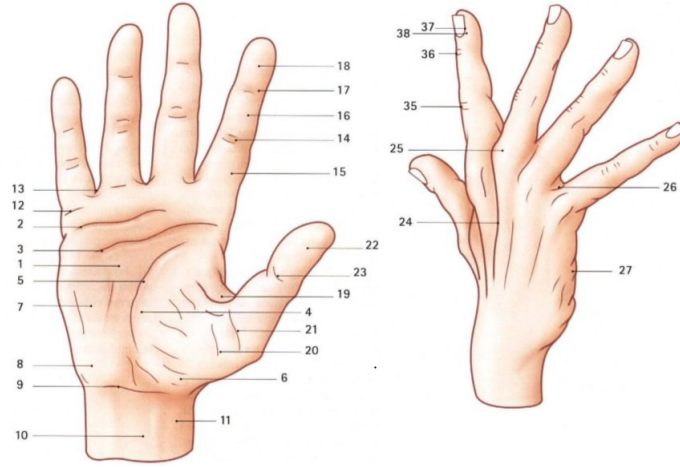


FIGURE A.2: Hand Particularities. Source: Kapandji et al., 2006

These particularities can be found in the *volar*, or anterior part of the hand, and in the *dorsal*, or posterior part of the hand. Additionally, the hand can be divided in two halves called *radial side*, which contains the fingers 1 to 3, and the *ulnar side*, which contains the fingers 4 and 5.

Continuing with the description of the biological structures, the bone, or more specifically the bone's tissue, is defined as a connective tissue with an anisotropic, non-homogeneous, viscous-elastic behaviour [32]. However, it is assumed in this project that body segments are “rigid”, i.e. that the underlying bone is a rigid structure. Then, it can be also assumed that all distances and relative positions of points on a single segment will remain invariant[33]. The bones in the hand are known as phalanges, metacarpals and the carpals, which have a head and a base, distally and proximally. These are depicted in the Figure A.3.

Connecting the bones together we have the ligaments, which are bands of connective tissue. The most relevant ligaments in hands are called *collateral ligaments*, which can be found on either side of the phalanges and prevent abnormal sideways bending of the phalanges as shown in Figure A.4 [12]. Another relevant ligament is called the *volar plate*, which can be found in the palmar surface connecting the middle and proximal phalanges. It is the strongest ligament in the hand, however, does not participate in flexion of the fingers [3].

As stated before, the muscle tissue is responsible for the body motion, although there are several types of muscles: smooth, cardiac and skeletal, only the latter is used to move and maintain postures.

Consequently, the hand has skeletal muscles with an effect in the hand's movement, which can be found in or out its boundaries. Within the hand's boundaries are the Intrinsic Muscles,

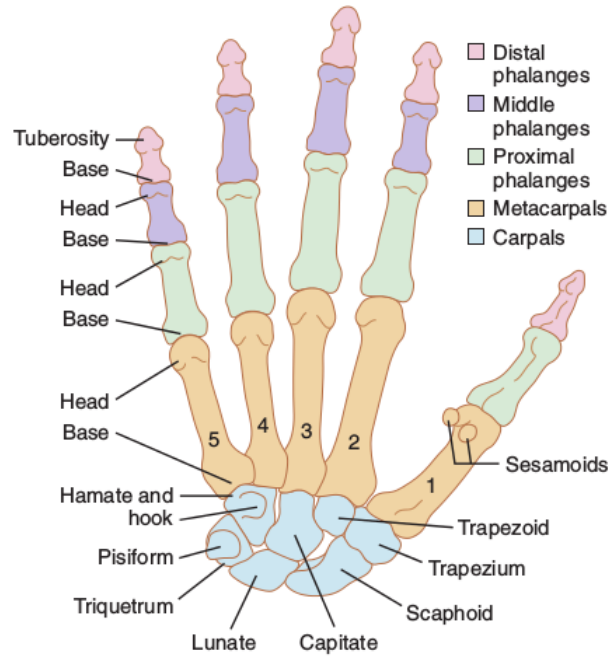


FIGURE A.3: Hand bones. Source: Skirven, 2011 [28]

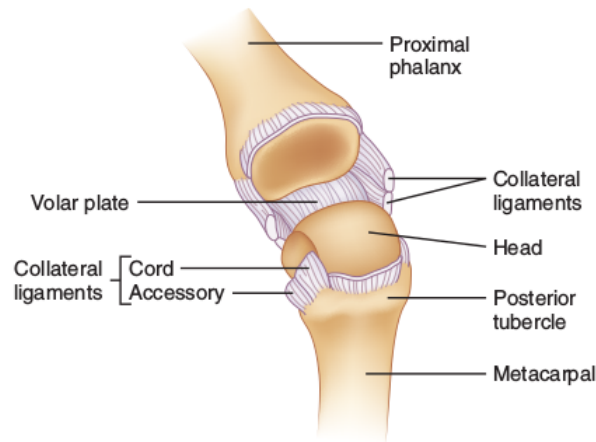


FIGURE A.4: Detail on hand ligaments in the MCP joint. Source: Skirven, 2011.

such as the Muscles of the Thenar Eminence, which moves the thumb, and the Hypothenar Muscles, which moves the small finger. In a similar manner, the Lumbrical Muscles (LU), the Dorsal Interosseous (DIR) and the Palmar Interosseous (PIU) muscles participate in the fingers' flexion and abduction/adduction. The latter are further classified by the literature as the Ulnar Interosseous (UI) and the Radial Interosseous (RI), which act on the proximal phalanges [28]. Likewise, outside of the hand's boundaries there are others such as the Extensor and Flexor Muscles, which have nonetheless an effect in the fingers' movement. It is important to point out that the human hand has evolved to perform precise and fine movements, rather than develop

large forces [18].

It is important to understand the types of muscle activation since they are closely related to muscle exercises, which would be mentioned in the following sections. Broadly speaking, there are two types of muscle activation: One where the muscle exerts a force but its longitudinal length does not change, which is called *Isometric contraction*, and the other one where the muscle length changes (the muscle contracts) while maintaining a uniform tension [34], called **Isotonic contraction**. The latter can be further classify in concentric and eccentric muscle contractions. The concentric contraction refers to the case where the muscle force is sufficient to overcome an external load or “resistance” and the muscle shortens, while in the eccentric contraction the force is insufficient to overcome the external load and the muscle lengthens to decelerate the joint rotation[35].

Furthermore, the skeletal muscles are attached to the bones with fibrous connective tissue specialized to withstand tension called tendons. These “cables” are conducted through “tunnels,” or specialized ligaments, such as the *Carpal Tunnel* in the wrist, forming pulleys, as was first proposed by Landsmeer [36]. These pulleys are schematically shown in Figure A.5 below.

