Robotic Orthotic Device for Finger Rehabilitation

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Declaration

I declare that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also declare that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I declare that all information sources and literature used are indicated in the thesis.

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November 2011

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Abstract

An upper limb robotic orthotic device was developed for rehabilitating post stroke and other neurologically damaged patients. The automated control was performed by a personal computer loaded with LabVIEW and an Arduino electronic board. The system consisted of four servo motors with a crank mechanism attached to them, which converted their rotational motion into a linear one, and as a result enabled to flex and extend the fingers of the hand. The purpose of this motion was to reduce spasticity, paresis and muscular tone by promoting early movement of the hand after suffering a stroke or other debilitating neurological condition, and also to encourage neuroplastic changes in the brain, by creating new connections between functional neurons to control the affected limbs. Using the proposed device the patient would have the opportunity to practice and perform key aspects of their rehabilitation program with the supervision of a therapist. In addition, the main constrains for this project were to use "low cost" commercially available components, and that all of the fingers except for the thumb were able to move independently in a manual and automatic mode.

Chapter 1 Introduction

Stroke is the second most common cause of death [1] and the number one cause of acquired disability [2] in adulthood worldwide. As a result, a major economic burden is imposed on families and countries all around the world.

For stroke survivors, rehabilitation is a key element of their recovery process. It could be focused on motor, speech, visual, neurological, psychological and any other therapy related to the disabilities encountered after the event.

Even though, there are several types of stroke rehabilitation, this thesis will only deal with physical therapy. The main focus of physical therapy is to improve the level of independence and mobility of stroke victims. This is done with the help of a professional therapist that enables the person to overcome the disabilities and debilitating effects of their condition. It is important to state that physical therapy does not try to "cure" the condition; it only attempts to reduce the functional limitations resulting from the disorder.

Different types of treatments are implemented in the rehabilitation program to cover the limitations involved in the patient's disability. These could include: muscle re-education, massage, joint manipulation to reduce stiffness and pain, exercises to improve strength, mobility and breathing among others.

As part of the rehabilitation process, therapists sometimes recommend the use of orthotic devices to increase the likelihood of recovery or to aid with permanent disabilities. In the case of orthoses for stroke rehabilitation, these are modified to comply with the neurophysiological principles of human recovery. The devices are also used to correct or prevent deformity, and stabilize or immobilize parts of the body. They can be used for short term rehabilitation or for an extended period depending on the condition of the patient.

Adopting new technologies in the area of rehabilitation enables the delivery of more efficient and cost effective recovery programs. In a world where specialized labour cost is on the rise, robotic orthoses represent an excellent opportunity to reach more patients without increasing the number of therapists, and keeping the patients motivated without the need of direct supervision. This new type of device also enables the patients to undergo rehabilitation at their homes eliminating the need to transport them to a distant location and thus saving time and effort that could be better used to continue with their exercise program.

With the use of computers and other electronic controllers, the recovery process is greatly benefited by implementing interactive challenges and games in which the patients receive feedback of their performance. This kind of task oriented exercise promotes patient involvement on the rehabilitation process and increases the level of motivation that could be otherwise affected from performing only repetitive exercises.

The possibilities of programming an electronic orthosis are endless and this offers the opportunity to modify the exercise program to fit exactly the needs of the person using it, and in a matter of minutes being able to adapt it to the next patient in line. Consequently, with just one device health providers could have the chance to aid patients with different conditions on the same limb.

The main purpose of this thesis is to document the development of a low cost device to aid with the rehabilitation of patients that are disabled after suffering a stroke. But that doesn't imply that other people with neurological disabilities couldn't benefit from its use. The system focuses on finger flexing and extending to reduce spasticity, paresis[1] and muscle tone on the hand. For this project, the areas of Biomedical and Mechatronic Engineering were used in conjunction to create the final model and achieve the desired finger movement.

[1] Partial loss of movement of joints or limbs.

Chapter 2 Literature Review

2.1 *Stroke*

A stroke or cerebrovascular accident is defined as "a sudden neurological deficit caused by impairment in perfusion to the brain"[3]. Oxygen, glucose and other nutrients are required to maintain a balanced brain activity; these elements are supplied by the blood vessels going into the brain. If a part of the brain is completely deprived of its blood supply for a period of four to eight minutes[4], the tissue surrounding that area will die and the specialized tasks related to it will be lost. If only a reduction on blood supply occurs, some of the cells could survive and recover after the condition is resolved.

To be considered a stroke, the symptoms should prevail for at least 24 hours; on the other hand, if the symptoms resolve in less than a day then the condition is defined as Transient Ischemic Attack. According to the World Health Organization each year more than 15 million people suffer a stroke worldwide, of these numbers 33% are left permanently disabled and 33% die, the rest of them fully recover. [5].

Risk factors for stroke are commonly classified as non modifiable and modifiable. Non-modifiable are characteristics like: race, age, genetic factors and low birth weight among others. Modifiable risks are further subdivided into first and second tier factors, according to their identified importance in correlation to stroke. The major first tier modifiable risk factor for stroke is hypertension, the others that follow in order of importance are: diabetes mellitus, atrial fibrillation, left ventricular dysfunction and smoking [6]. Second tier risks include: alcohol and/or drug consumption, asymptomatic carotid stenosis, hyperlipidemia, migraine and obesity among others [7].

Strokes are often divided into two main categories depending on their cause: ischemic and hemorrhagic.

2.1.1 Ischemic Stroke

This type of stroke is caused by a partial or complete blockage of the vessels that supply blood to the brain. It accounts for approximately 70% [8] of all stroke events in the world. A graphical representation of an ischemic stroke is shown in Figure 2.1. Most of ischemic strokes occur when a blood clog is present either on the brain or other parts of the body. However, narrowed vessels caused by excess of fat and other substances (a condition called atherosclerosis) also play an important role on the conditions leading to this type of stroke.

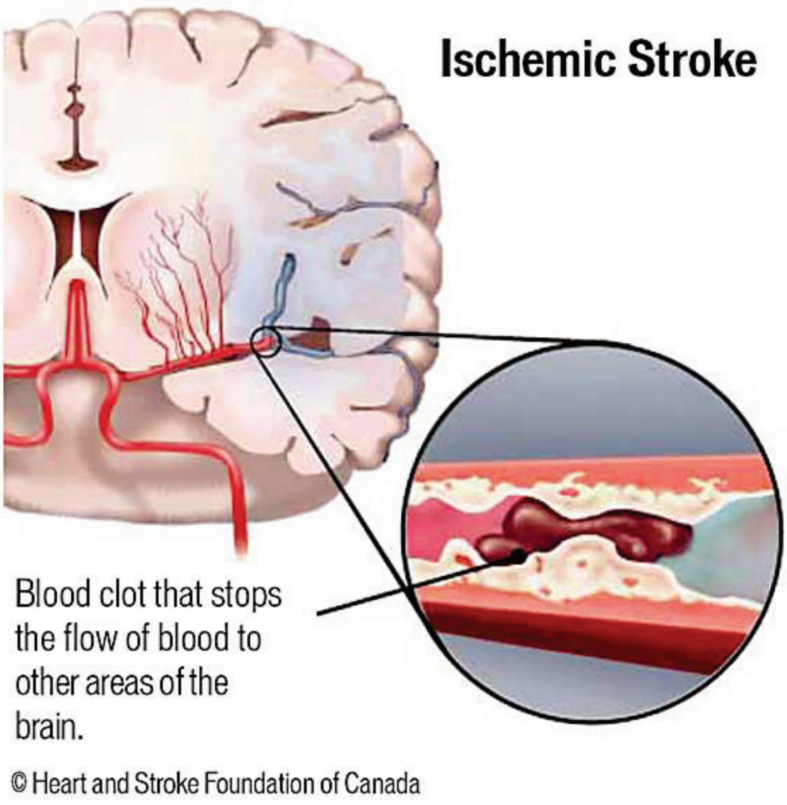

Figure 2.1 - Ischemic Stroke [9]

The three main types of Ischemic Stroke are:

- **Embolic:** It occurs when a blood clot is formed in the circulatory system outside of the brain, commonly on the heart and the large arteries of the chest and neck. The clot travels in the bloodstream and finally reaches a vessel that is too small to go through, and consequently interrupts the blood supply to the brain.
- **Lacunar:** The cause for this type of stroke is occlusion of a single penetrating artery. It often result on a small infraction (death of tissue as a result of obstruction of its blood supply) zone of around 3-20 mm [10] in diameter, located in the deep white or gray matter of the brain.
- **Atherothrombotic:** In this case, an artery previously affected by atherosclerosis becomes completely blocked by a clot formed inside the brain. Since the

complete blockage of the vessel takes time, reduced blood flow could be identified before infraction of brain tissue occurs.

2.1.2 Hemorrhagic Stroke

This type of stroke occurs when a blood vessel inside or around the brain ruptures. As a result, there is necrosis of the tissue that ceases to receive its nutrients from the bloodstream. Figure 2.2 shows the rupture of a blood vessel inside the brain. Most patients who remain conscious during a stroke, describe feeling the "worst" headache of their lives [11] . The hemorrhagic type accounts for less than 30% of the total number of strokes worldwide but it has the highest mortality rate [12].

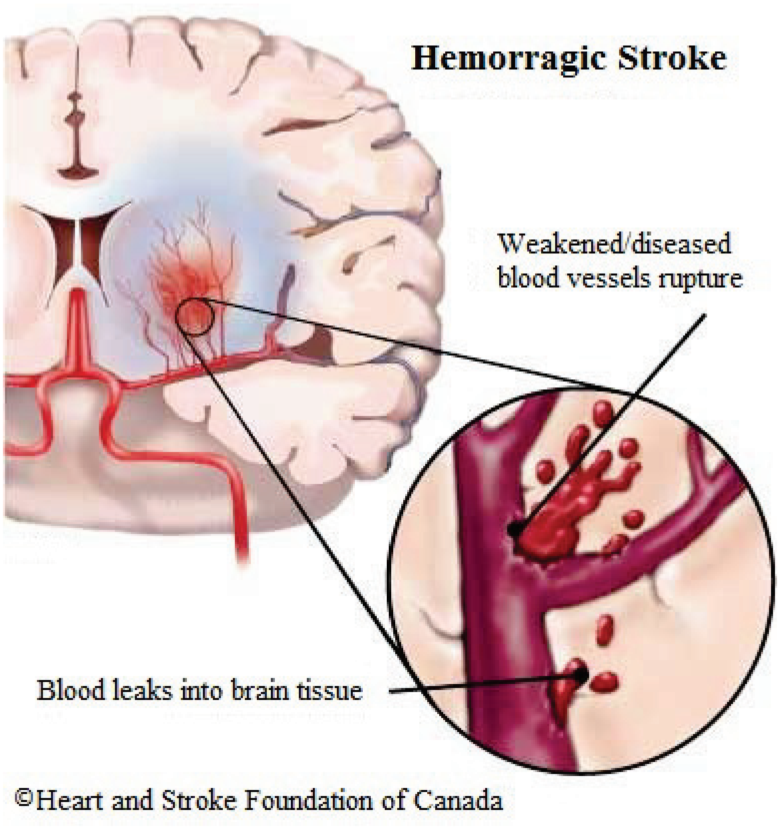

Figure 2.2 - Hemorrhagic Stroke [9]

Depending on the area of the brain that was affected by the stroke, this type of stroke is further divided into:

- **Intracerebral:** Caused by bleeding inside the brain, most of the time due to high pressure on the walls of a vessel affected by atherosclerosis. The bleeding starts to increase the pressure inside the brain and finally brain function is affected.

- **Subarachnoid:** In this case, the rupture and bleeding occurs on the region between the brain and the skull. They are commonly caused by a burst of a cerebral aneurysm[2].

[2] Balloon like bulge in the wall of a blood vessel.

2.2 *Effects of Stroke*

Stroke is the second most common cause of death [1] and the number one cause of acquired disability [2] in adulthood worldwide. These statistics demonstrate that there are millions of stroke survivors that require rehabilitation to fully recover.

The first step to plan a rehabilitation program is to determine the effect that the stroke had on the person's body. The functions and/or abilities people lose after a stroke depend on the part of the brain that was affected and the damage's extension.

The human brain is commonly divided into four parts (Figure 2.3): right and left hemispheres, brain stem and cerebellum.

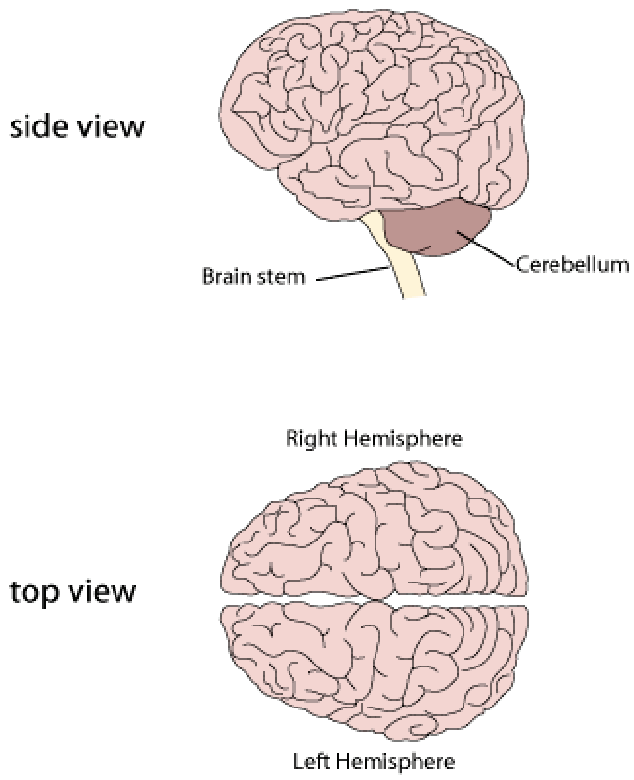

Figure 2.3 - Major parts of the brain [13]

2.2.1 Right Hemisphere Damage

The right hemisphere controls perceptual and analytical tasks and movement on the left side of the body. A stroke to this region of the brain usually affects and causes:

- Short term memory: Problems with retaining new information.
- Spatial abilities: Problems with judging distances, size, speed etc.
- Perceptual abilities: Difficult to tell left from right, up from down, etc.
- Left hemiplegia: Paralysis of the left side of their body.
- Left side neglect: The person tends to ignore objects on their left side due to visual complications.
- Impulsive behaviour: Judgment difficulties in everyday life.

2.2.2 Left Hemisphere Damage

The left hemisphere controls speech, language and movement on the right side of the body. Damage to this area usually affects and causes:

- Cautious behaviour: The person needs frequent instruction to complete tasks.
- Speech and communication abilities: Difficulty to formulate sentences, move muscles involved in speech, etc.
- Language abilities: Unable to comprehend words, write, read, etc.
- Right hemiplegia: Paralysis of right side of the body.
- Memory loss: Similar to right hemisphere damage.

2.2.3 Brain Stem Damage

The brain stem controls involuntary functions including: breathing, blood pressure and heartbeat among others. It is also involved in swallowing, hearing, eye movement and speech. Even a little damage to this part of the brain is very dangerous because of the abilities and function it affects. It can also cause:

- Total paralysis or hemiplegia on either side of the body.
- Coma
- Double vision

2.2.4 Cerebellum Damage

The cerebellum affects balance, coordination and many body reflexes. A stroke on this site could also cause:

- Dizziness
- Nausea
- Slurred Speech
- Vomiting

2.3 *Recovery*

In the first hours after the stroke has occurred and the patient has been stabilized, the brain and body start to recover. The first few weeks are vital on this process because these are the ones where the fastest recovery occurs. “Over 50% of the total recovery made within the first 3 months will have occurred within the first 2 weeks”[14].

The recovery process involves social, psychological and physical factors that are interrelated and affect the final outcome of the patient. The relationship and role of these factors are not completely understood and it has led to a development of different theories on how the brain responds after a stroke [4]:

- **Reduction of brain swelling around the stroke area:** The natural response of the body after death of tissue is to fill it with water and white cells. As the damage in this case it’s inside the brain, the small space between the brain and the skull is filled and pressure builds around the healthy tissue. These functional parts of the brain cease to work due to the excessive compression and the reduction of their blood supply; as a result the abilities related to these areas are disabled. After the swelling starts to decrease and the dead tissue is removed naturally, the lost functions are regained and there is a noticeable recovery in the patient. However, this is only the case for the healthy tissue that was not affected by the stroke.
- **Possible growth of nerve axons:** There is only a limited amount of regrowth of damaged brain cells; nevertheless it can help to regain, in some degree, some lost functions. The neural precursor cells[3] proliferate and differentiate into new neurons close to the damaged area; as a result, new connections that didn’t exist before the stroke are created. This process occurs within 7 to 10 days after the stroke[15].