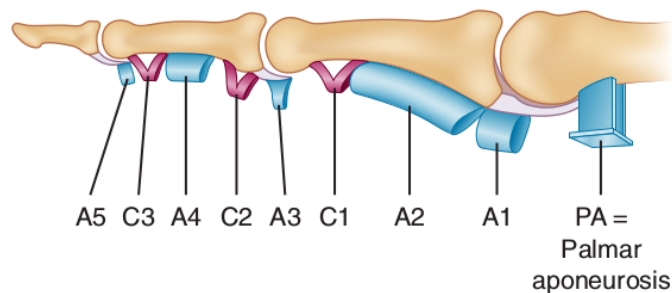


FIGURE A.5: Schematic representation of the ligament pulleys. Source: Skirven, 2011.

The hand has several tendons, that can be classified according to the muscle to which they connect. The tendons that connect outside the muscles with the phalanges in the dorsal surface of the hand are called Extensor Tendons. Specifically, the *Extensor Digitorum Communis (EDC)* participates actively in the finger extension. It divides in the finger into the three slips, called the *central extensor slip (ES)*, the *ulnar lateral band (UB)* and the *radial lateral band (RB)*. The radial and ulnar lateral band re-joint to form the *Terminal Extensor (TE)* [18]. Additionally the Flexor Tendons connects the Flexor Muscles to the phalanges in the palmar surface of the hand. The Flexor Tendons can be classified in the *Flexor Digitorum Superficialis (FS)* and the *Flexor Digitorum Profundus (FP)*, which are attached to the base of the middle and distal

phalanges, respectively. The Figure A.6 shows the previously explained tendons and muscles from volnar.

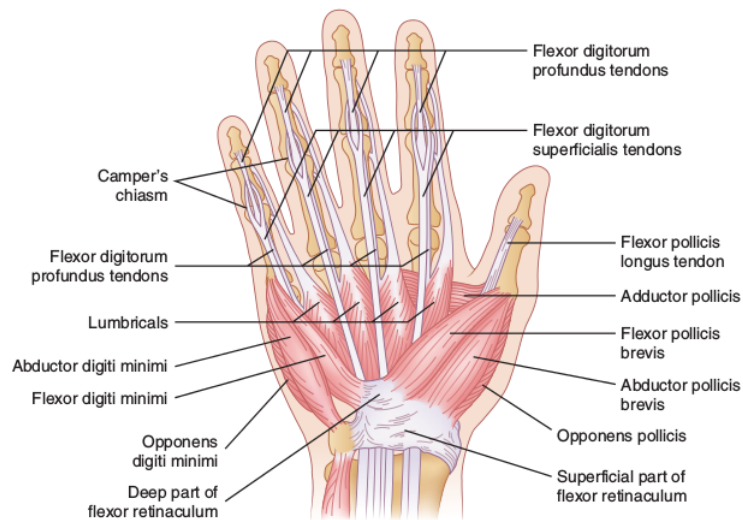


FIGURE A.6: Volar view of the superficial muscles and tendons. Source: Skirven, 2011.

Finally, the thumb's phalanges are connected to just one muscle outside the boundaries of the hand, called the Flexor Policis Longus Muscle, which connects to the base of the distal phalanx of the thumb. All the other muscles of the Thenar Eminence are connected from the wrist to the thumbs phalanges.

Although all human hands share similar anatomical components, as the ones previously described, its dimensions and weights vary significantly from one person to another, and several factor influence this variation such as age, genre, nationality, etc. The following section explains the consideration taken while evaluating the Anthropometry of the Human Hand for the Colombian context.

A.2 Anthropometry

As it was previously shown, the human hand is a very complex limb and consequently is quite challenging to accomplish an extensive and complete anthropometric study of the hand; understanding *anthropometry* from etymology as the science of “*human measurement*”. However, the anthropometric study of the hand is fundamental to develop a wide variety of tools, hand wears, wheels, handlebars, as well as medical devices such as splints and so on.

Furthermore, the anthropometric measurements will depend extensively on the studied population, e.g. the data from Europeans, Chinese and Latin American would differ by a considerable amount [17]. Most anthropometric studies of the hand can be broadly categorized in general or application surveys, where the first one take large populations as samples, while the latter gather data from an specific population with a product in mind. The problems that may arise from general surveys include conflicts between sample size and comprehensive measurement, and on the other hand, results from application surveys are more difficult to generalized to different populations [17].

With that in mind, the present document present a methodology to establish the anthropometric data required to continue with the design. Due to insufficient data in literature regarding hand anthropometry for Latin America, a correlation was carried out between an application survey made by the US Army, known as ANSUR [17] and a more general survey made for a Latin American population [22]. The ANSUR reported a detailed anthropometric description of the hand, with over 80 hand dimensions, in which image processing techniques were employed to gather the data. Therefore, standard landmarks were established, as shown in Figure A.7. Comments and specific descriptions on the landmarks can be found in ANSUR [17].

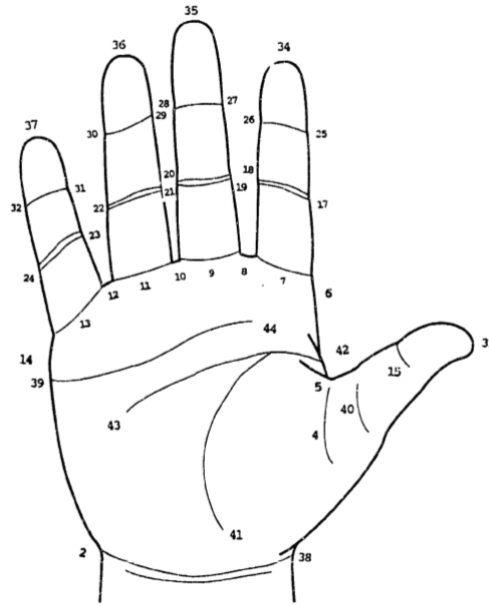


FIGURE A.7: The hand landmarks established by ANSUR for the anthropometric study.
Source: ANSUR [17].

Both studies share three fundamental measurements of the hand, which are hand length, hand breadth and palm length. On one hand, the ANSUR reported results for a population between 18 and 49 years old, while the Latin American data reported results for the ages between 18 and

65 years old. This difference would be consider negligible, because the age range of our target user is between 16 and 60 years old ¹. Comparing these three fundamental measurements, it was found that the measurements for percentile 25%, 50%, 95% and mean in Latin American hands were consistently smaller than the ones reported by ANSUR; specifically 8% for men and 6% for women (See Appendix ...). Therefore, it is assumed that the anthropometric values for digit length and breadth from ANSUR can be adjusted by this factor to a Latin American population. However, it must be clarified that this method can only serve as a guideline of the expected anthropometric lengths required for this project and further research is required to define anthropometric lengths for the Colombian population.