[3] Self-renewing cells, capable of converting themselves into the main phenotypes of the nervous system.

On the other hand, neural axons[4] can grow to occupy the space left by the dead tissue. This enables the creation of new pathways that allow the body to readapt and recover lost abilities.

- **Use of other parts of the brain:** In this case healthy parts of the brain (that were not used to perform the lost functions) adapt to manage the connections and processes affected due to the stroke. The field of neuroplasticity is gaining recognition among the scientific community and there have been some important breakthroughs on the past few decades. Still, a full comprehension of the processes involved is missing.
- **Coping with the disability and adaptation by others:** The person manages to learn new ways to perform tasks with the aid of other parts of their body, the help of an external device or a person. This process is really important because the person could live with the disability but still manage to do ‘everyday” tasks. Family members, friends and doctors are directly involved in this process and they are always of great help to support the patients and increase their chances of recovery.

[4] Long fibres that extent from nerve cells. Its function is to carry electrical impulses to other cells.

2.4 *Rehabilitation after stroke*

Rehabilitation is a key element of the patient's recovery process. It could be focused on motor, speech, visual, neurological, psychological and any other therapy related to the disabilities encountered after the event. An early start of rehabilitation is very important because the brain tends to respond faster and repair more during the first weeks after stroke [16]. Even simple exercises to move paralysed muscles or change the position of the patient in bed could improve their final outcome.

Depending on the time that has elapsed after the stroke episode, the patient's rehabilitation varies in several factors such as: intensity, focus, duration and types of exercises among others. For this reasons the therapy is divided in four consecutive phases:

- **Acute phase:** Deals with the first hours to the first week after the stroke. Rehabilitation with special focus on respiratory function and the ability to cough and swallow.
- **Sub-acute phase:** From the second to the fourth week after the stroke. Initial rehabilitation focusing on motor and speech control.
- **Post-acute phase:** From the first to the sixth month after the stroke. At home rehabilitation and occupational therapy.
- **Chronic phase:** From the sixth month onwards. Long term patient independence and task specific problems.

Although, stroke leads to premature death, the main economic and time consuming burden is chronic disability. That is why a well planned rehabilitation program is essential, not only for the patient, but also for the health care system in general.

It is important to remember that each patient is different and their rehabilitation could last from a few weeks to a couple of years. This increases the challenge for therapists and doctors, because the process to determine the grade of disability and track the progress of each person is sometimes very complex, and it could lead to the creation of a rehabilitation program full of unnecessary activities that don't contribute to the patient's recovery.

Depending on the severity of the damage caused by the stroke, the first therapy is often conducted in the hospital were the patient was admitted. The patient then undergoes a full assessment of their progress and limitations, so that the group of therapists are able to develop a new program for the patient to follow at home or at a different location such as[5]:

- **Skilled Nursing Facility:** Nursing homes certified to provide therapy and care after stroke.
- **Long Term Acute Care Hospital:** For patients suffering acute conditions that require constant medical care and monitoring.
- **Outpatient Rehabilitation Facilities:** Designed for patients who are able to leave their homes to receive therapy.
- **Inpatient Rehabilitation Facilities:** Provide multidisciplinary rehabilitation for patients who are able to tolerate up to three hours of therapy.

After the first ten to twenty-one days, the patient is commonly discharged from the hospital. People who receive therapy at home tend to recover as well or even better as those who stay in the hospital [17]. Discharging patients from the hospitals also helps to free space for new stroke victims and to decrease the overall cost of the treatment. A flow diagram of the process followed to discharge patients from the hospital and provide them with rehabilitation is shown in Figure 2.4.

[5] Based on the United States of America health system.

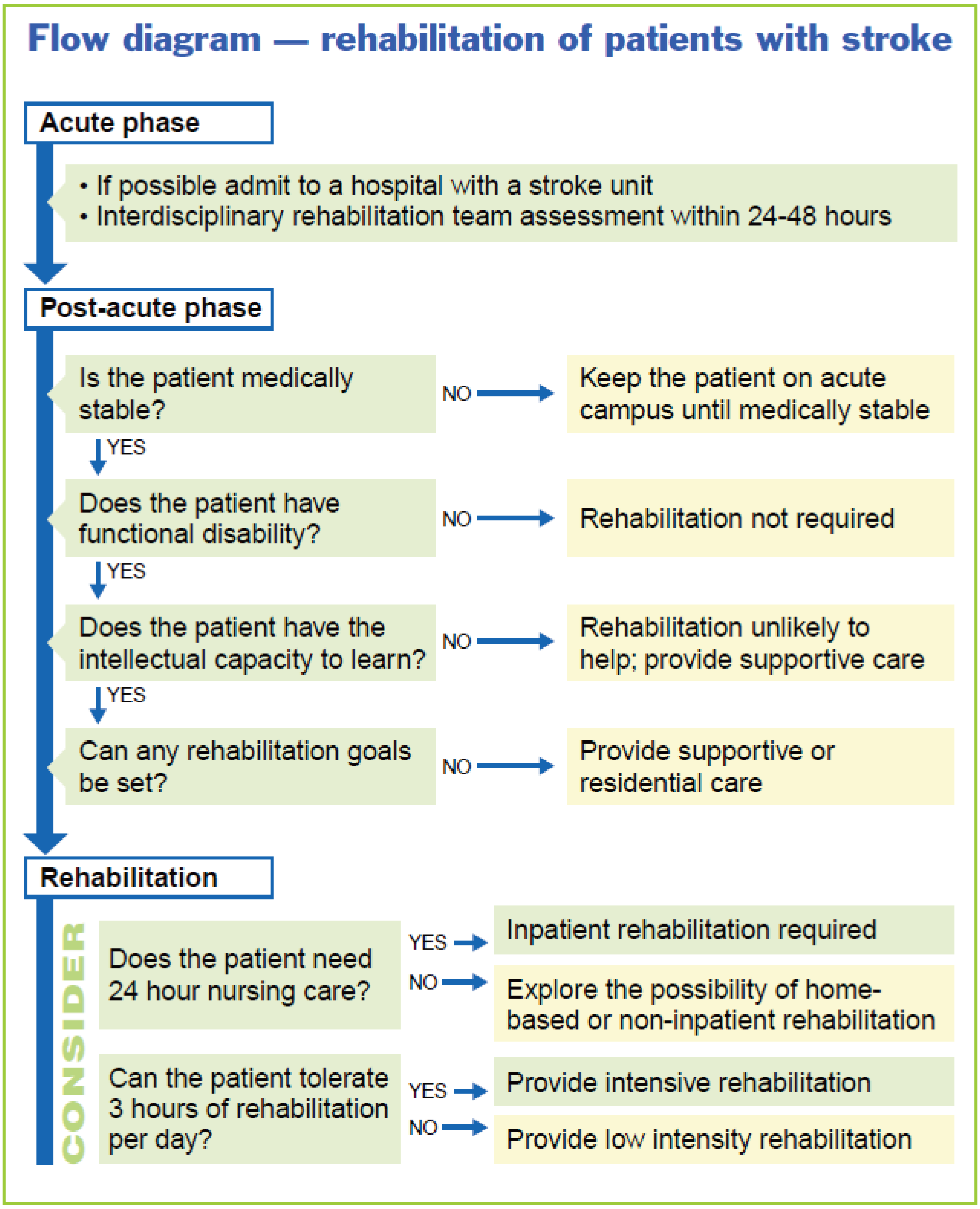

Figure 2.4 - Flow Diagram, rehabilitation of patients with stroke [18]

Rehabilitation not only deals with recovery but also with reintegration into the community and with gaining the highest level of independence possible. The family and team of therapists need to make a great effort to keep the patient motivated and focused on the goals set at the beginning of the therapy. The patient's will to perform the assigned exercises and tasks is paramount to achieve progress and overcome their disabilities. Continuing assessment of the progress should be documented and used to implement new strategies and goals, because many issues may not become evident until several months after the stroke.

2.4.1 Physical Therapy

The main focus of physical therapy is to improve the level of independence and mobility of stroke victims. This is done with the help of a professional therapist that enables the person to overcome the disabilities and debilitating effects of their condition. It is important to state that physical therapy doesn't try to "cure" the condition; it only attempts to reduce the functional limitations resulting from the disorder.

The outcome for the patient not only depends on their physical improvement, as a result the therapist needs to communicate and interact with the speech and occupational therapists, the physician, nursing staff and social worker, to gather information and evaluate the overall results of the rehabilitation program.

The first step before commencing physical rehabilitation is to evaluate the condition of the patient in different aspects [19]:

- **Range of motion:** Using geometric measurements, limitations on the flexibility of different joints are recorded.
- **Strength:** It's measured on the isolated and uninvolved extremities on a scale of 0 to 5.
- **Mobility:** The therapist asses the patient's ability to perform functional tasks (sitting up, lying down, going down the stairs, etc.) and ranks them according to the level of independence of the patient on a scale from total assistance to completely independent. Also, the quality of the movements, change in vital signs, safety and efficiency are assessed when performing the tasks.
- **Muscle Tone:** The joints are moved at different speeds from a resting position, to measure their resistance to passive motion. The muscle tone could be: minimal moderately or severely increased, normal or hypnotic.
- **Sensation:** Different stimuli are tested on the patient's body like: hot and cold temperature, deep and light or sharp and dull touch. The patient's capacity to detect and correctly locate the stimuli on their body is measured. Also, the

ability to sense the position, relation to each other and movement of different parts of the body is measured.

- **Motor Status:** The therapist measures the patient's ability to move different joints.
- **Balance:** Using timing tests and grading from poor to normal, the sitting and standing, static and dynamic balance is measured.
- **Respiratory Status:** Different aspects of breathing are measured like: sound, pattern and effectiveness of cough.

After the evaluation is completed the physical therapy program is planned with SMART (Specific, Measurable, Achievable, Relevant and Time based) goals, that enable the patient to be motivated and in track for a positive outcome. Different types of treatments are implemented in the program to cover the different limitations involved in the patient's disability. These could include: muscle re-education, massage, joint manipulation to reduce stiffness and pain, exercises to improve strength, mobility and breathing among others. The program should also include steps to prevent secondary complications like pain or discomfort in certain parts of the body.

Before 1950, physical rehabilitation focused on using the working side or limb to compensate for the lost abilities of the part of the body that was affected by a stroke. After this type of approach was proven to completely isolate and ignore the impaired part of the body, various therapists and practitioners developed new therapies that improved the function and movement of the previously ignored limbs. These therapies were mostly based on observation and experience; nevertheless, some of them took concepts from neurophysiology[6] to support their findings. To date, some of the most used approaches are [20]:

- **Brunnstrom:** While working with patients with hemiplegia, Signe Brunnstrom supported the use of reflex activity and sensory stimulation to recover voluntary movement. She used primitive and synergic movement as the basis for motor recovery. The stages of recovery of this approach are:
  - Period of flaccidity
  - Basic synergy on a reflex level. Spasticity[7] starts to develop.

[6] Area of medicine concerned with the function of the nervous system.
[7] Velocity dependent resistance to stretch muscles.

- Voluntary control of synergic movement
- Less restricted motion. Spasticity and synergic movement start to decline.
- Isolated joint movement is mastered and complex motion is visible.
- Normal motor function is resorted and spasticity disappears.

- **Bobath:** Developed by Bertha and Karel Bobath while working with children with cerebral palsy[8]. The main focus of this approach is to "control the responses that result from postural reflex mechanisms"[20]. The therapist manually handles key points in the body to control postural muscle tone and to enable normal movement .In contrast to Brunnstrom, primitive reflexes are not used as part of this therapy.
- **Rood:** Margaret Rood's approach was to use cutaneous sensorimotor stimulation (stretches, tapping, icing, stroking, pressure, etc.) to improve motor activity. The basis for her studies was that sensory factors and motor functions were highly related, as a result, localized sensory stimulation could help on the recovery process of the patient. This therapy doesn't use functional tasks as part of the rehabilitation program.
- **Knott and Voss:** This approach is also called Proprioceptive neuromuscular facilitation (PNF). It uses activities in a developmental sequence and sensory stimulus to improve motor learning. They promoted movement patterns instead of moving individual muscles because they believed that the brain controlled "general" movements and not individual muscle actions.
- **Johnstone:** Her main approach was the management of spasticity over the different steps of rehabilitation. She held that positioning and splinting played a major role in controlling postural reflexes. The trunk is the main focus of this approach and the rehabilitation starts with simple body movements like rolling or crawling.
- **Carr and Shepherd:** These Australian therapists created the approach known as "motor relearning programme". The main focus is to teach patients how to perform tasks that are part of their "everyday life". Therapists following this approach need to clearly explain the task and its goals, to the patient. Verbal

[8] Group of permanent disorders that affect body movement. Caused by damage to the motor control centres of the brain. Usually occurs in the developing stage of the brain before birth.

feedback and biomechanical knowledge are fundamental when working with this program. This therapy focuses on four different factors to achieve recovery:

- Eliminate unnecessary muscle activity
- Feedback
- Practice
- The relationship between movement and postural adjustment.

The different approaches are often used in combination and the therapist is the one responsible of choosing a program or combination that fits the individual disabilities of the patient. One thing that all the approaches have in common is that they don't approve the use of the unimpaired limb or parts to compensate for the disabled ones. The reason for this is that the patient could get used to compensating his movement only with his healthy parts, leading to a total disuse of their damaged ones and facing no recovery at all. The most effective approach has not been identified and further study needs to be performed in this area of medicine to obtain a better understanding of how these therapies work in different individuals.

Over 80% of surviving patients return home after being admitted in to the hospital [14], therefore, special attention into developing exercises and activities that improve their independence around the house are also important. The therapy could also be adapted to be fully conducted or repeated at home with the aid of family members, or if possible by the patient alone.

The progress of the physiotherapy needs to be continuously assessed by the therapist and adapted to increase the level of difficulty of the individual tasks, according to the achieved improvements. The same evaluation form used at the beginning of the assessment could be employed to compare the differences in motor abilities after a certain amount of time. Sometimes the progress reaches a plateau, and no further improvement is measured, in this case it is the therapist's responsibility to continue or stop the specific activity, taking into consideration the overall rehabilitation program of the patient.

Because every patient is different, their rehabilitation should be customized to maximize the opportunity for improvement. In some cases patients take more time to regain their previous abilities. Especially in younger patients there is evidence of recovery even after six months of the start of therapy [21].

Occasionally the patient doesn’t achieve a full recovery of previous abilities; in this case the therapist could recommend the use of aiding equipment (cane, hoists, Velcro straps, walker, etc.) to improve functionally inside their home or when interacting outside.

2.5 *Orthotic Devices*

As part of the rehabilitation process, therapists sometimes recommend the use of orthotic devices to increase the chances of recovery, or to aid with permanent disabilities. In the case of orthoses for stroke rehabilitation, these are modified to comply with the neurophysiological principles of human recovery. These devices are also used to correct or prevent deformity, and stabilize or immobilize parts of the body. They can be used for short term rehabilitation or for an extended period depending on the condition of the patient.

Orthotic devices are divided in three different categories [22]:

- **Assistive:** Their main purpose is to reduce spasticity and assist on joint movement.
- **Protective:** Their major objectives are: to stabilize unstable joints, bones or tendons, prevent deformity, restrict range of motion and protect vulnerable tissue or structures.
- **Corrective:** These aids correct subluxation[9] and contracture of joints and tendons.

A common orthotic device used for assisting wrist and hand movement is shown in Figure 2.5.

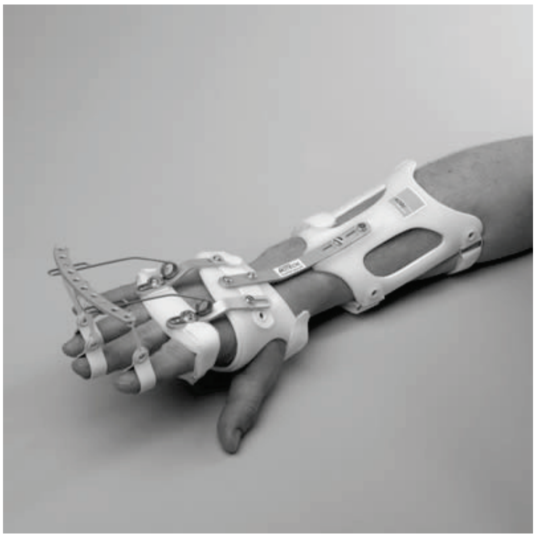

Figure 2.5 - Wrist and Hand Orthotic Device [23]

[9] Partial or incomplete dislocation of a joint or organ.

2.5.1 Upper Limb Orthoses

Orthotics are applied externally on the body, and they can act directly (surrounds the structure they are trying to influence) or indirectly (modifies the forces on a structure while being positioned beyond its physical boundaries). They are used in different parts of the body (head, shoulder, ankle, etc.) but this thesis will only focus on the ones for upper limb rehabilitation. The main purpose of the orthosis is to "avoid orthopaedic complications due to muscle weakness and abnormal tone" [24].

After stroke the affected joints usually suffer from spasticity or/and paresis that limits their normal range of motion and if left untreated could lead to permanent contracture and deformity. Upper limb orthoses promote corrective and assisted movement that increases the chances of overcoming the debilitating conditions due to a stroke.

Upper limb orthoses are divided in static and dynamic, depending on their function [16]. Static orthoses give support to the joints to reduce pain, facilitate function and avoid deformation. While, dynamic orthoses give mechanical assistance to move paralysed or weak muscles.

2.5.2 Robotic Orthotic Devices

In the last few decades there has been an increase in the number of orthotic devices that use electronic and mechanical components to perform their functions. The reason for this is that adopting new technologies in the area of rehabilitation enables the delivery of more efficient and cost effective recovery programs. In a world where specialized labour cost is on the rise, robotic orthoses represent an excellent opportunity to reach more patients without increasing the number of therapists, and keeping the patients motivated without the need of direct supervision. Also, automated orthoses offer intensive and constant rehabilitation without causing severe fatigue on the therapist and thus removing completely the chances of human error due to repetitive and continuous effort to move the patient.

The use of computers for controlling and providing feedback to the patient creates a great opportunity for the implementation of task oriented and/or interactive rehabilitation. Instead of repeating the same exercise to improve the range of motion of a particular joint, the computer can act as a HMI[10] that enables the patient to engage in challenges and games that generate a feeling of accomplishment once the patient has completed them. In addition, the challenges can increase in difficulty as the patient makes further progress, making the recovery process more enjoyable and less tiring and tedious.

In the case of rehabilitation centres and hospitals without major facilities and equipment that otherwise could not enable the patients to practice everyday life scenarios, robotic devices can offer the implementation of two and three dimensional simulations that immerse the user on task oriented[11] exercises. This type of rehabilitation has proven to be extremely helpful in improving the chances of recovery, so much so that in 2006 the National Institute for Neurological Disorders and Stroke (NINDS) Stroke Progress Review Group concluded that “task oriented training had emerged as the dominant approach to motor restoration”[16].

For patients that cannot attend a therapist’s centre or office, a robotic orthosis at home could help them receive quality rehabilitation during their free time and adjusted to their own personal requirements. In this case, a therapist could perform periodic visits to assess the progress and make any adjustment necessary to continue the program. On the other hand, telemonitoring could be used to gather all the necessary data trough online media, that way the therapists would not have to leave their offices to analyse and receive all the information relevant to the patient’s recovery process, and the patients would not have to leave their homes to receive feedback.

The fact that all the control is performed by electronic components gives infinite possibilities to the engineer or therapist programming the device. Every program could be customized to focus on the disability of the person using it, and it could be changed in a matter of minutes to fit the next patient in line. Consequently, with just one device you could have the opportunity to aid patients with different conditions on the same limb.

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[10] Human Machine Interface

[11] Learning and rehabilitation is goal oriented rather than on muscles or movement patterns.

2.5.3 Robotic orthoses for finger rehabilitation

This type of orthosis focuses on increasing the range of motion and decreasing the spasticity and stiffness of the fingers due to a neurological disability. They can be used to trigger the five fingers independently or with a simultaneous movement, depending on the number of actuators used.

They commonly operate on three different modes:

- **Passive Mode:** In this mode the fingers are continuously moved from a maximum to a minimum position. The system operates open loop[12] and the physical limits, number of repetitions and length of the exercise program can be varied. The force and velocity are constant and they are set at the beginning of the exercise.
- **Active Mode:** A closed loop is implemented by using sensors to detect finger movement. For this case the patient is “assisted” by the device to move their fingers when the complete range of movement is not possible, but the fingers can be voluntary moved to some extent. The applied force and velocity of the movement are affected in real time by the input of the patient. As in passive mode, the motion limits, repetitions and length of the exercise can be varied.
- **Interactive mode:** A scenario or game is presented to the patient, and through the use of sound, visuals, touch and other sensory aids, the device interacts with the patient giving them feedback on their performance. In this mode the game’s difficulty increases as the patient improves. This translates into a complete adaptation of the rehabilitation program to the patient’s current limitations. This mode can be used in conjunction with a passive or active program depending on the system’s sensors and actuators.

2.5.4 Current technology for finger rehabilitation

A number of finger rehabilitation devices have been developed in universities and companies around the world. On Table 2.1, Table 2.2 and Table 2.3 some of the more relevant to this thesis are presented.

[12] A system without feedback.

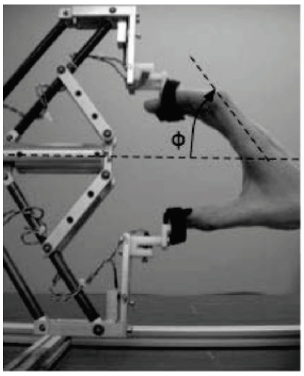
Reference and Figure	Name	Type of actuator	Transmission Method	Independent or Grouped Movement	Number of actuated fingers	Modes of Operation	Comments
[25] 	Hand Rehabilitation System for Paralysis Patient.	RC servo motor.	Wires and pulleys.	Independent.	Only two. Index and little finger.	Passive and Active.	Active mode is controlled by a “data” glove placed on the healthy hand.
[26] 	A Haptic Knob for Rehabilitation of Hand Function.	DC Motor.	Belts.	Grouped.	Five	Passive and Active.	Also targets wrist movement. The patient doesn’t have to “wear” the equipment.
[27] 	HandCARE.	DC Motor.	Cables and pullies.	Independent.	Five	Passive and Active.	By using a clutch system the five fingers are actuated with just one motor.

Table 2.1 - Robotic Orthoses for finger rehabilitation

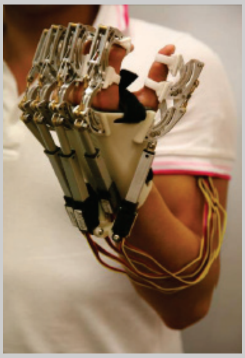
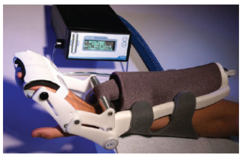
Reference and Figure	Name	Type of actuator	Transmission Method	Independent or Grouped Movement	Number of actuated fingers	Modes of Operation	Comments
[28] 	An Intention Driven Hand Functions Task Training Robotic System.	Motorized linear actuators.	Mechanical joints moving on tracks.	Independent.	Five	Passive and Active.	All five finger assemblies are identical and can be adjusted to fit different hand sizes.
[29] 	Mentor	Air Muscle.	Mechanical Joints.	Grouped.	Four	Passive and Active.	Also targets wrist movement.
[30] 	Amadeo	DC Motors.	Belts.	Independent.	Five	Passive, Active and Interactive.	The patient is presented with a set of games and challenges at the beginning of the rehabilitation.

Table 2.2 - Robotic Orthoses for finger rehabilitation. Part II

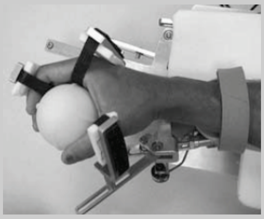
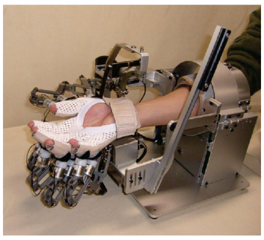
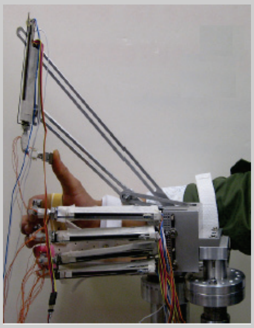
Reference and Figure	Name	Type of actuator	Transmission Method	Independent or Grouped Movement	Number of actuated fingers	Modes of Operation	Comments
[31] 	HWARD (Hand-Wrist Assisting Robotic Device).	Double acting pneumatic cylinders.	Mechanical joints moving on tracks.	Grouped.	Five	Passive and Active.	Allows patients to feel real objects while doing the exercises. Also targets wrist movement.
[32] 	Hand Motion Assist Robot for Rehabilitation Therapy by Self-Motion Control.	Servo Motors.	Mechanical Joints.	Independent	Five	Passive and Active.	The patient wears a feedback glove on the healthy hand to control the device on the impaired limb. Also targets wrist and abduction/adduction movement of the fingers.
[33] 	Interactive rehabilitation robot for hand function training.	Motorized Linear Actuators.	Mechanical Joints.	Independent.	Five	Passive, Active and Interactive.	Electromyography feedback is used to drive the robot in active and interactive mode.

Table 2.3 - Robotic Orthoses for finger rehabilitation. Part III

The size and weight of the device is critical, especially in the case of robotic exoskeletons[13] that have to be fully supported by the hand or arm of the user. The type of actuators used vary greatly depending on the specific device, but the more popular ones use motors and pneumatic cylinders or muscles.

Independent finger movement is vital for patients that have damage on only some of their joints. Nevertheless, grouped movement has also been demonstrated to improve motion control. Most of the designs have position and force sensors to provide feedback

[13] Wearable robot that performs a specific task on the body.

and active control of the device. An interactive mode has been developed in only a few of the orthoses, particularly those that are at a later stage of their testing and development.

To date, none of the devices has been proven to be superior in all respects to its competitors and further testing and medical trials need to be performed to fully understand the advantages and disadvantages of the rehabilitation programs performed by the robots.

2.6 *The human hand*

The essential function of the human hand is prehension [34], enabling the possibility of grasping and reaching objects in space. However, this is not its only function, it also receives information from the outside world trough the sensory systems, and it can be activated to perform countless motor tasks in everyday life. To be able to execute these functions it uses several joints, nerves, bones and muscles that are activated and moved in a complex manner.

The hand's major components are the palm, wrist and fingers, which are all involved in the movement of this part of the body. One of the unique characteristics of the human hand is that it uses the thumb or first digit to "oppose" the remaining four fingers, allowing finer motor skills, when compared to other animals. Even though the hand consists of veins, arteries, muscles, nerves, ligaments and other structures, this chapter will only cover the bone, joint and muscle elements that are relevant to the developed orthotic device.

2.6.1 Bones

The human hand (Figure 2.6) is supported by 27 major bones [35] that provide it with stability and shape. In addition, an extra set of small bones called the sesamoids are located within the tendons and typically each hand contains two of them on the base of the thumb [36].

Depending on their location and function, the major bones are divided into the following:

- Fourteen Phalanges (Finger bones): Each finger has three bones (distal, middle and proximal); except for the thumb that has only two (distal and proximal). The "proximal and distal" term refers to the position of the bones in relation to the forearm. The proximal being the closest to it and the distal the farthest.
- Five Metacarpals (Palm bones): Serve as the connection between carpals and phalanges bones. They also create the rigid structure of the palm.

- Eight Carpals (Wrist bones): Allow movement of the wrist while providing stability to the whole hand. These bones are fully developed after birth and before that only cartilaginous tissue occupies their place.

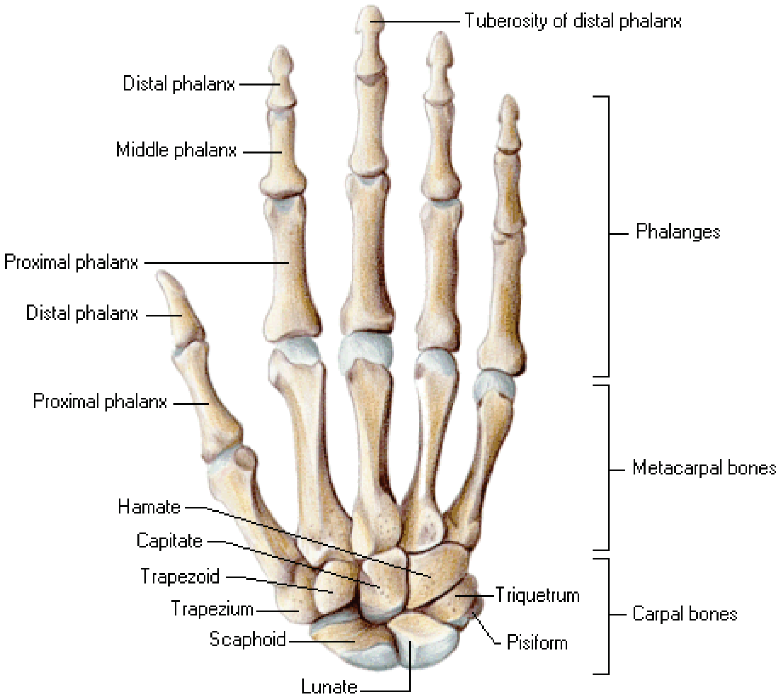


Figure 2.6 - Bones of hand and wrist [37]

2.6.2 Joints

The articulation of the hand enables the connection between bones and their movement. They are commonly named after the set of bones they connect and they are commonly divided into:

- Intercarpal joints: Plane joints that allow only gliding movements. Also, connect the wrist with the palm.
- Metacarpophalangeal joints: Condyloid joints that allow flexion/extension and abduction/adduction. They create the connection between the fingers and the palm.
- Interphalangeal joints: Hinge joints that allow flexion and extension. They are located between the fingers' bones.
- Wrist joints: Condyloid joints that allow flexion/extension, abduction/adduction and circumduction.

The orthotic device developed for this thesis, rehabilitates the fingers by moving them in a flexion and extension motion. As a result, the interphalangeal and the metacarpophalangeal joints are moved with the assistance of the device.

The individual names (Figure 2.7) of the joints involved in this process are:

- Distal Interphalangeal Joints (DIP)
- Proximal Interphalangeal Joints (PIP)
- Metacarpophalangeal Joints (MCP)

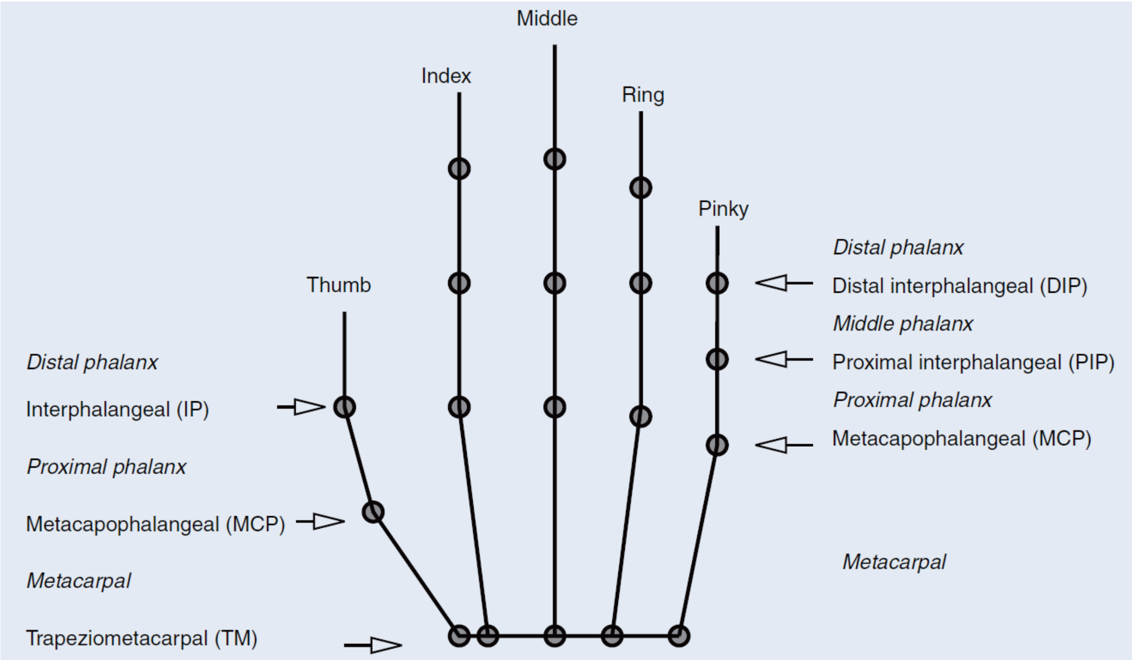


Figure 2.7 - Finger Joints [38]

The range of movement of the different joints of the hand is usually measured using a goniometer[14] that lines up with the joint at the starting position (usually full extension) and then the joint is flexed to measure the angle achieved by the patient [39].