A convention for describing the phalanx dimensions was used and shown in Table 5.3. With this, the results were conveniently listed in Tables 5.4 and 5.5.

A.3 Activities of Daily Living

The Daily living activities include two separate areas called, the activities of daily living (ADLs), also known as personal or basic activities of daily living (PADLs or BADLs), and instrumental activities of daily living (IADLs). The ADLs are concerned with tasks of self-care such as bathing/showering, dressing up, eating, toilet hygiene, sexual activity, etc. This category also includes the care for personal medical devices, such as orthopaedic devices. On the other hand, IADLs are more complex tasks regarding relations with other human beings and the environment in general. Some examples include rearing a child, using a telephone, using a personal computer, etc [5].

In order to have a standardized point of view, these categories are classified by the WHO under the document “International Classification of Functioning, Disability and Health”, or ICF [5]. This document defines,

- *Activity* as performing a task or action.
- *Participation* as the act of involving oneself in a vital situation.
- *Activity limitations* as the difficulties that a person may have while performing an activity.

¹Range of age for Colombian working population DANE

- *Participation restrictions* as the problems that a person may experience while involving itself in a vital situation.

Several items from the “Activities and Participation” domain classified by the ICF are selected, in the sense that a hand disability may limit the activity and/or restrict the participation of the individual in each of these items. The following Table A.2 describes some of the items selected, but a complete list can be find in the Appendix X.

TABLE A.2: Activities of Daily Living affected by hand disability by a limitation in the activity or a restriction in participation (partial).

ICF Code	Activity Name
d335	Producing nonverbal messages
d420	Transferring oneself
d510	Washing oneself
d630	Preparing meals

In order to perform these activities, the hand makes certain movements which are classified in the following section.

The 20 grips listed before shall be one of the components needed to identify the ROM of the hand functions while performing ADLs, following the methodology described in section [REFERENCE], as synthesized in the following section.

A.4 Hand Rehabilitation

The main objective of hand rehabilitation is to restore the functional range of motion (FRoM) of the hand, through different therapeutic procedures. It has different stages, which can overlap or follow no-chronological order, and always depend on the patient individual characteristics [28]. However, the therapists identify four basic stages of the rehabilitation which are the initial medical review, the clinical examination, the diagnosis, the intervention and the re-evaluation. It is of special interest to detail the intervention sub-stages of the rehabilitation, which can be the swelling reduction stage, regaining the arc of movement stage and strengthening stage.

Before describing each stage of the rehabilitation, it is convenient to introduce the concepts of *passive* and *active motion* since they are present in all stages of the rehabilitation procedures. For one side, when a limb is moved but the subject does not participate voluntarily in the

motion, it is called a *passive movement*. The opposite goes for *active movement*, where the subject does participate voluntarily.

With those concepts in mind, the rehabilitation stages would be briefly described, beginning with the swelling reduction stage. In this first stage, the therapist goal will be to reduce the edema² cause by the injury or surgery procedure. Several techniques may be applied, but the literature identify *elevation*, *active motion*, compression, and gentle external massages [28].

Regarding passive rehabilitation, literature documents that early movement of the injured articulation would have several benefits such as tissue homeostasis, increases in venous and lymphatic flows, increases in tensile strength of the hand, and directs alignment and orientation of collagen fibres [28]. Salter et al. [37] introduces in 1980 the Continuous Passive Motion (CPM) concept and CPM devices, employed extensively in post-operative knee operations, to promote precisely venous and lymphatic flows, accelerating the rehabilitation's first phase.

Once the edema has decreased, the therapist will proceed to execute therapeutic procedures to restore the passive range of motion. The use of orthoses and CPM are often use during these therapeutic procedures. It is important to point out that the literature claim that there is not a standardized ideal load, speed or duration for the passive motion [28]. On the other hand, the active motion allows lymphatic flow and helps reducing edema [28]. One of the side effects of not using the normal muscle's recruitment patterns, as soon as possible, is that the motor cortex may "learn" these maladapted patterns, making more difficult to restore the active range of motion.

There are several types of active exercises which are classified according to the muscle contraction that enables to exercise, such as isokinetic, eccentric, co-contraction, co-activation of the agonist and antagonist muscles, reactive, isometric and isotonic [28]. It must be notice that these exercises are closely related and may present dual behaviour, e.g. an eccentric isotonic exercise. The present document focuses on the isotonic exercises due to its relevance in finger strengthening, but further information regarding the exercises can be found in several physical rehabilitation and training manuals such as [28].

In rehabilitation, the isotonic exercises can have two categories: assisted or resistive therapy. As the name implies, the difference lies whether an external force is used to help in the patient movement or the opposite, i.e. an external load resists to the patient movement. Once again,

²Understood as an excess of fluid in the spaces between the cells (interstitium)[28]

certain exercises can combine both movements, e.g. using elastic bands in the fingers could oppose a resistance while flexing (resistive therapy) and assist the fingers extension (assisted therapy).

Appendix B

Normative Model of Human Hand for Biomechanical Analysis: Adaptation

This Appendix intends to explain the Normative model proposed by Chao et al. [13] and the adaptation made for this project, in order to determine the torques expected from a hand in *power grip* in each joint.

First, a new coordinate system is proposed by Chao with 6 coordinate axes. In which three of them are called the principal axes and coincide with the centres of rotation of the phalanges, which were already defined in the present document as Axes A1i, B1i, A2i and A3i. Additionally, three secondary axis are located in the centres of the concave articular surfaces, as shown in the Figure B.1.

In order to construct the normative model, Chao et al. measured lengths of the phalanges from ten cadaver specimens and then normalized the results by using the middle phalanx length for fingers 2 to 5, and the proximal phalanx for finger 1. The latter to avoid variations due to anthropometric differences. The values describing the new coordinate system is called *Normalized Coordinate Systems Position for Finger i*.

By using X-Ray and thin wires, the position of each tendon was described as coordinates of the primary and secondary axes. In other words, the tendon was described as vector with two points: one measured from the proximal coordinate system and the other from the distal

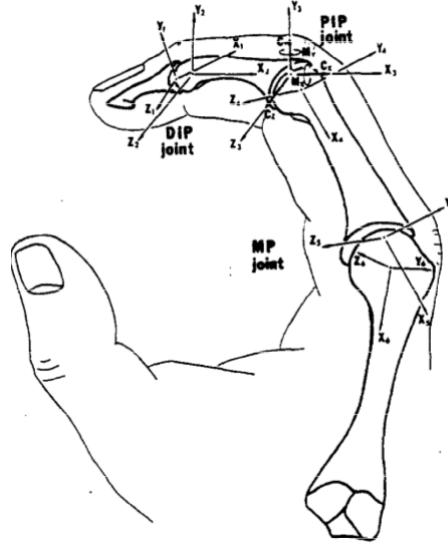


FIGURE B.1: Normative model axes convention modified from Chao, 1979.

coordinate system. Assuming that the tendon is linear between the *ligament pulleys*. This approach allows to evaluate the tendon position while flexing or exerting the phalanges by a coordinate transformation procedure.

Although, the coordinates from the direct measurement of the tendon position in cadavers were not used for describing the positions as they may present significant variances among the specimens. Therefore, the author introduced two *auxiliary* concepts: *force potential* and *moment potential*. The force potentials are expressed in terms of director cosines of a vector describing the tendon's direction and the moment potentials are expressed in terms of the moment arm, from the tendon to the respective joint center. Some refinement of this data was made in order to assure that the parameters of the force potential form a unit vector and the moment arm and its unit force vector were orthogonal. Once the parameters were refined, two points for each vector were selected, one with respect of the proximal and the other with respect to the distal coordinate system, for each joint; these values are gathered in a matrix called **Tendons Positions in Neutral Position for Finger i**. Although, the tendon position was calculated with respect to the neutral position, any position can be calculated with an appropriated coordinate transformation [13].

To determine the moment expected in each joint during power-grip while holding a 50 mm diameter bar, the expressions in B.1 were taken as entries for the model.

TABLE B.1: Entries for torque estimation in joints

Entry	Type	Name
Normalized Coordinate Systems Position for Finger i	Matrix	Ci_p
Tendons Positions in Neutral Position for Finger i	Matrix	Ti_p
Middle Phalanx Anthropometric Length for Finger i	Scalar	Di_23
Measured Angles for 50mm diameter grip for Finger i	Vector	a.i = [t1, t2, t3]
Ratio of tendon force by the exerted force for Finger i	Vector	F_i
Maximum force during Power-Grip	Scalar	F_max

Then, the following manipulations were made to obtain the Matrix τ of torques, showed previously on Chapter 5.

First, the model is considered for finger 2 (index finger), then $i = 2$, for all the expressions. Additionally, the matrices C2_p and T2_p were multiplied by the middle phalanx length Di_23.

Using the transformation matrix below, the T2_p is transformed to the new configuration (power-grip) using the angles in a_2. The distal and proximal tendons positions coordinates with respect of the proximal coordinate system describe the tendon as an unitary vector and can be used to find the director cosines for each tendon, using the equation below.

$$\alpha_i = \cos(a) = \frac{\vec{v}}{|\vec{v}|} \quad (\text{B.1})$$

Using the value F_i from [3], and the previous derived direction, the tendon force is completely defined. And finally, τ was calculated as the sum of the cross products of the tendons' vectors and the tendons' proximal positions vectors.

Appendix C

Hand Functions in Daily Living Activities

This Appendix is divided in three sections and culminate with the Functional Range of Motion (FROM) of the hand. The first section is a list of Daily living Activities that were taken into account for this project and then a list of hand grips as classified by [12] is presented. Latter, a logic matrix combines the previous lists to obtain the functional DOF, which are measured to obtain the FROM.

C.1 Activities of Daily Living

C.2 Hand Grips

As defined by Kapandji [12]. See next page.

C.3 ADL Grips

Please visit the web resource: <https://drive.google.com/folderview?id=0B1sQ9wGh10yKfm5pQ290NEFiZC1zNDc2NG1ZN2ZsOGF1N3Byam5td0RjR2hUemloY0piMUE&usp=sharing>

TABLE C.1: Activities of Daily Living affected by hand disability by a limitation in the activity or a restriction in participation.

ICF Code	Activity Name
d340	Producing messages in formal sign language
d345	Writing messages
d360	Using communication devices and techniques
d420	Transferring oneself
d430	Carrying, moving and handling objects
d440	Fine hand use
d445	Hand and arm use
d455	Moving around
d475	Driving
d510	Washing oneself
d520	Caring for body parts
d530	Toileting
d540	Dressing
d550	Eating
d560	Drinking
d630	Preparing meals
d640	Doing housework
d650	Caring for household objects
d660	Assisting others
d710	General interpersonal interactions
d920	Recreation and leisure

C.4 Functional Range of Motion (Complete)

FIGURE C.1: Complete functional range of motion for the hands

Finger	Axis	M1(°)	M2(°)	M3(°)	M4(°)	M5(°)	M6(°)	M7(°)	M8(°)	M9(°)	M10(°)	M11(°)	M12(°)
1	A01	45	40	40		45	50	40	40	45	45	60	50
	B01	35	25	25		25	30	45	35	35	35	45	30
	A11	115	145	115		150	140	155	125	125	120	160	165
	A21	115	130			140	125	145	170	170	100	165	150
2	A12	110	100	110	160	140	135	150	130	110	140	185	185
	B12	-10	-10		-5	10	5	-5	-10	-5	5	-5	10
	A22	110	135	100	130	130	120	130	130	170	125	165	165
	A32	140		125	150	155	150	135	145	180	140	165	160
3	A13					155	135	140	125	110	145	160	-10
	B13				-5	-5	5	-20	-5	-5	-15	-15	-10
	A23				140	125	125	130	130	160	125	150	155
	A33				130	140	145	140	140	170	135	160	150
4	A14				150		150	125	135	120	140	150	-20
	B14						5	-10	15	10	20	20	10
	A24						115	120	110	160	110	155	145
	A34						130	145	145	170	130	160	155
5	A15									135	120	140	185
	B15									10	10	10	35
	A25										100	165	160
	A35										145	165	170

a)

Finger	Axis	M13(°)	M14(°)	M15(°)	M16(°)	M17(°)	M18(°)	M19(°)	M20(°)	M21(°)	MAXIMUM	MINIMUM
1	A01		40	55	40	40	45	35	40		60	40
	B01		35	50	35	35	25	30	30		45	25
	A11		165	160	125	165	145	135	140		165	115
	A21		165	140	170	125	165	160	170		170	100
2	A12	100	100	125	135	140	155	120	135	115	185	100
	B12			-10	-5	10	-5	-20	-5		10	-10
	A22	105	100	130	140	125	185	170	135	105	170	100
	A32	140	140	150	165	150	190	180	130	140	180	125
3	A13	95	95	125	135	150	110	115	130	100	160	-10
	B13			-5	-5	-10	-15	-5	-5		5	-20
	A23	110	110	140	145	125	105	170	155	110	160	125
	A33	125	125	145	160	140	130	180	165	130	170	130
4	A14	95	95	145	130	145	95	115	140	115	150	-20
	B14			5	5	25	5	10	5		20	-10
	A24	100	100	130	110	125	110	170	145	100	160	110
	A34	125	125	155	135	150	145	180	160	130	170	130
5	A15	100	100	155	105	135	95	120	150	110	185	120
	B15			5		10		5	-5		35	10
	A25	110	110	125	110	135	110	170	150	120	165	100
	A35	140	140	150	145	150	125	180	160	125	170	145

b)

Appendix D

Investigation Instrument

Three types of interviews were submitted to 3 rehabilitated patients, 3 patients with a rehabilitation in course and 3 health specialists experts in hand rehabilitation.