2.6.3 Muscles

The muscles of this part of the body are activated trough the nervous system to enable movement of the different components of the hand. They provide strength and tone while maintaining and almost immediate response to any command coming from the nerves.

The fingers don't contain any muscles in their structure; they are controlled by tendons connected to the muscles on the forearm.

[14] Hinged rod with a protractor in the centre.

The muscles of the hand are divided into [40]:

- Extrinsic: They all originate on the outside of the hand and they contain the most powerful muscles of this part of the body. They enable wrist and finger flexion and extension. These muscles are further divided into: extensors (located on dorsal aspect of the forearm) and flexors (located on the palmar aspect).
- Intrinsic: These are smaller muscles that are located inside the structure of the hand. They are involved in precision tasks and fine motor skills. They are further divided into: hypothenar and thenar, which enable positioning of the small finger and thumb for pinching, and the interossei and lumbricals, which permit interphalangeal joint extension and metacarpal phalangeal joint flexion.

Some of the muscles of the hand are shown in Figure 2.8.

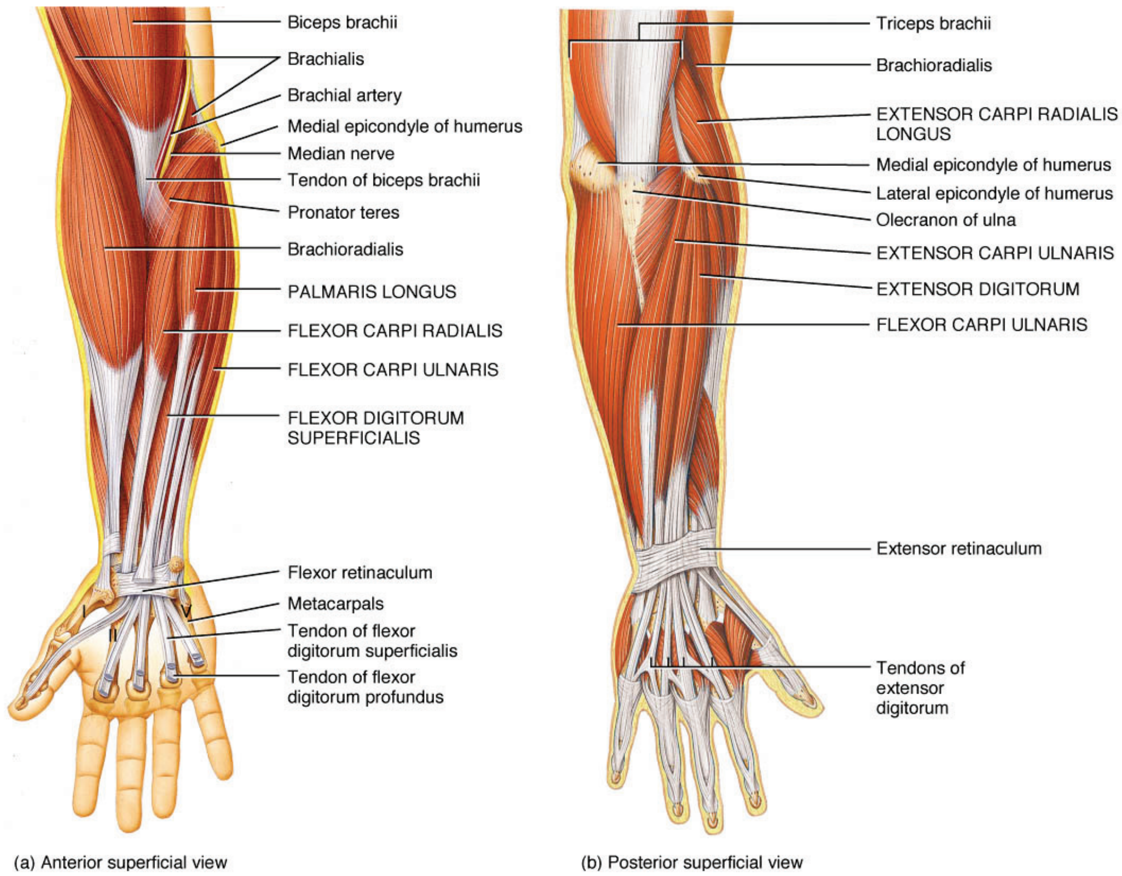


Figure 2.8 - Muscles of the hand [41]

Chapter 3 System Design: Initial Prototype

During the course of this thesis two devices were designed and manufactured. The first one was the initial prototype that was able to move just one finger. And the final one was capable of moving four fingers in an independent motion. For both devices some of their main constraints were to use off the shelf low cost materials and create a simple design to reduce production costs. This chapter will be divided into two parts comprising the design of the first prototype and the final device.

3.1 *First Design*

The main goal for the initial prototype was to move one finger in an extension and flexion motion while maintaining the patient's impaired arm and wrist in a resting position. The purpose of this motion was to reduce spasticity, paresis and muscular tone by promoting early movement of the hand after the patient suffered a stroke or other debilitating neurological condition. As discussed on the literature review, early rehabilitation that includes movement of the affected limb is vital to regain control and strength. Using the proposed device, the patient would have the opportunity to practice and perform key aspects of their rehabilitation program with the supervision of a therapist.

The ultimate objective for this project is to be able to move the five fingers of the hand on an active, passive an interactive mode. To achieve this, a number of electronic and mechanical components were considered and they will be the main topic of discussion for this chapter. It is important to note that for this initial prototype, dimensioned drawings of all the mechanical components, electronic schematics and Arduino and LabVIEW program codes can be found in the CD included in the appendix.

3.1.1 Actuators

The first part of the project was to select an actuator technology to move the fingers. Selecting the right type of actuator was vital for the project because it would set the initial constraints for weight, size, power and transmission for the final prototype.

The considered actuation technologies for this project and their advantages and disadvantages are presented in Table 3.1[42],[43]:

Actuation Technology	Advantages	Disadvantages
Hydraulic	Large Force and Torque capability. High bandwidth. Positional stiffness.	Need to use high pressure. High cost. Tendency to leak. Complex structure. Need several safety mechanisms to operate. Need pumping device.
Shape Memory Alloys	Compact. Light. High power to weight ratio.	Low bandwidth. Hysteresis. Small displacements. Need to apply a change in temperature to change their shape.
Motor	Low Noise. Clean (no fluids used only cables). Easy to install. Easy to control. Easy to integrate.	Backlash. Friction. Need gears to reduce velocity and increase torque. Low static force. Low Power to weight ratio.
Pneumatic	Simple construction. Non-flammable. Light. Low Pressure. Low cost. Safe. Clean (no leaking).	Static friction problems. Low Bandwidth capability. Low positional stiffness compared to hydraulic.
Piezoelectric Motor	Small Inertia. Easy to control. High power to weight ratio.	Difficult to manufacture. Expensive. The technology needs further development. Small displacements.
Electro active polymers	Durable. Capable of applying large forces.	Commercial reality is still far. Slow response time.

Table 3.1 - Actuation Technologies

From the comparison between actuators the pneumatic and electric motor technologies were selected as the main candidates for providing movement to the fingers. They presented a clean and low cost solution while providing safety and fine control of their operation. The other technologies were discarded due to their installation complexity, price and in some cases their lack of commercial availability.

For the pneumatic technology servo valves for controlling cylinders and "pneumatic muscles" were compared as viable options.

A servo valve (Figure 3.1) is a specialized type of valve that uses an electric motor to move a spool to control the flow of air that goes through it. An electronic controller built into the valve compares the position of the spool against an input signal and this creates a closed loop that regulates the movement of the cylinder connected to it. Due to its high cost and the need to acquire cylinders, pressure regulators, fittings and tubing, this option was removed from the final list of possible actuator technologies for the project.

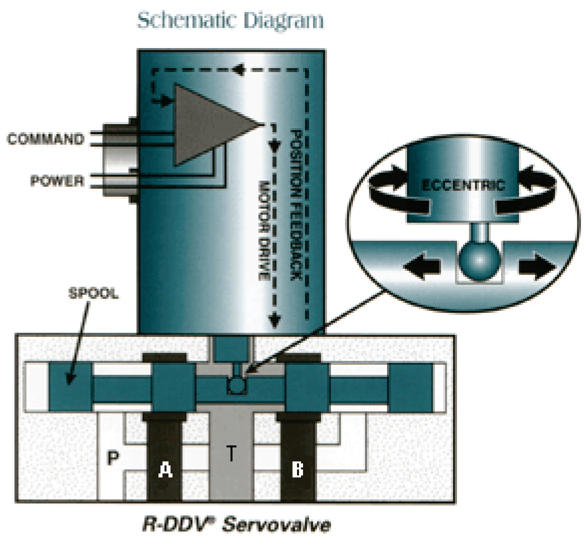


Figure 3.1 - Pneumatic servo valve [44]

A pneumatic muscle (Figure 3.2) contains a lightweight thin bladder that expands and contracts inside a woven mesh that limits its maximum inflation. These pneumatic actuators are called "muscles" because they resemble a human muscle in contraction and expansion. As air goes in, the muscle expands radially and contracts axially creating a pulling force. When the air is removed the muscle returns to its initial state.

Figure 3.2 - Pneumatic Muscle [45]

Their construction is fairly simple and the necessary materials are inexpensive and widely available. Their simple function allows the user to create muscles that move only a desired distance, and simple valves can control their pulling force. Their power to weight ratio is around 400:1, giving them an advantage compared to DC electric motors (16:1) [46].They usually operate at a pressure between 0 to 6 bars, eliminating the need to have high pressure pumps.

Their main disadvantage is that they only exert force when inflating and once the air leaves the bladder there is a small and variable force that extends the muscle back to its elongated state. This limits there use as a single unit to move a mechanical component back and forward. The solution for this problem is inspired on the behaviour of muscles inside the human body.

The agonist and antagonist principle describes how most muscles inside the human body work in pairs to create motion. As with “pneumatic muscles”, most muscles on the body are only capable of exerting a pulling force and they cannot return to their initial state without the aid of another parallel muscle. On these antagonistic pairs, the extensor muscle increases the distance between two points and the flexor muscle decreases this distance when activated. An example of this pair of muscles is shown in Figure 3.3.

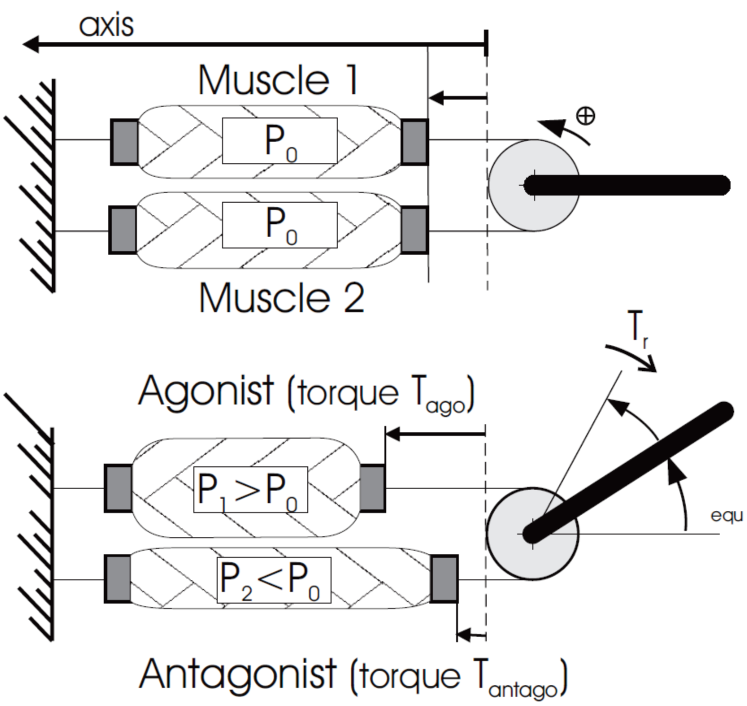


Figure 3.3 - Agonist Antagonist Muscles [47]

By connecting a cable or wire between two ends of the muscles and using a simple fixed pulley, the linear motion can be converted into rotation without the use of any other special equipment. For its cheap construction and simple function, this actuator type was selected as the main option, if pneumatic technology was to be selected.

For the electric motor technology, servo motors were chosen as the best alternative for this project. This type of motor is widely used on robotics and RC (Radio Control) applications. RC servo motors were a low cost option with sufficient power and speed to meet the requirements for actuating the orthotic device. They were also commercially available in different sizes, torque capacities and operating voltages and currents.

A typical RC servo consists of four different parts (Figure 3.4):

- DC (Direct Current) Motor.
- Gear reduction unit.
- Control Circuit.
- Position sensing device (usually a potentiometer).

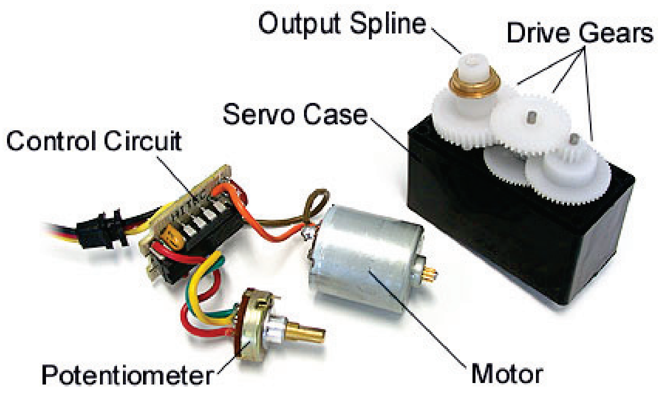


Figure 3.4 - RC servo motor [48]

This type of motor uses Pulse Width Modulation (PWM) as its control signal to position the motor in a desired angle. Its main difference compared to DC or AC motors is that they control the position of the shaft and not its continuous rotation.

A simplified block diagram of a servo motor is shown in Figure 3.5. The process starts when a pulse of variable width is received by the control circuit. This signal is processed and converted into a voltage to allow the motor to move. As the motor's shaft moves, the gears increase the torque and reduce the velocity at the output of the servo. They also enable the movement of an internal potentiometer that varies its resistance depending on the position of the shaft. The signal from the potentiometer is compared to the desired position and the error between these values is driven to a minimum. This creates a closed loop feedback that allows the motor to keep its position even if there is an external force trying to move it. It is important to note that in order to hold its position the servo needs to be constantly receiving the desired angle command, and that the maximum force it can withstand is not infinite but directly limited by the torque rating of the servo.

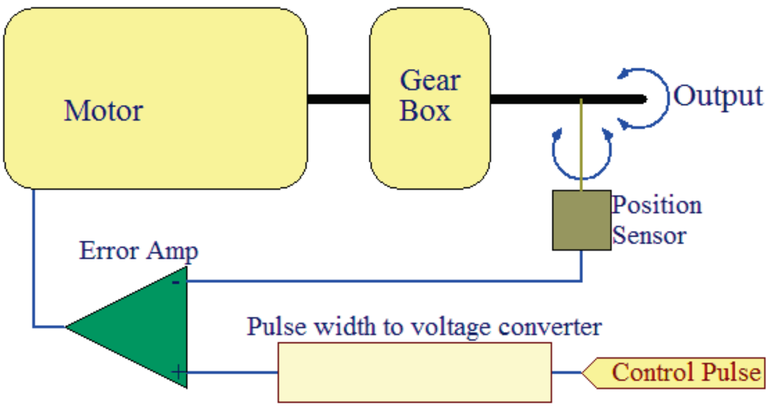


Figure 3.5 - Servo Motor Block Diagram [49]

RC servos usually have three different input wires:

- Black: Connected to the power source's ground
- Red: Connected to the power source's voltage supply.
- Yellow: Used for position control. The user sends a pulse with the next characteristics:
    - Period of 20 ms (milliseconds).
    - Maximum pulse width of 2 ms.
    - Minimum pulse width of 1 ms.
    - Voltage of the pulse: 4.8-6 Volts

The majority of RC servos move to a neutral position when they receive a pulse width of 1.5 ms, which is right in the middle of the total displacement of the motor (usually 180 degrees). Figure 3.6 shows the typical pulse characteristics and their effects on the desired shaft position.