D.1 Model 1. Patients with a Rehabilitation in Course

1. ¿Cuál es su profesión?
2. ¿Cuál es su edad?
3. ¿Cuál es su peso?
4. ¿Cuál es su estatura?,
5. ¿Cuál es su lado dominante y en qué lado se presenta la lesión?
6. ¿Cuál fue la razón que lo motivo a la búsqueda de un especialista en rehabilitación?
(fractura, dolor o restricción de movimiento)
7. ¿Es su primera lesión o ha sufrido lesiones recidivantes, cuantas?
8. ¿Lleva a cabo con juicio los deberes asignados por el profesional de la salud?
9. ¿Tiene en cuenta las precauciones, cuidados y ejercicios para el hogar dejados por el fisioterapeuta durante la realización de sus AVD? 1
10. Si no los cumple, ¿cuál es la razón para no hacerlo? 11. ¿Cómo siente que es la comunicación con los profesionales de la salud? 1

11. ¿Cuál es su percepción de los dispositivos empleados en los centros de rehabilitación? 1
12. ¿Siente que el ejercicio realizado con estos equipos es útil, es decir siente cambios positivos (mejorías)? 1
13. ¿Siente que los equipos empleados para su rehabilitación son cómodos o justos a su medida? 1
14. ¿Cuál es su percepción de los protocolos o procedimientos empleados en los centros de rehabilitación? 1
15. ¿Presenta dolor en su(s) mano(s) al realizar AVD? 1
16. ¿Ha notado falta de fuerza, debilidad o poca resistencia en su(s) mano(s)? 1
17. ¿Ha visto limitado su normal desarrollo en AVD? (a nivel laboral) 1
18. ¿Cuál es el nivel máximo al que puede usar su(s) mano(s) sin dolor para sus actividades de la vida diaria? 2
19. ¿Su sueño ha sido alterado por la lesión en su(s) mano(s)? 21. ¿La lesión en su(s) mano(s) lo ha afectado a nivel emocional? 2
20. ¿Qué tipo de complementos le recomendó el profesional? 2
21. ¿Qué recomendación haría a los dispositivos/protocolos existentes para la rehabilitación de mano? 2
22. ¿Qué opina acerca de la posibilidad de llevar el dispositivo a su casa y ser supervisado por el profesional a través de internet?

D.2 Model 2. Rehabilitated Patients

1. ¿Cuál es su profesión?
2. ¿Qué edad tenía cuando se lesionó?
3. ¿hace cuánto fue?
4. ¿Cuál es su peso?

5. ¿Cuál es su estatura?
6. ¿Cuál es su lado dominante y en qué lado se presentó la lesión?
7. ¿Cuál fue la razón que lo motivo a la búsqueda de un especialista de la salud? (fractura, dolor o restricción de movimiento)
8. ¿Cómo sintió que fue la comunicación con los profesionales que lo atendieron?
9. ¿Cuáles y cómo fueron los protocolos implementados, coméntelos?
10. ¿Qué tan efectiva fue la rehabilitación?
11. ¿Sintió que fueron suficiente los protocolos aplicados?
12. ¿Ha sufrido lesiones recidivantes?
13. ¿Cuántas veces las ha sufrido?
14. ¿El Fisioterapeuta le recomendó, posterior a la rehabilitación, realizar ejercicios para fortalecimiento muscular o algún otro complemento para mantener saludable la articulación lesionada y la articulación contraria? (estiramiento, gimnasio, natación, etc.)
15. ¿Cómo han sido las terapias en los diversos sitios de rehabilitación?
16. ¿Presenta o presentaba dolor en su(s) mano(s) al realizar AVD?
17. ¿Ha visto o vio limitado su normal desarrollo en AVD?
18. ¿Cuál es el nivel máximo al que podía usar su(s) mano(s) sin dolor para sus actividades de la vida diaria?
19. ¿Su sueño fue alterado por el dolor de su(s) mano(s)?
20. ¿Ha notado o noto falta de fuerza, debilidad o poca resistencia en su(s) mano(s)?
21. ¿Se sintió frustrado por la lesión en su(s) mano(s)?
22. ¿Cómo percibió el protocolo aplicado para la recuperación de su(s) mano(s)?
23. ¿Sintió que el ejercicio realizado con estos equipos fue útil, es decir sintió cambios positivos (mejorías)?
24. ¿Reconoció algún dispositivo diseñado para la rehabilitación o elementos calibrados?

25. ¿Fue efectiva la terapia?
26. ¿Realiza actualmente ejercicios para fortalecimiento muscular y prevenir próximas lesiones recidivantes? (estiramiento, gimnasio, natación, etc.)
27. ¿Sintió que los equipos empleados para su rehabilitación eran cómodos o justos a su medida?
28. ¿Sería bueno para usted, como paciente, conocer su progreso durante el tiempo de la recuperación?

D.3 Model 3. Health Specialists

1. ¿Cuál es el porcentaje de pacientes remitidos provenientes de otra ciudad?
2. ¿Cuáles son las lesiones más comunes que deben ser atendidas y los respectivos protocolos?
3. ¿Realiza una evaluación general para determinar un programa de rehabilitación o basta con saber la zona afectada?
4. ¿Aplica siempre un protocolo o diseña un programa de rehabilitación según lesión vs edad, composición corporal, acondicionamiento físico, estado de salud, alineación corporal y estado mental?
5. ¿Hay un esquema u orden del progreso en la rehabilitación o depende de factores físicos individuales?
6. ¿Cuál es el orden de recuperación de movimientos y cumplimiento de metas de la terapia?
7. ¿Cuál es la frecuencia indicada para la rehabilitación?
8. ¿Sería bueno para usted, como profesional, conocer el progreso del paciente durante el tiempo de la recuperación?
9. ¿Qué tan bien cumplen los deberes asignados los pacientes?
10. ¿Cuáles son los canales de comunicación que se utilizan para brindar información acerca del procedimiento a los pacientes?
11. ¿Qué tan efectivos son dichos canales?