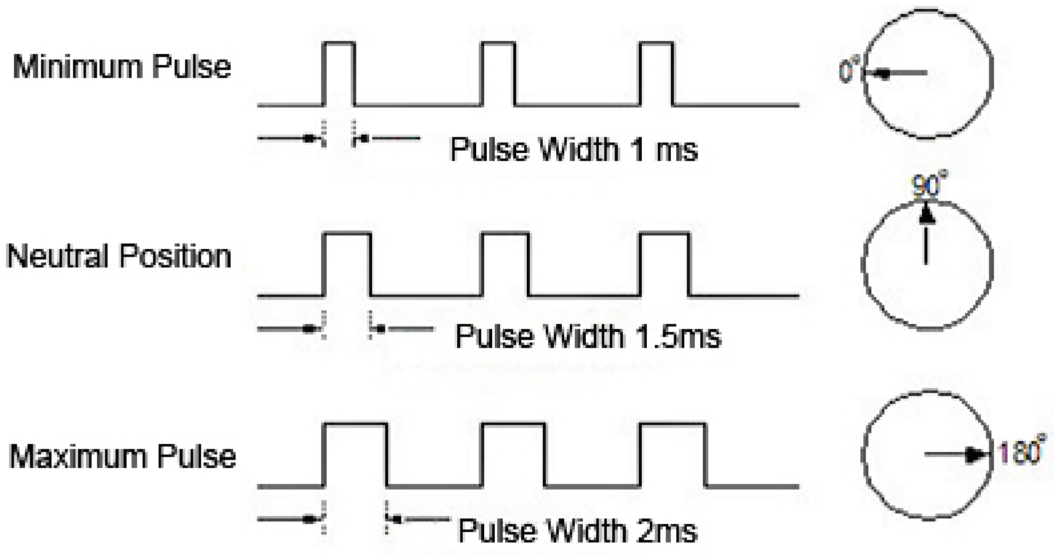


Figure 3.6 - Pulse characteristics [48]

The fact that the pulse width equivalence in degrees of movement is fixed and constant, gives the user the opportunity to know the exact position of the servo without the use of any other external feedback. Consequently, it significantly reduces the space and cost of projects that can only rely on the accuracy of the servo to move. Also, the small size of RC servos represents one of their main advantages when compared to other types of motors.

After the electric and pneumatic actuators were selected, a comparison between them was performed to decide which one was going to be used. The results of this comparison are shown in Table 3.2.

Actuator	Advantages	Disadvantages
Air Muscle	Similar behaviour to human muscles. Strong. Extremely low cost. 400:1 Power to weight ratio. Simple construction. Quiet operation.	Only exert a pulling force. Friction on the cables and pulleys. Need to maintain tension in cable or wire. Need to create custom made pulleys. If using antagonist configuration, need to control two muscles and two valves per each degree of freedom. Need to acquire an air compressor to operate.
RC Servo Motor	Capable of pushing and pulling depending on the application. Fine resolution and movement. Integrated feedback. One motor per each degree of freedom. Small size.	Noise when holding position. Lower power to weight ratio. Expensive compared to air muscles. Prone to gear damage if overloaded. Torque drops with speed. Low torque to inertia ratio.

Table 3.2 - Comparison between Air Muscles and Servo Motors

The main reason for selecting servo motors over pneumatic muscles was that in order to work with pneumatic muscles, several other elements would need to be acquired, such as: an air compressor, pneumatic servo valves and pressure gauges among others, that would greatly increase the cost and complexity of the project. Also, the fact that the muscles are only capable of pulling would increase the number of elements and overall size of the device. In contrast, servo motors are capable of pulling and pushing with the same amount of torque, allowing the use of one actuator per degree of freedom, and their behaviour can be modelled as almost linear, allowing for simpler and more predictable control.

Several brands like Futaba, Hitec, JR, Dynamixel and Kondo were compared in order to select the servo motor that would be used in the project. The selected motor was a Hitec HS-645 MG; Table 3.3 shows the specifications for this model.

Control System: +Pulse Width Control 1500usec Neutral
Required Pulse: 3-5 Volt Peak to Peak Square Wave
Operating Voltage: 4.8-6.0 Volts
Operating Temperature Range: -20 to +60 Degree C
Operating Speed (4.8V): 0.24sec/60° at no load
Operating Speed (6.0V): 0.20sec/60° at no load
Stall Torque (4.8V): 106.93 oz/in. (7.7kg.cm)
Stall Torque (6.0V): 133.31 oz/in. (9.6kg.cm)
Operating Angle: 45 Deg. one side pulse traveling 400usec
360 Modifiable: Yes
Direction: Clockwise/Pulse Traveling 1500 to 1900usec
Current Drain (4.8V): 8.8mA/idle and 350mA no load operating
Current Drain (6.0V): 9.1mA/idle and 450mA no load operating
Dead Band Width: 8usec
Motor Type: 3 Pole Ferrite
Potentiometer Drive: Indirect Drive
Bearing Type: Dual Ball Bearing
Gear Type: 3 Metal Gears and 1 Resin Metal Gear
Connector Wire Length: 11.81" (300mm)
Dimensions: 1.59" x 0.77"x 1.48" (40.6 x 19.8 x 37.8mm)
Weight: 1.94oz. (55.2g)

Table 3.3 - Specifications Hitec HS-645 MG [50]

The operating speed and size of the motor were ideal for the application and more importantly the minimum torque of 7.7 kgf cm (0.755 Nm) was considered sufficient enough to actuate the joints of the fingers in a flexion and extension motion, based on the values acquired from physiotherapy data, which are presented on Table 3.4.

Joint		Thumb [Ncm]	Index [Ncm]
CM	Extension	29.3	
	Flexion	29.0	
	Abduction	32.8	
MP	Extension	13.0	24.7
	Flexion	26.0	29.3
	Abduction	-	16.7
PIP	Extension		28.7
IP/ DIP	Extension	22.3	17.7
	Flexion	24.8	19.7

Table 3.4 - Required Torque to extend and flex finger joints [51]

These values were obtained using a torque gauge that measured the necessary force to move the joints during assistive rehabilitation of stroke victims.

3.1.2 Finger Motion

After the servo motor was selected as the actuation technology for the project, the next step was to design the mechanism that would allow the fingers to move.

The first idea was to actuate the fingers using pulleys located on the side of each joint. Using cables to transmit the power from the motor to the joints, each finger would have three independently driven pulleys that would allow the flexion and extension of the distal, proximal and metacarpophalangeal joints.

For the first prototype the thumb was not considered in the design, and only the remaining four fingers were included. Each finger was modelled as having three hinge joints that allowed only extension and flexion motion. The abduction/adduction motion was not included because it was not the main focus of the rehabilitation system. Using this simplified model of the hand reduced the number of DOF (Degrees of freedom) to twelve, which were going to be actuated by twelve independent motors. Each of the motors would have a cable going through a fixed pulley that would rotate the joint in either direction by using the push/pull movement of a horn connected to the motor's shaft. Figure 3.7 shows a simple model of the proposed system.

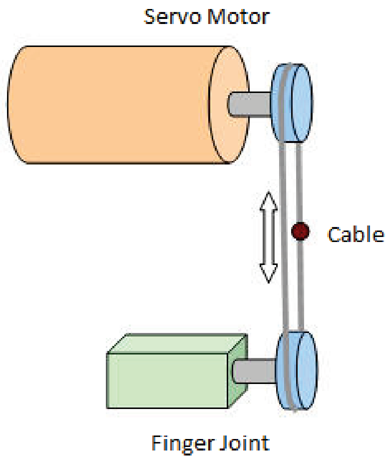


Figure 3.7 - Pulley System (Adapted from [52])

The design would keep the motors away from the hand, reducing the weight, size and complexity of the device. The only structure that would have to rest on the patient's hand would be a set of pulleys fixed to an exoskeleton adjacent to the different fingers. The main challenge of this design was to reduce the size of the pulleys and fixing elements, to be able to have them side by side on the space between the fingers. Also, some other problems were that the cable generated some non linear behaviour due to the friction between it and other elements. In addition, the tension of the cable would have to be maintained to achieve sufficiently fast response of the device.

Even though the servo motors were really affordable ($32 USD), using twelve would greatly increase the cost of the project. Also, the possibility of controlling each joint independently was initially presented as an advantage, until the physical constraints of the hand were taken into consideration. Modelling each finger as having three independent DOF was far from the real physical limitations of the hand.

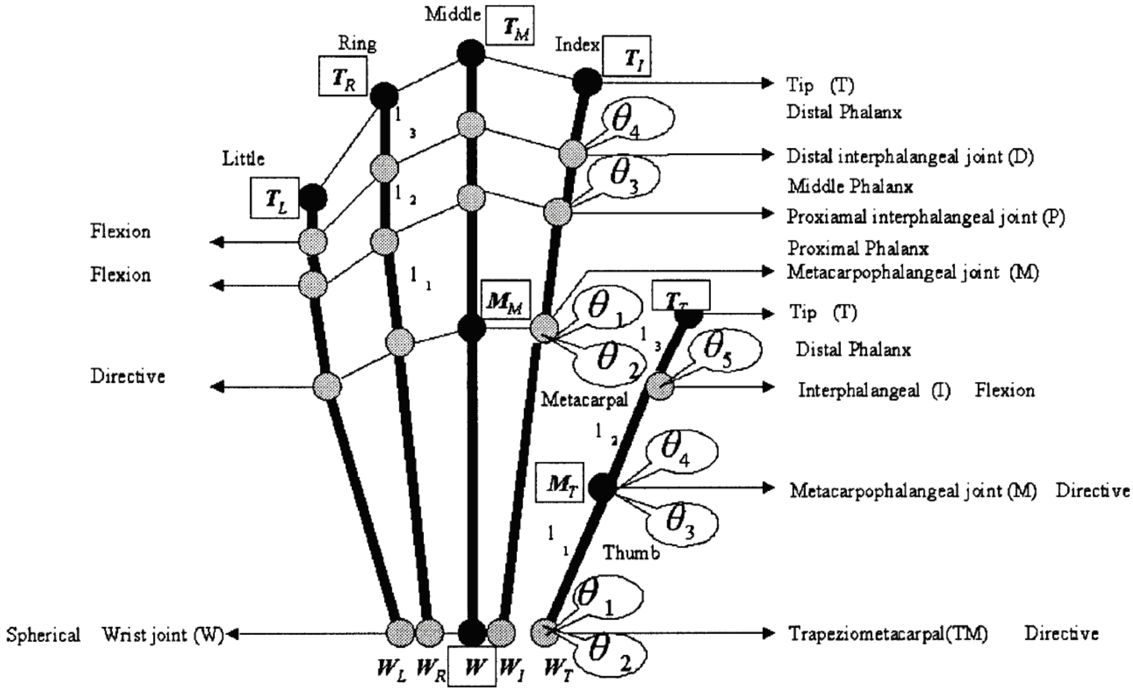


Figure 3.8 - 27 DOF Hand Model [53]

A hand model with 27 DOF is shown in Figure 3.8. The number of DOF can be reduced to 12 by considering the physical limitations of the hand [53].This model includes the wrist and thumb, which are not part of the device's initial design. As a result only the 12 DOF of flexion and extension of the index, middle, ring and little finger were taken in to account, and their constraints are:

> Constraint 1 [54]: The flexion and extension angles of the distal and proximal joints are dependent, and are governed by Equation (3.1):
>
> $$\theta_4 = \frac{2}{3}\theta_3 \tag{3.1}$$
>
> Constraint 2 [55]: The flexion and extension angles of the proximal and metacarpophalangeal joints are dependent, and are governed by Equation (3.2):
>
> $$\theta_1 = k\theta_3 \quad 0 \le k \le 1/2 \tag{3.2}$$

Using these constraints to model the patient's hand, the number of independent DOF can be reduced to one per each finger. As a result, the total number of servo motors can be reduced from twelve to four. The use of three motors per finger would be redundant because the joints extend and flex in a dependent manner and moving them independently could promote unnatural motion that could lead to discomfort in the fingers. A solution for this could be to control the twelve motors in manner that reproduces the actual constraints of the hand, or to reduce the number of motors to four and design a method to interconnect the joints to provide dependent motion.

Instead of using pulleys and cables to create an exoskeleton that would increase the overall weight of the hand, and more importantly create an unnatural feeling while wearing it, a design in which only the tip of the fingers would be attached to enable flexion/extension motion was proposed.

This type of end effector device was similar to the HandCare [27] and Amadeo [30] systems in which the joints are actuated by connecting to only one point on the fingers. Using the CAD software "SolidWorks" a 3D model of an index finger (Figure 3.9) was created to simulate its motion when actuated on the distal phalanx. The dimensions of the finger where based on the designer's hand and anthropometric data [56] of British male adults.

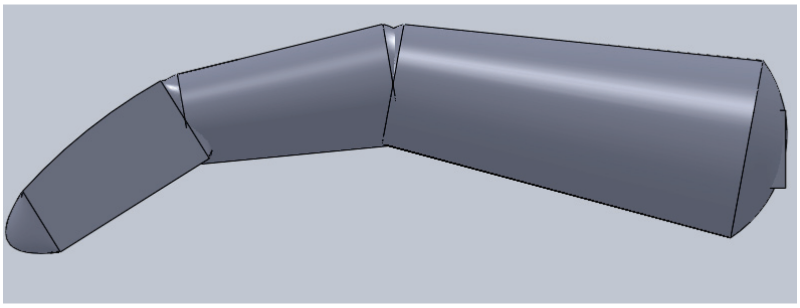


Figure 3.9 - Index Finger 3D Model

The MCP joint was attached to a fixed point, to act as the patient's palm. All of the joints were only capable of rotating in a flexion/extension motion and the limits for the angles between them were adapted from a previous study [57] in which their ROM[15] (without any force applied) was measured. The used limits are shown in Table 3.5.

Joint	Hyperextension (Degrees)	Flexion (Degrees)
MCP	15	90
PIP	20	115
DIP	20	90

Table 3.5 - ROM limits

Using the finger's model, a simple support was created to test if its linear motion could be converted into joints' flexion and extension. After mating all the parts on the 3D assembly, the motion was successfully accomplished. As the support was moved back

[15] Range of Motion.

and forward, the tip holder rotated, enabling the finger to flex and extend. This motion is shown in Figure 3.10.

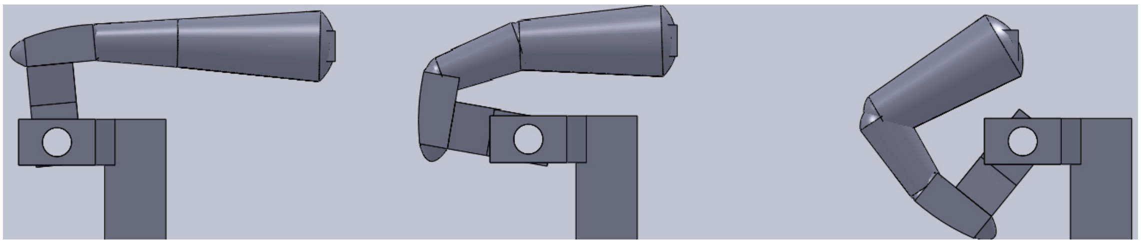


Figure 3.10 – CAD model showing flexion and extension of index finger

3.1.3 Transmission

Once the initial idea for flexing the fingers was proven to work, the transmission method to convert the rotational motion of the motor to a linear displacement had to be determined.

One of the most reliable and successful method for achieving this, is the mechanical linear actuator. The kind that uses a screw mechanism with bearings would have been perfect for this application, but their high price was the main reason they were not selected for this project. Nevertheless, if there was no budget limitation, this would be the best option for driving the device.

After discarding the linear actuators, simple mechanisms and linkages were considered to achieve the same outcome. The one that was selected was the crank-slider mechanism because of its simplicity and low cost. Also, it could be easily manufactured and assembled using tools and machines found on a typical mechanical workshop.

A crank-slider mechanism (Figure 3.11) is a simple linkage, in which the rotating movement of a crank is converted to a linear motion by connecting it to a rod that pushes a slider back and forward.

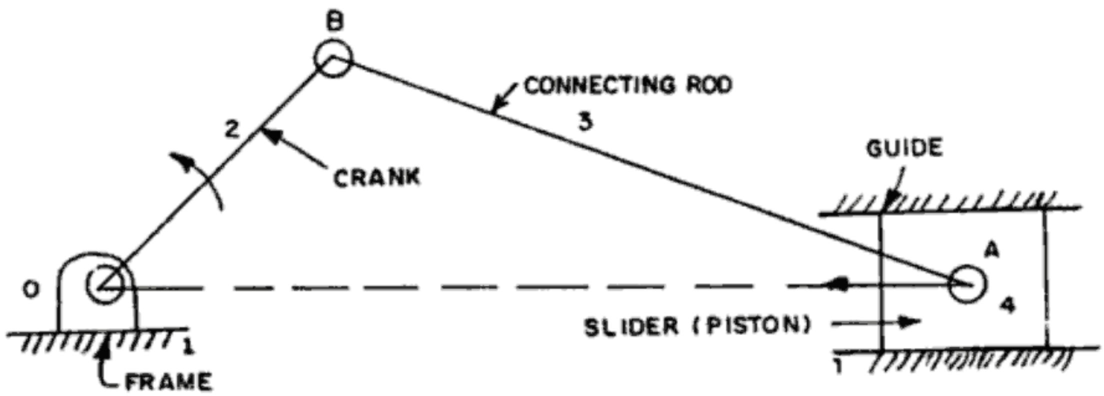


Figure 3.11 - Crank Slider Mechanism [58]

Some of the design considerations for this mechanism were:

- The crank should always be shorter than the connecting rod.
- The length of the stroke of the slider is equal to twice the radius of the crank.
- The connecting rod should be 3.2 to 4 times longer [59] than the crank to minimise vertical loading and friction in the guide walls in which the slider is moving.
- The displacement of the slider (Figure 3.12) follows the kinematic relation shown in Equation (3.3):

$$x = R - R\cos(\theta) + L - Lcos(\varphi) \tag{3.3}$$

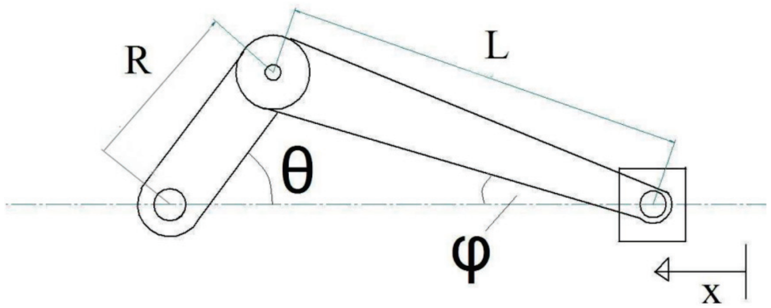


Figure 3.12 - Crank Slider Displacement [60]

As the arm of the patient would have to be resting above the mechanism, an offset crank slider[16] was designed to avoid any interference between the crank or/and connecting rod and the supporting frame of the device. The length of the stroke was based on the maximum displacement of the middle finger of the designer's hand. The middle finger was selected because it is the one with the greatest length and displacement, of all the

[16] Crank slider mechanism in which the crank is not horizontally aligned with the slider.

fingers in a standard adult's hand. The measured stroke was 125 mm but the final device allowed 150 mm, in order to accommodate for bigger hands and fingers.

Using a value of 150 mm for the slider's stroke, a crank of 75 mm and a connecting rod of 300 mm were designed. As mentioned before, the connecting rod is four times greater than the crank to avoid unnecessary vertical loading that could reduce the life of the mechanism and affect its overall motion.

3.1.4 Finger Support

The finger support needed to be attached to the finger's distal phalanx to enable full rotation. This was done to flex and extend the finger as the slider moved back and forward. As a result, the part was divided into two components: the tip support and the main finger support.

The tip support (Figure 3.13) was designed to be attached to the finger using a Velcro strap bolted to one of its sides. This strap would make a loop surrounding the finger and ending on the other side to secure it to the part. This attachment design would also accommodate different finger widths and the soft texture of the loop strap would reduce any discomfort when in contact with the skin of the patient's finger. The tip support would be connected to the main finger support trough a pin that would enable its rotation.

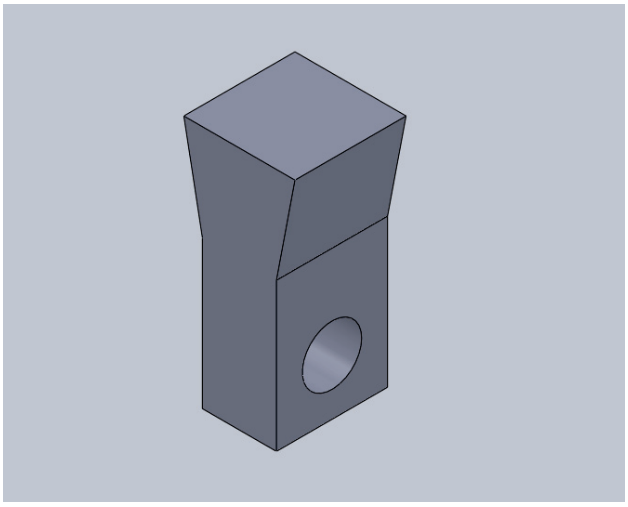


Figure 3.13 - Tip Support

The area of the part that was to be in contact with the finger, was based on a previous anthropometry study [61] of U.S. army personnel, in which the 50th percentile for the breadth of the 3rd digit's phalanx was 19.7 mm and its length 28.4 mm. The 3rd digit was used to be consistent with the previous design specifications. The final area for the tip support was 15 mm x 15 mm, as it was considered to be large enough to accommodate more than the 50% of the total area of the finger. Also, with this size, the finger would be firmly attached and the extra skin outside of the support would not create any discomfort.

The main finger support (Figure 3.14) was designed to run in two rails that would serve as its linear guides. Enabling it only to move only on a horizontal direction and preventing any sideways movement or rotation. The part was also designed to connect to the rod from the crank slider mechanism to enable the desired back and forward motion. In addition, its top was shaped as a fork terminal to prevent the tip support from falling and to allow the pin to pass through both parts.

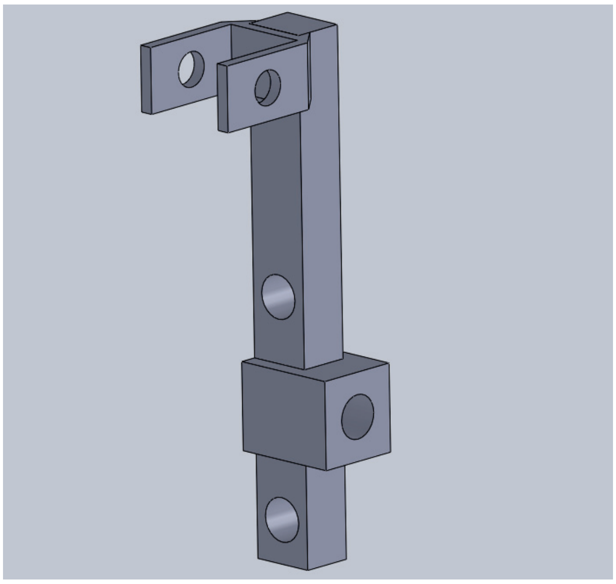


Figure 3.14 - Finger Support

3.1.5 Linear Guides

Initially only one linear guide was going to be used to hold the finger support, but after some tests, it was agreed that one guide would not be sufficient to prevent the support from rolling due to its own weight. This issue could potentially cause constant misalignment of the device, which could lead to a faulty operation. As a result, two shafts (Figure 3.15) were considered on the final design, to hold the support in a vertical position as it was moving.

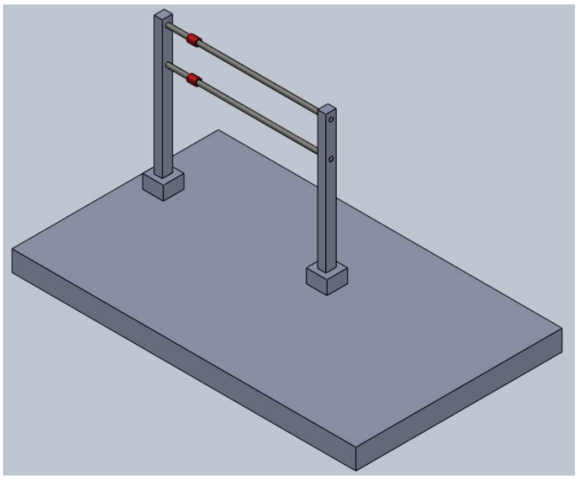


Figure 3.15 - Linear Guides

Two linear bearings (bushes) were fitted within holes drilled trough the finger support to reduce the friction between elements and to extend the service life of the device. The selected bearings were self lubricated to avoid the need of applying constant lubrication to them and to prevent any spills that could come in contact with the skin of the user.

The guides would be resting on a pair of columns that would be fastened to the base of the whole assembly. Their size and tolerances would need to be the same to avoid any misalignment of the shafts.

3.1.6 Assembly

A 3D model of a human hand and arm (Figure 3.16) was created to establish the necessary height of the linear guides to avoid any contact between the patient and the mechanism. A distance of 300 mm from the base to the top of the finger support was considered sufficient to avoid this problem.

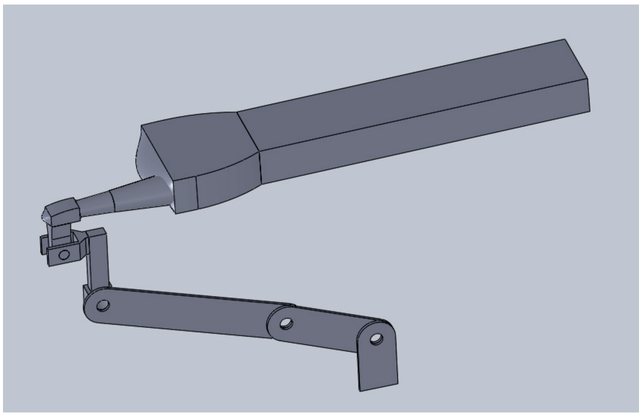


Figure 3.16 - Human hand and arm model

A solid block was fitted (Figure 3.17) to raise the height of the servo motor to prevent the crank from hiting the base when rotaiting. Also, two other blocks were created to increase the area of the bottom of the columns, to be able to fix them with more than one screw.

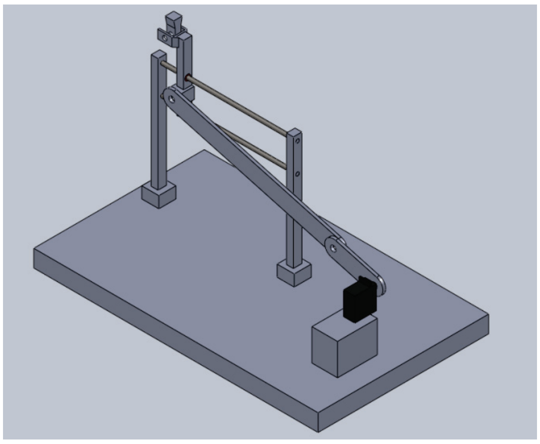


Figure 3.17 - Model of first prototype

After the model was completed, drawings of each of the parts were taken to the university's mechanical workshop for approval, and to receive feedback from the staff about the machining process and materials that could be used to create this device.

3.1.7 Manufacturing

All of the parts expect for the pin, base and linear guides were going to be made of aluminium because of its availability and low price. The base was going to be made out of wood as it was widely available in the workshop, and it was simple and fast to manufacture.

The linear guides and pins were going to be stainless steel to allow a smooth movement between them and the aluminium parts. Contact between aluminium parts should always be avoided if one of them is moving, as it can prematurely wear out the parts due to excessive friction. The friction coefficients for the two types of contacts are shown in Table 3.6,

Material	Against Material	Dry Contact
Aluminum	Aluminum	1.35
Aluminum	Steel	.45

Table 3.6 - Friction coefficients of aluminium and steel contacts [62]

After the drawings were approved, it was agreed that the parts were going to be machined using standard vertical milling machines. The staff in the workshop also proposed some changes to the device to allow the use of available material to reduce the overall cost of the project. The main changes were:

- Substituting the two stainless steel shafts with a single linear guide and block from THK (Model: RSR12ZMUU+270LM). The machinist in charge of the job explained that if the shaft were to be made from stainless steel and the columns needed to be completely aligned, the cost of the system would greatly increase. Instead, he suggested the use of a commercial linear block and guide that used ball bearings to move in one plane (Figure 3.18). This type of device runs with less friction than linear bearings and it also prevents any misalignment of the block because of the way is attached to the guide. Also, by acquiring this part the overall cost could be reduced, and the possible human error caused by machining to the close tolerances of the previous design would be eliminated.

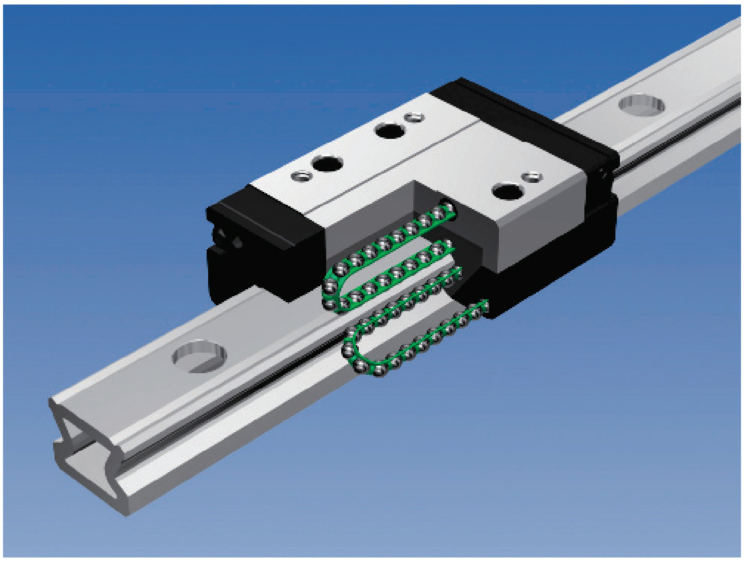


Figure 3.18 - THK linear guide [63]

- Instead of having supporting blocks for the columns, aluminium angle bars (Figure 3.19) were used to create brackets to fix the columns in place. With this setup the parts were securely fixed to the base with two screws. Using the commercially available angle bars instead of the customized solid blocks, helped to reduce the cost, amount of material and machining time for these parts.

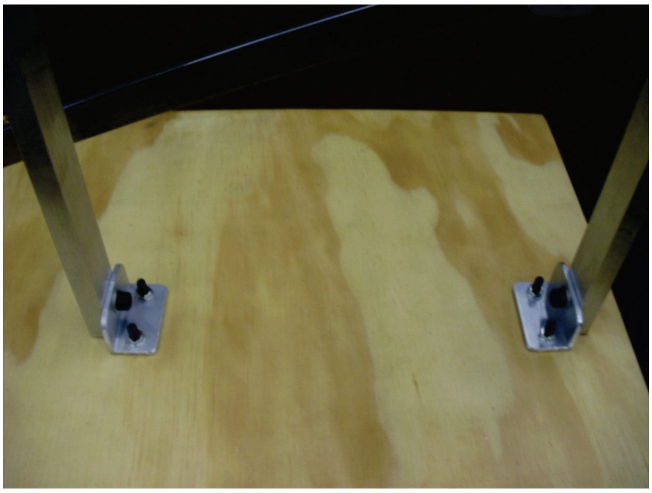


Figure 3.19 - Angle bars for columns

- Nylon washers (Figure 3.20) were inserted between the aluminium joints of the crank mechanism. Again, this was done to reduce the friction between parts made out of the same material.