12. ¿Cuál es la actitud con la que llegan los pacientes a los centros de recuperación, como es esta cuando terminan las terapias?
13. Al asignar un deber, ¿está usted preocupado por que el paciente posiblemente no lo cumpla?
14. ¿Existe alguna forma de evaluar los deberes asignados?
15. ¿Cuáles son las principales razones que exponen los pacientes para no cumplir sus deberes?
16. ¿Recomienda a los pacientes, al finalizar la terapia, incluir en sus AVD ejercicios de fortalecimiento muscular para prevenir lesiones recidivantes y nuevas lesiones?
17. ¿Cuáles son las marcas de dispositivos de ayuda más comunes?
18. ¿Cuáles son los equipos que más utiliza para la rehabilitación de mano? ¿Porque?
19. ¿Qué recomendación haría a los dispositivos/protocolos existentes para la rehabilitación de mano?
20. ¿Que opina acerca de la posibilidad de llevar el dispositivo a su casa y ser supervisado por el profesional a través de internet?

D.4 Final questions to all the users (related to tele-operation)

1. ¿Qué recomendación haría a los dispositivos/protocolos existentes para la rehabilitación de mano?
2. ¿Qué opina acerca de la posibilidad de llevar el dispositivo a su casa y ser supervisado por el profesional a través de internet?

Appendix E

Four bar Mechanism Design

This appendix intends to describe the kinematic and kinetic considerations and derivations while designing the Four Bar mechanism, as briefly described in Section 10.1.2.1. The appendix is divided in three major parts, which are the kinematic, static-kinetic and dynamic-kinetic considerations.

E.1 Four-Bar Kinematics

E.1.1 Four Bar Angles

In order to establish a relation between the angles in the four bar mechanism, the sum of vectors representing bars 1 and 2 is equal to the sum of vectors representing bars 0 and 4. Then, the angles and bar lengths are related from geometrical expressions.

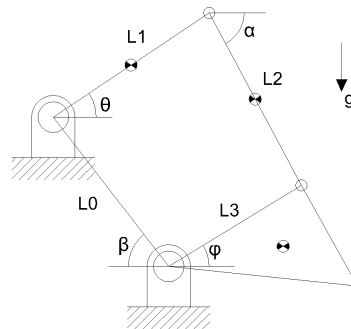


FIGURE E.1: Four-bar mechanism angles and lengths. Source: Tang, C. [38].

The vectorial equation is depicted below,

$$\vec{l}_1 + \vec{l}_2 = \vec{l}_0 + \vec{l}_3 \quad (\text{E.1})$$

This equation gives a system of equations.

$$\begin{aligned} l_2 \cos(\theta) + l_3 \cos(\alpha) &= l_1 \cos(\beta) + l_4 \cos(\phi) \\ l_2 \sin(\theta) + l_3 \sin(\alpha) &= l_1 \sin(\beta) + l_4 \sin(\phi) \end{aligned} \quad (\text{E.2})$$

Where the lengths and angle β are geometric paramters, or input values of the design. On the other hand, ϕ is related to the FROM by the following equation,

$$\phi = \gamma - FROM \quad (\text{E.3})$$

Where γ is a fix angle (geometric parameter) of the third bar triangle. Consequently, ϕ would be an input parameter as well, an furthermore, would be the independent variable of the system.

The left side of the system of equations would be redefined as follows,

$$\begin{aligned} A &= l_1 \cos(\beta) + l_4 \cos(\phi) \\ B &= l_1 \sin(\beta) + l_4 \sin(\phi) \end{aligned}$$

Then, the sum of the squares of Equations [E.2](#) results in the expression below, where a new variable C, is defined.

$$C = \frac{-l_2^2 + l_3^2 + A^2 + B^2}{2l_3} = A \cos(\alpha) + B \sin(\alpha) \quad (\text{E.4})$$

The left handside of the previos equation can be rewritten with trigonometric identities into a quadratic form as follows,

$$\frac{A(1 - \tan^2 \frac{\alpha}{2}) + B(2 \tan \frac{\alpha}{2})}{1 + \tan^2 \frac{\alpha}{2}} = C \quad (\text{E.5})$$

Solving the quadratic equation gives the angle α in terms of the input partameters (l_1, l_2, l_3, l_4 , and β) and the angle ϕ .

$$\alpha = 2 \arctan \left(\frac{B \pm \sqrt{B^2 + A^2 - C^2}}{A + C} \right) \quad (\text{E.6})$$

With a similar procedure, the angle θ is expressed in terms of the input parameters,

$$\theta = 2 \arctan \left(\frac{B \pm \sqrt{B^2 + A^2 - D^2}}{A + D} \right) \quad (\text{E.7})$$

Where D is defined as,

$$D = \frac{-l_3^2 + l_2^2 + A^2 + B^2}{2l_2} = A \cos(\theta) + B \sin(\theta) \quad (\text{E.8})$$

E.1.2 Transmission Angles Derivation

Once the principal angles of the Four-Bar mechanism were defined, the design continues with the transmission angle. It is defined as the ratio between the force tending to move the driven link and the total force applied to the driven link [15]. In order words,

$$\sin \mu = \frac{\text{Force component tending to move the drive link}}{\text{Total force applied to the driven link}} \quad (\text{E.9})$$

As described in Chapter 10, μ would be ideally 90° but this will not be the case in actual mechanism, since it changes as the bars rotates. Then, an acceptable deviation is agreed upon the force implied during operation. For the device, a deviation of 40° is set.

Geometrical conditions of the mechanism allow the derivation of μ using cosine law,

$$\cos(\mu) = \frac{l_3^2 + l_2^2 - l_0^2 - l_1^2}{2 + l_2 * l_3} + \frac{l_0 * l_1}{l_2 * l_3} * \cos(\theta) \quad (\text{E.10})$$

E.1.3 Angular Velocities and Accelerations

When deriving by time the geometrical expressions in Equation E.2, one can define the angular velocities of the system as,

$$\begin{bmatrix} -l_{2ij} * \sin(\theta_{ij}) & -l_{3ij} * \sin(\alpha_{ij}) & l_{4ij} * \sin(\phi_{ij}) \\ l_{2ij} * \cos(\theta_{ij}) & l_{3ij} * \cos(\alpha_{ij}) & -l_{4ij} * \cos(\phi_{ij}) \end{bmatrix} * \begin{bmatrix} \dot{\theta}_{ij} \\ \dot{\alpha}_{ij} \\ \dot{\phi}_{ij} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (\text{E.11})$$

From the previous expression, one can derive an equation with θ_{ij} as the independent variable as follows,

$$\begin{bmatrix} \dot{\theta} \\ \dot{\alpha} \end{bmatrix} = \begin{bmatrix} S1(\theta, \alpha, \phi) \\ S2(\theta, \alpha, \phi) \end{bmatrix} * \dot{\phi} \quad (\text{E.12})$$

Using matrices manipulations, $\vec{S} = [S1 \ S2]$ are defined, see Equations E.13 and E.14.