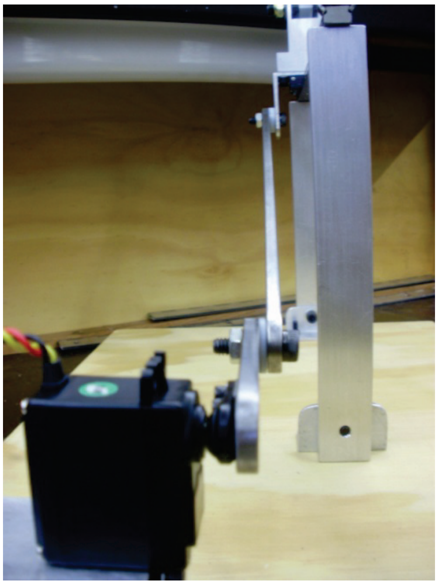


Figure 3.20- Nylon washers in aluminium joints

- The finger support was completely redesigned to simplify its manufacturing. The overall shape (Figure 3.21) was machined from a block of aluminium and most of the material was kept expect for the shoulders and the neck of the part. Instead of using a pin to enable the rotation of the tip support, a shoulder bolt[17] was used to fix the part in place.

[17] Type of screw that has an unthreaded portion, which is normally used to create revolving joints between two parts.

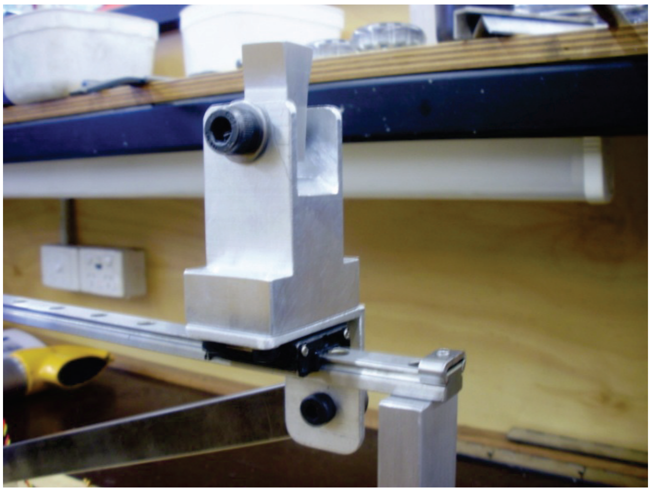


Figure 3.21 - First Prototype Finger Support

To enable the connection between the rod and the finger support an aluminium angle bar was used. The part was positioned between the finger support and the linear block and it was fixed using countersunk screws.

A wooden cover (Figure 3.22) was created to support the arm of the patient and to create a separation between them and the driving mechanism. This box also included a slot in which the finger support was able to stand out, to allow the finger to be attached to it. This slot was kept as small as possible to prevent any injury caused if fingers or other objects were inserted into the box. The box sat on a wooden base and was secured by four timber plates to prevent it from moving when a person intended to use the system. Four rubber feet where glued to the base to elevate the device, and to leave enough space to allow the therapist to lift the box from the bottom and move it from one place to another.

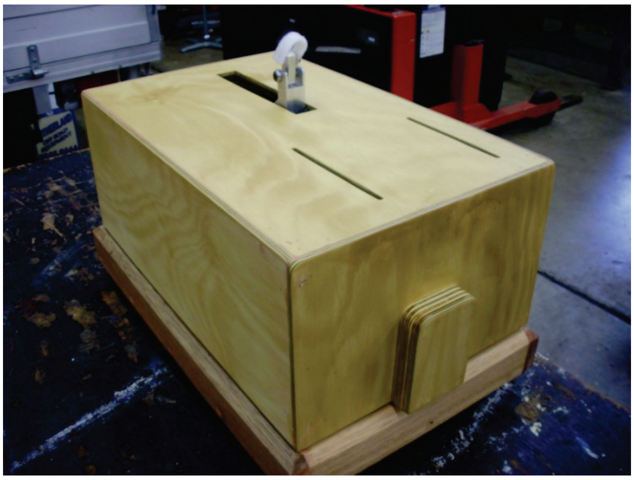


Figure 3.22 - First Prototype Cover

For the joints of the mechanism, shoulder bolts were used to allow a revolving motion of the parts. For the fixation, socket cap screws were fitted on all of the clearance and tapped holes. In addition, the employed fasteners used standard metric and imperial sizes, which are commonly available in hardware stores. The final assembly is shown in Figure 3.23.

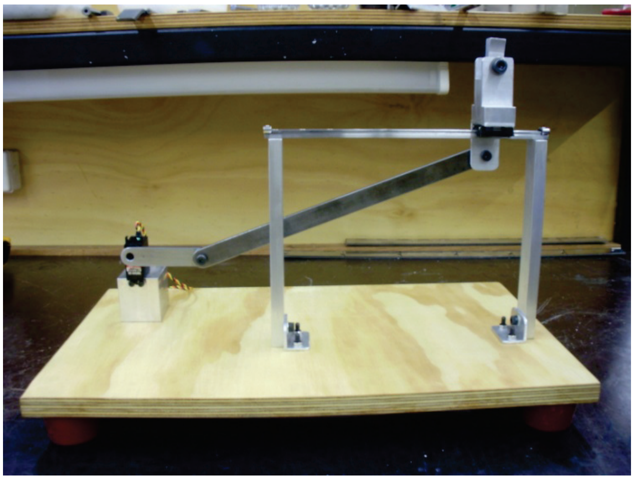


Figure 3.23 - First Prototype Assembly

After the assembly was completed, the electronic control in charge of commanding the different operation modes of the device was developed. The outline and steps involved on the creation of this system are presented in the next chapter.

3.1.8 Control

Three major components were involved in the control of the system (Figure 3.24):

- A PC (personal computer) with LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) software.
- An Arduino microcontroller board.
- The rehabilitation device.

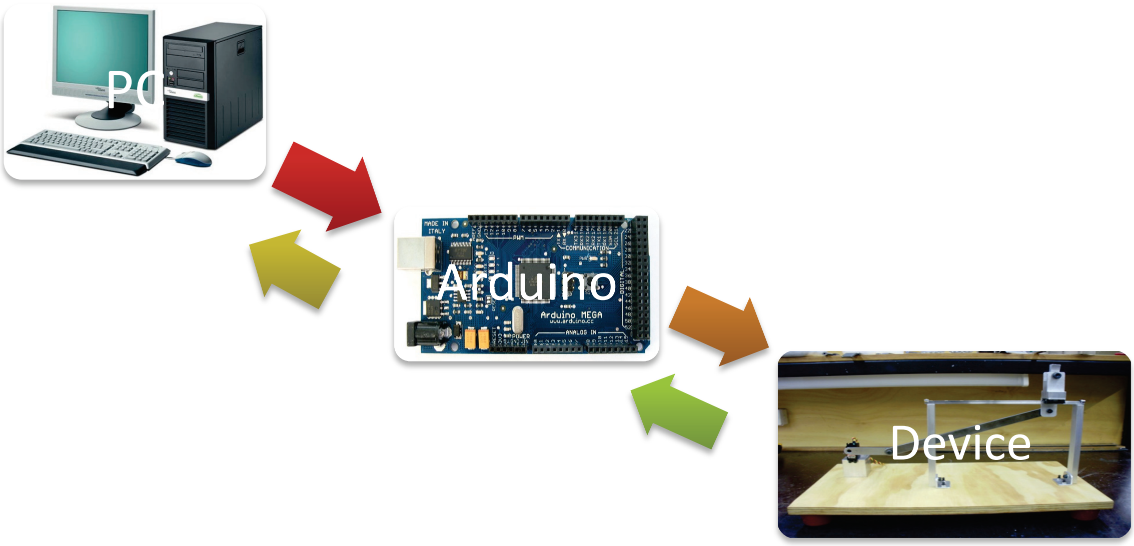


Figure 3.24 - Control Scheme [64],[65]

LabVIEW

LabVIEW was selected because of its visual programming capability, which is very straightforward and easy to learn. Another advantage is that it allows the programmer to create a visual user interface, which in this case would be vital for the therapist controlling the device. Also, the engineer in charge of the project already had experience using the software, and this helped to reduce the learning curve needed for developing the program.

LabVIEW communicated to the Arduino board trough a USB port, which was configured using the built-in VISA Serial VI[18]. This subroutine configures the USB connection as serial due to the functionality of the Arduino board that generates a virtual serial port when connected to the PC.

After the configuration of the port, all of the commands and data were sent using ASCII[19] characters. This coding was selected to send and receive characters using the standard Arduino libraries, and to simplify the overall communication process by using common symbols and letters.

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[18] Subroutines are called Virtual Instruments (VI) in LabVIEW.
[19] American Standard Code for Information Interchange. Basic character encoding based on the English alphabet.

The front panel of the application is shown in Figure 3.25. Trough this interface the therapist could monitor different variables and control the mode in which the device operated.

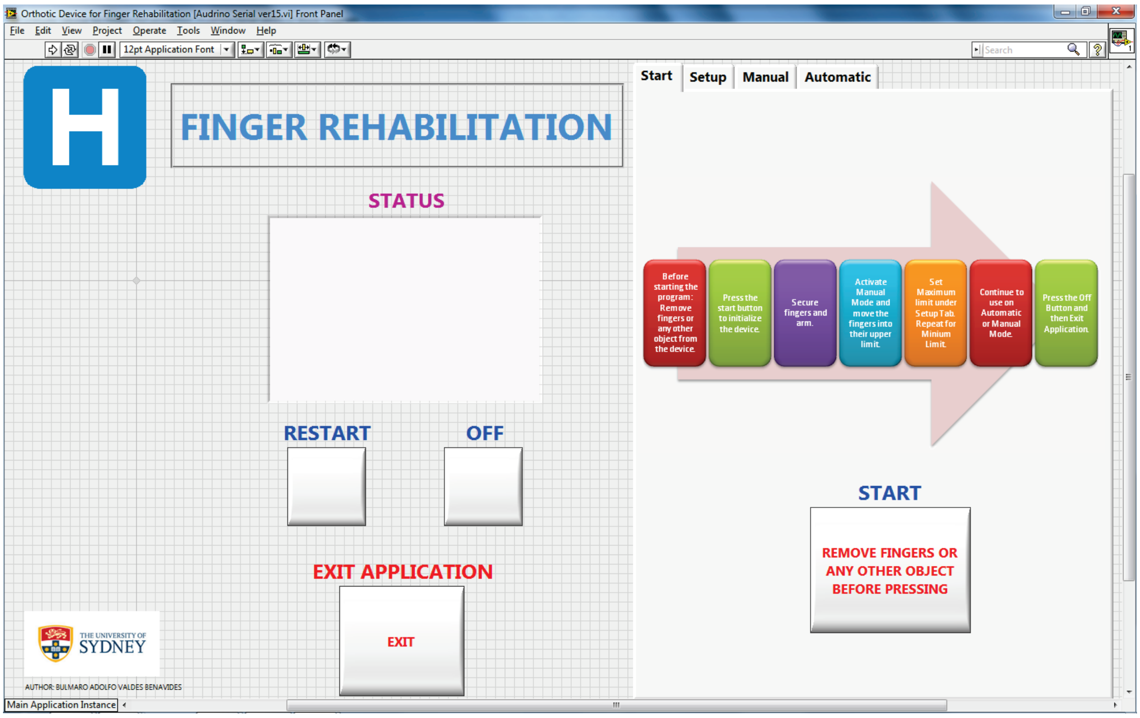

Figure 3.25 - Front Panel Application

The main screen was divided in different windows, indicators and tabs, the first of them being the status indicator (Figure 3.26). On this text indicator, different values coming from the Arduino board were presented as they were read trough the serial interface. These values were:

- Pulse Width (micro seconds): This value represented the duration of the ON pulse that was sent to the servo motor to achieve a certain position.
- Angle (degrees): It was the equivalence of the pulse width in degrees or rotation of the horn attached to the motor's shaft.
- Max and Min (microseconds): These were the motion limits of the current mode of operation.
- Auto and Manual Steps: These values represented the magnitude of the increments in manual and automatic mode.
- Mode: The name of the current mode of operation was displayed on this line.

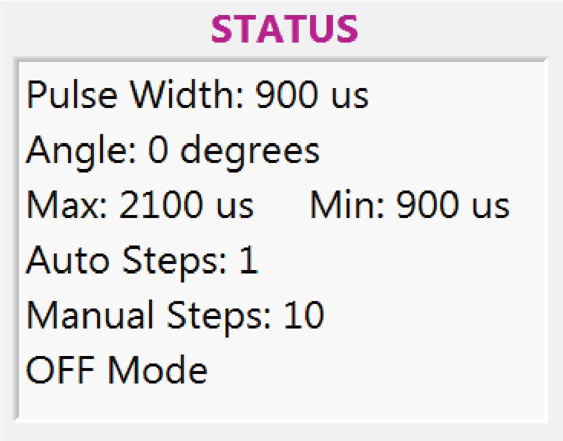

Figure 3.26 - Status Window

Also, from the main screen users were able to turn off and restart the device, at any time and when the rehabilitation had come to an end, they could press the “Exit Application” button to terminate the LabVIEW program. These buttons were left on the main screen to facilitate their access and for safety reasons in case the device started malfunctioning.

Start Tab

On the “Start” tab the therapist could read the instructions on how to set up the device and begin the rehabilitation process. The flow chart of the rehabilitation sequence is shown in Figure 3.27.

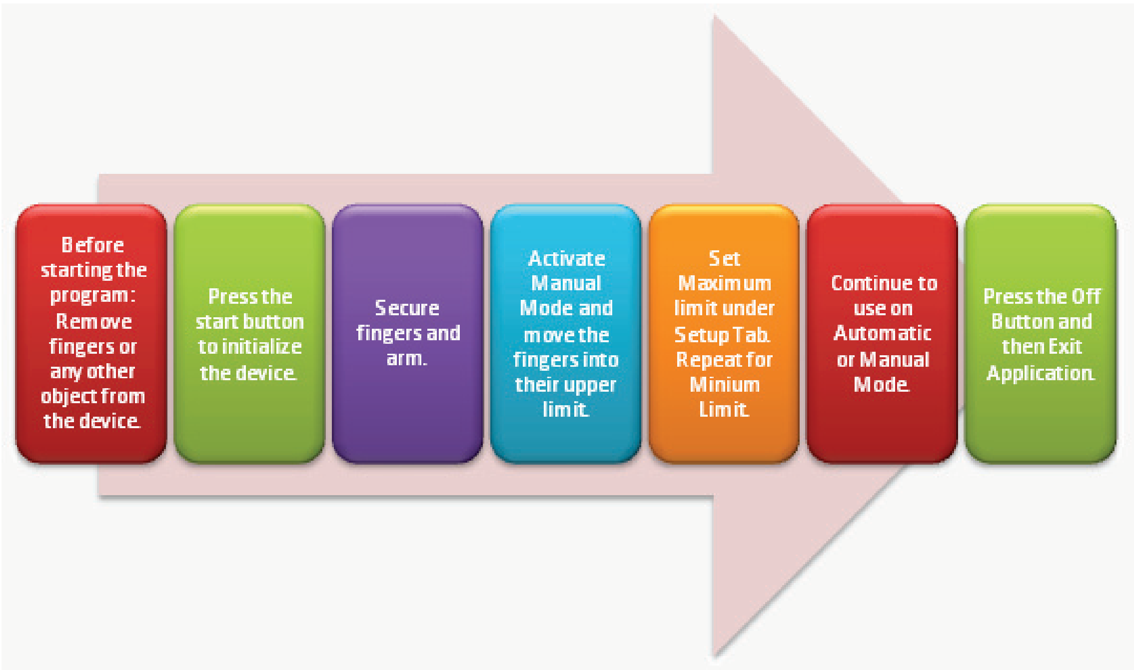

Figure 3.27 - Rehabilitation flow chart

The first step before starting the device was to remove any finger or object from the finger support and the box containing the mechanism. This was done to prevent any injury due to the connection of the servos to their power source. Following that, the start button was pressed and the system began its initialization process in which it positioned the finger support at its neutral position. Next, the finger was attached to the support using the Velcro straps and the manual mode was activated to move the finger to its maximum and minimal limits. In each of these locations the upper and lower limits were set trough the "Setup" tab. Subsequent to that, the therapist could start the rehabilitation using the automatic or manual mode using their correspondent tabs. Finally the device could be turned off and the application could be terminated.