$$S1(\theta, \alpha, \phi) = \frac{\partial \theta}{\partial \phi} = \frac{l_{4ij} * \sin(\alpha_{ij} - \phi_{ij})}{l_{2ij} * \sin(\alpha_{ij} - \theta_{ij})} \quad (\text{E.13})$$

$$S2(\theta, \alpha, \phi) = \frac{\partial \alpha}{\partial \phi} = \frac{l_{4ij} * \sin(\phi_{ij} - \theta_{ij})}{l_{3ij} * \sin(\alpha_{ij} - \phi_{ij})} \quad (\text{E.14})$$

As for the accelerations, the Equation E.15 repeated below was used to define the acceleration in joint B with respect to A, B with respect to C, and C with respect to D.

$$\begin{aligned} \vec{a}_B &= \ddot{\theta} \times r_{A/B} - \dot{\theta}^2 r_{A/B} \\ \vec{a}_B &= \vec{a}_C + \ddot{\gamma} \times r_{B/C} - \dot{\gamma}^2 r_{B/C} \\ \vec{a}_C &= \ddot{\phi} \times r_{C/D} - \dot{\phi}^2 r_{C/D} \end{aligned} \quad (\text{E.15})$$

As it was evident from Equation E.15, γ and its derivative must be defined before continuing with the accelerations. This acceleration is defined with respect to the instantaneous center of rotation (IC) by drawing perpendicular lines to the velocities vectors that act on each side of the bar. The angle γ is defined as,

$$\gamma = \theta - \phi \quad (\text{E.16})$$

Then, using sines law, the magnitud of the vector $r_{b/CI}$ was found.

$$\frac{r_{B/CI}}{\sin(\mu)} = \frac{l_{2ij}}{\sin(\gamma)} \quad (\text{E.17})$$

The kinematic equation is once again fomulated for B with respect to IC, giving as a result the angular velocity $\dot{\gamma}$.

$$\dot{\gamma} = \frac{v_B}{r_{B/CI}} \quad (\text{E.18})$$

Now, continuing with the accelerations, the vectorial Equation E.19 give 6 linear equations and 6 variables. The angular accelerations (aANcm1, aANcm2, aANcm3) derived from this analysis along with FROM can be seen below.

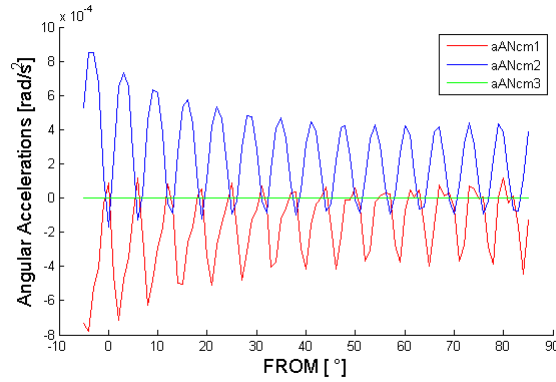


FIGURE E.2: Angular accelerations for the four-bar mechanism along FROM

Once the angular acceleratios were defined, the derivation for the acceleration in each Centre of Mass (CM) can be done with the following equations.

$$\vec{a}_A = \vec{a}_{CM} + \vec{\ddot{\theta}} \times r_{A/CM} - \dot{\theta}^2 * r_{A/CM} \quad (\text{E.19})$$

where,

$$a_{CMx} = a_{CM} * \sin(\theta)$$

$$a_{CMy} = a_{CM} * \cos(\theta)$$

E.2 Four-Bar Kinetics

The reactions forces and the input torque expected during rehabilitation were derived applying the Lagrangian formulation of classical mechanics, following the approach presented in [39] . It begins identifying the general coordinate(s) of the system to analyse. In the case of the four bar mechanism, the selected and unique general coordinate is ϕ . Then, the kinetic (T) and potential (V) are formulated as the Equations E.20 and ??.

$$T = \frac{1}{2} \left(m_1 \| v_{c1} \|^2 + I_1 \dot{\theta}^2 \right) + \frac{1}{2} \left(m_2 \| v_{c2} \|^2 + I_2 \dot{\alpha}^2 \right) + \frac{1}{2} \left(m_3 \| v_{c3} \|^2 + I_3 \dot{\phi}^2 \right) \quad (\text{E.20})$$

where,

$$\begin{aligned} \| v_{c1} \|^2 &= l_{c1}^2 \dot{\theta}^2 \\ \| v_{c2} \|^2 &= l_1^2 \dot{\theta}^2 + l_{c2}^2 \dot{\alpha}^2 + 2l_1 l_2 \cos(\theta - \alpha) \dot{\theta} \dot{\alpha} \\ \| v_{c3} \|^2 &= l_{c3}^2 \dot{\phi}^2 \end{aligned}$$

In a similar fashion for the potential energy,

$$V = m_1 g y_{c1} + m_2 g y_{c2} + m_3 g y_{c3} \quad (\text{E.21})$$

where,

$$\begin{aligned} y_{c1} &= l_{c1} \sin \theta \\ y_{c1} &= l_1 \sin(\theta) + l_{c2} \sin(\alpha) \\ y_{c1} &= l_{c3} \sin(\phi) \end{aligned}$$

From definition, $L = T - V$, and after some mathematical the expression below is obtained.

$$L(\theta, \alpha, \phi, \dot{\theta}, \dot{\alpha}, \dot{\phi}) = J_1 \dot{\theta}^2 + J_2 \dot{\alpha}^2 + J_3 \dot{\phi}^2 + P_1 C_1(\theta, \alpha) \dot{\theta} \dot{\alpha} + G(\theta, \alpha, \phi) \quad (\text{E.22})$$

where,

$$\begin{aligned} J_1 &= \frac{1}{2}(m_1 l_{c1}^2 + I_1 + m_2 l_1^2) \\ J_2 &= \frac{1}{2}(m_2 l_{c2}^2 + I_2) \\ J_3 &= \frac{1}{2}(m_3 l_{c3}^2 + I_3) \\ P_1 &= m_2 l_1 l_{c2} \\ C_1(\theta, \alpha) &= \cos(\theta - \alpha) \\ G(\theta, \alpha, \phi) &= (-m_1 g l_{c1} - m_2 g l_1) \sin(\theta) - m_2 g l_{c2} \sin(\alpha) - m_3 g l_{c3} \sin(\phi) \end{aligned}$$

Now using the definitions stated while derivating the velocities: $\dot{\theta} = S_1 \dot{\phi}$ and $\dot{\alpha} = S_2 \dot{\phi}$, the equation above is re-written.

$$L(\theta, \alpha, \phi, \dot{\theta}, \dot{\alpha}, \dot{\phi}) = J_1 \dot{\theta}^2 + J_2 \dot{\alpha}^2 + J_3 \dot{\phi}^2 + P_1 C_1(\theta, \alpha) S_1 S_2 \dot{\phi}^2 + G(\theta, \alpha, \phi) \quad (\text{E.23})$$

Now, the Euler-Lagrange formulation to derive the equation of motion is derived by,

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\phi}} \right) - \frac{\partial L}{\partial \phi} = F_i \quad (\text{E.24})$$

The derivation of each of the parts is derived below.

$$\frac{\partial L}{\partial \dot{\phi}} = 2 [J_1 S_1^2 + J_2 S_2^2 + J_3 + P_1 C_1 S_1 S_2] \dot{\phi} \quad (\text{E.25})$$

$$\begin{aligned}
\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\phi}} \right) &= 2 [J_1 S_1^2 + J_2 S_2^2 + J_3 + P_1 C_1 S_1 S_2] \ddot{\phi} \\
&+ 2 \left[2J_1 S_1 \left(\frac{\partial S_1}{\partial \phi} + \frac{\partial S_1}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_1}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) + \right. \\
&\quad 2J_2 S_2 \left(\frac{\partial S_2}{\partial \phi} + \frac{\partial S_2}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_2}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) + \\
&\quad C_1 P_1 \left[S_1 \left(\frac{\partial S_2}{\partial \phi} + \frac{\partial S_2}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_2}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) + \right. \\
&\quad \left. \left. S_2 \left(\frac{\partial S_1}{\partial \phi} + \frac{\partial S_1}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_1}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) \right] \right] \dot{\phi}^2
\end{aligned} \tag{E.26}$$

$$\begin{aligned}
\frac{\partial L}{\partial \phi} &= \left[2J_1 S_1 \left(\frac{\partial S_1}{\partial \phi} + \frac{\partial S_1}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_1}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) + \right. \\
&\quad 2J_2 S_2 \left(\frac{\partial S_2}{\partial \phi} + \frac{\partial S_2}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_2}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) + \\
&\quad P_1 C_1 \left[S_2 \left(\frac{\partial S_1}{\partial \phi} + \frac{\partial S_1}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_1}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) + \right. \\
&\quad \left. \left. S_1 \left(\frac{\partial S_2}{\partial \phi} + \frac{\partial S_2}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial S_2}{\partial \theta} \frac{\partial \theta}{\partial \phi} \right) \right] \right] \dot{\phi}^2 + \\
&\quad \frac{\partial G}{\partial \phi} + \frac{\partial G}{\partial \alpha} \frac{\partial \alpha}{\partial \phi} + \frac{\partial G}{\partial \theta} \frac{\partial \theta}{\partial \phi}
\end{aligned} \tag{E.27}$$

From the previous equations, the driving torque can be derived taking the T_{bio} as an additional restriction.

E.2.1 Static Derivation

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -\sin(\theta_{f_1}) & -\sin(\theta_{f_2}) \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & -\cos(\theta_{f_1}) & -\cos(\theta_{f_2}) \\ d1 * \sin(\theta_{f_1}) & -f1 * \sin(\theta_{f_1}) & -d1 * \cos(\theta_{f_1}) & f1 * \cos(\theta_{f_1}) & 0 & 0 & 0 & 0 & 0.0035 * \sin(\theta_{f_1}) + 0.00071 * \cos(\theta_{f_1}) & 0.024 * \sin(\theta_{f_2}) + 0.024 * \cos(\theta_{f_2}) \\ 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & d2 * \sin(\alpha) & 0 & d2 * \cos(\alpha) & f2 * \sin(\alpha) & 0 & f2 * \cos(\alpha) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & f3 * \sin(\phi) & d3 * \sin(\phi) & -f3 * \sin(\phi) & -d3 * \cos(\phi) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -2 * (\cos(22.4) + \cos(13)) & 1 \end{bmatrix} \tag{E.28}$$

Having the Unknowns' Vector $\vec{x}$.

$$\vec{x} = [p01x \ p12x \ p01y \ p12y \ p23x \ p13x \ p23y \ p13y \ F_1 \ F_2]' \tag{E.29}$$

Where d_i and f_i are the distance to the center of mass from the proximal and distal joint of bar i , and F_1 and F_2 are the forces exerted by the cable on the bar.

As a result, the following vector is achieved.

$$p_{01x} = 409N$$

$$p_{12x} = 379N$$

$$p_{01y} = -175N$$

$$p_{12y} = -611N$$

$$p_{23x} = -175N$$

$$p_{13x} = -611N$$

$$p_{23y} = -175N$$

$$p_{13y} = -611N$$

$$F_1 = 88N$$

$$F_2 = 334N$$

Appendix F

State of Art and Technique Matrix

Please visit the web resource: <https://drive.google.com/folderview?id=0B1sQ9wGh10yKfm5pQ290NEFiZC1zNDc2NG1ZN2ZsOGF1N3Byam5td0RjR2hUemloY0piMUE&usp=sharing>

Appendix G

Semi-Structured Interviews Matrix

Answers matrix from the Semi-Structured Interviews is presented. The questionnaire can be found in Appendix [D](#).

Please visit the web resource: <https://drive.google.com/folderview?id=0B1sQ9wGh10yKfm5pQ290NEFiZC1zNDc2NG1ZN2Zs0GF1N3Byam5td0RjR2hUemloY0piMUE&usp=sharing>

Appendix H

Design Requirements

The complete list of Design Requirements is presented, with the considerations given in Chapter [7](#). Additionally, the last column present the individual conceptual proposals for each design requirement, as was introduced in Chapter [8](#).

See next page.

Appendix I

System Architecture

The Hand Rehabilitation System Architecture is presented following the guidelines presented in Chapter9, with the modified IDEF0 convention.

Appendix J

System Activity Diagrams

For the complete Activity Diagrams, please visit the web resource: [https://drive.google.](https://drive.google.com/folderview?id=0B1sQ9wGh10yKfm5pQ290NEFiZC1zNDc2NG1ZN2Zs0GF1N3Byam5td0RjR2hUemloY0piMUusp=sharing)

[com/folderview?id=0B1sQ9wGh10yKfm5pQ290NEFiZC1zNDc2NG1ZN2Zs0GF1N3Byam5td0RjR2hUemloY0piMUusp=sharing](https://drive.google.com/folderview?id=0B1sQ9wGh10yKfm5pQ290NEFiZC1zNDc2NG1ZN2Zs0GF1N3Byam5td0RjR2hUemloY0piMUusp=sharing)

Appendix K

Electronic Circuit

This appendix shows the electronic circuit for the device. It is divided in modules, power, control, signals, sensors, actuators and security.

Appendix L

Datasheet of Selected Sensors

The datasheet of the selected flex sensor and flexi force are presented in this Appendix.