Setup Tab

On the setup tab (Figure 3.28) the therapist could set the maximum and minimum ROM limits of the currently attached finger. This was done by first accessing the manual mode and moving the finger into a position in which no further safe displacement could be made. After that, the "Set Max" or "Set Min" button was pressed depending on the current location of the finger. By pressing the "Reset Limits" button the therapist could return the limits to their default value in case a new finger was to be rehabilitated.

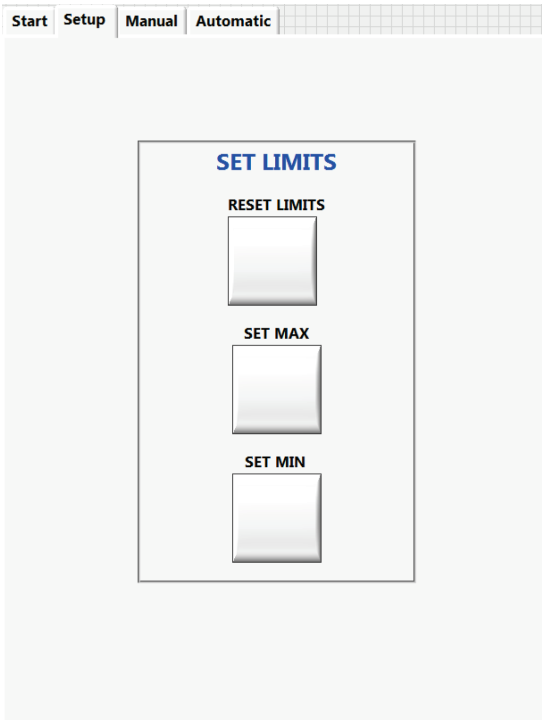

Figure 3.28 - Setup Tab

Manual Tab

On this tab (Figure 3.29), the user could activate the manual mode and start moving the support forward or backwards. The increments between each step of the servomotor could be modified by pressing the “Manual Steps Increase” or “Manual Steps Decrease” buttons. There were default limits for these values, which were set in the program for safety reasons. Also, as in the case of the ROM limits a “Manual Steps Reset” was included to enable the therapist to return these parameters to their default values.

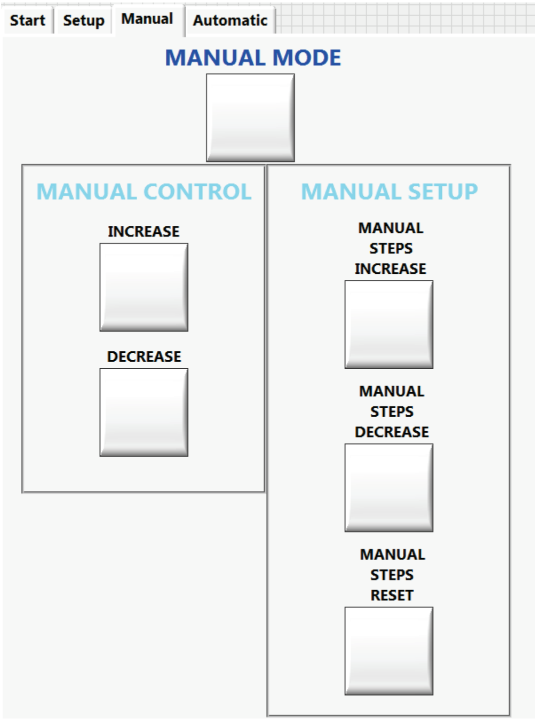

Figure 3.29 - Manual Tab

Automatic Tab

All the controls for the automatic mode were located on this tab. When the automatic mode was activated, the device started moving the finger from its current position to the upper ROM limit and when it reached this point the direction of the servo motor was reversed to start moving towards the lower ROM limit. This process was repeated, until the therapist decided that the exercise regime was completed for that particular finger. As with the manual mode, the steps of the automatic mode could be adjusted trough the “Automatic Steps Increase” and “Automatic Steps Decrease” buttons. Also, default limits were set for the maximum and minimum steps values. This was all done to prevent fast movements that could potentially injure the patient’s hand.

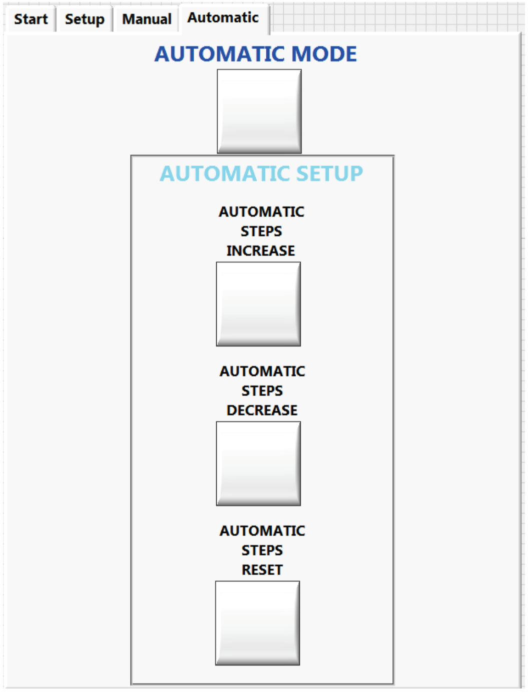

Figure 3.30 - Automatic Tab

In case the manual mode was activated when the automatic mode was in progress or vice versa, the device was programmed to turn itself OFF before making any changes to the active mode. Also, the maximum and minimum limits for each mode and for the general device could only be changed when the support wasn't moving. In case there was any movement due to a current active mode the device would also turn itself OFF to allow the limits to be changed.

Arduino

Arduino is an open source device that consists of an electronic board with a microcontroller that enables the use of inputs, outputs and port communications trough its different available terminals. It uses a simple programming language based on "Wiring"[20][66] and a development environment based on "Processing"[21][67]. The system can be assembled by hand or bought as a preassembled "ready to use" board.

This device was selected as the interfacing element between the PC and the rehabilitation device because of its capability of communicating trough a USB port and its available analogue and digital inputs/outputs. Also, it had built in libraries that were

[20] Open source electronic prototyping platform, composed of a programming environment and an electronic prototyping board.
[21] Open source programming language and environment originally used for working with images, animations and interactions.

used to control standard RC servo motors and communicate through a USB port. Therefore, it substantially reduced the time and code necessary to program the microcontroller to perform the desired tasks for the project.

The selected Arduino model was the Mega 2560 (Figure 3.31). This model was compared to other available options to decide which one would be the best fit for the number of inputs and outputs the final device would have to use. In the end, it was selected because of its 16 analogue inputs/outputs and 14 PWM pins. These available pins were more than sufficient to accommodate five servos and ten force sensing resistors that the final device would need.

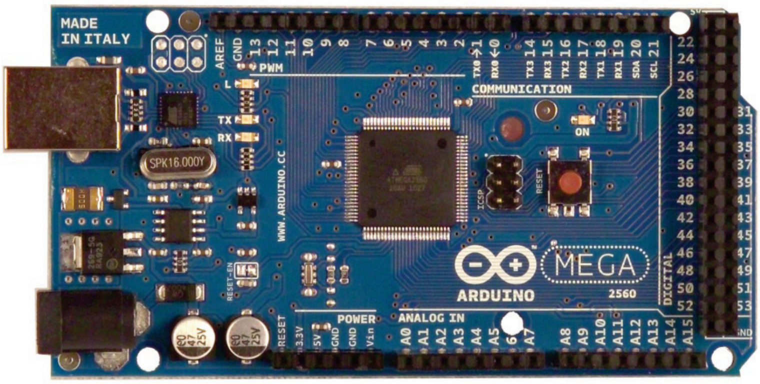

Figure 3.31 - Arduino Mega 2560

The general characteristics for the Arduino Mega are presented in Table 3.7.

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Table 3.7 - Arduino Mega 2560 characteristics [65]

The maximum current the board could supply was 500 mA. As a result, the servo motor couldn't be directly connected to the 5V supply of the Arduino. To solve this issue, a 5V/3A external power supply was used to provide the necessary power to the motor. The ground pin of the Arduino and the ground terminal of the power supply were connected together to share the same reference and avoid any electrical problem when sending the PWM signal to the servo motor.

The main program used the servo and serial libraries of the Arduino software to perform the basic functions of communication and control. The motor's signal cable was connected to pin 9, which was configured as a PWM output at the beginning of the program. This enabled a simple control of the position of the motor by using different time values for the transmitted pulses. A simple electrical schematic of the project is shown in Figure 3.32.

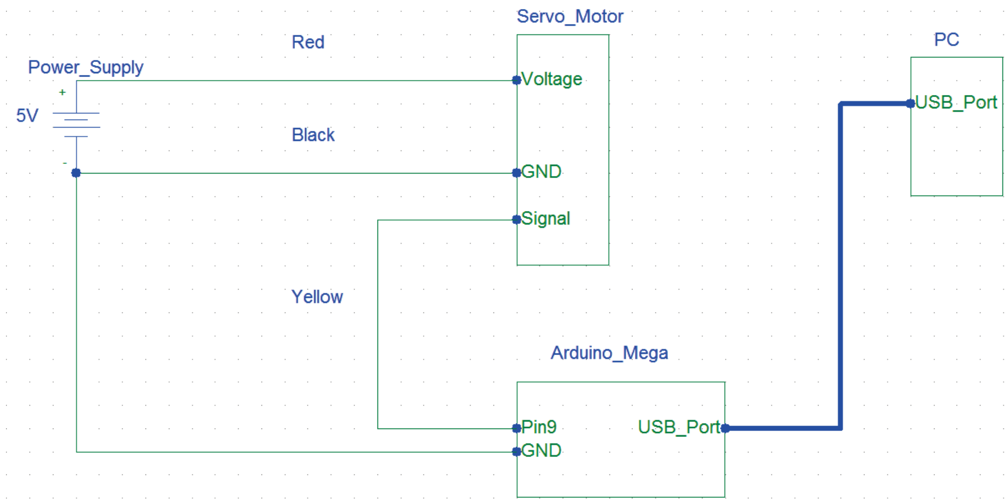

Figure 3.32 - Electrical Schematic

As mentioned before, all of the communication was made through a serial interface that used ASCII characters. When the Arduino received these characters, the program interpreted different symbols and started different routines and steps that controlled all of the modes of the device. All of the parameters used had a default value when the Arduino board was initialized. This was done to prevent any injury in case the communication failed or the Arduino board was disconnected from the PC.

3.1.9 Preliminary Results

The first prototype was tested on the designer's hand (Figure 3.33). All of the fingers of the right hand were tested to prove that the device was capable of flexing and extending them individually.

Figure 3.33 - First prototype test

For the arm rest, foam blocks were placed on the device's cover (Figure 3.34). These were used to provide a cushioned and comfortable support to the arm and to reduce the manufacturing time of having to build a customized and adjustable component for this purpose. When testing the device the foam gave the opportunity of modifying the height and position of the arm by just adding or removing blocks to the stack. The device's cover was sufficiently strong to support the weight of the forearm, and sufficiently stable to perform the rehabilitation of the finger.

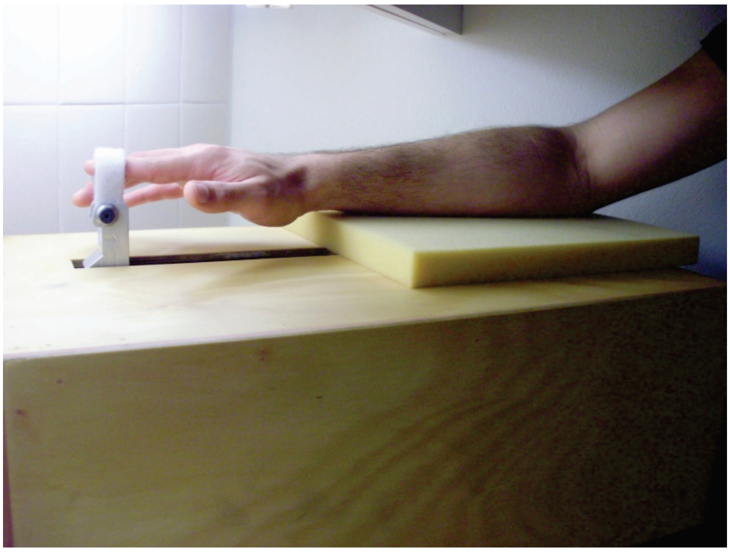

Figure 3.34 - Arm Support

The linear guides where fitted with mechanical stops (Figure 3.35) to prevent the block from falling of the end of the rail and more importantly to prevent the finger from over extending or flexing due to a malfunction of the servo motor or the mechanism. These mechanical stops were fixed using a set screw that could be loosened to permit different positions of the stops depending on the size of the user's hand.

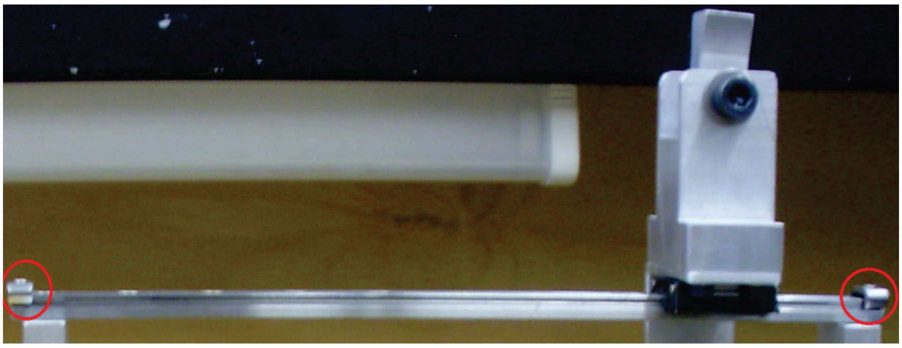

Figure 3.35 - Mechanical stops (circled in red)

The finger support was capable of rotating from -100° to 130°. Without taking into consideration the negative values, which could only be used for hyper extending the finger, the support could rotate 130° in total. Hyper extension was not the focus of this design, as it is an abnormal movement that could only ever be achieved by applying and external force to the fingers.

The conversion of the support's linear motion into flexion and extension of the finger was successfully achieved (Figure 3.36). This was the main goal of the first prototype, and it proved that the proposed motion could be used to create an improved design, to actuate all of the remaining fingers.

Figure 3.36 - Flexion and Extension motion

The maximum flexion angles that were achieved on the index finger are presented in Table 3.8. This finger was selected because the prototype was built with the rehabilitation of this digit in mind. Although, the device could also be used to exercise all of the others, expect for the thumb. These angles were measured using a simple protractor. As a result, these values are just an approximation and they lack the accuracy of more sophisticated methods for measuring angles. Consequently, a more accurate method should be implemented in the future to achieve more reliable results.

Joint	Index finger achieved flexion (Degrees)	ROM joint limits (Degrees) [57]
MCP	25	90
PIP	85	115
DIP	45	90

Table 3.8 - Flexion angles index finger

As shown in Table 3.8, the MCP was the less flexed joint. This is due to the design of the finger support that restricts any rotation outside 130 degrees. When the device was functioning this translated into little flexion of the MCP. The PIP flexion angle is closer to its maximum ROM limit. Consequently, this joint would be exercised in a similar manner as when receiving the aid of a therapist to perform full ROM exercises. The DIP joint was flexed to only half of its maximum range, and this was consistent with the constraint presented in Equation (3.1), in which the DIP and PIP motion is related. It is important to note that the values for the ROM joint limits [57] correspond to the angles achieved by patients with the aid of a therapist (passively) and not to the angles achieved actively (no assistance), in which the fingers follow their natural pattern of motion, as in this system. Increasing the rotational limit of the finger support could increase the flexing angles of all of the joints, and for this reason the design of the supports were modified on the final device.

The Hitec servo that was initially thought to be able to move 180° was only capable of moving 120°. This was a motion limit set by the manufacturer and it was a limitation of Hitec's analogue servos. This was not mentioned on the company's website and as a result, the maximum stroke of the finger was 13 cm, instead of the initial 15 cm of the proposed design.

With the 120° limit the Arduino board was able to divide the total stroke in 1200 micro seconds. Using the servo library the user could only input integer numbers starting from 0. This gave the Arduino's PWM output a resolution of 1 micro second and the motor a minimum step of 0.1°.

At 5 volts the motor was capable of exerting a maximum torque of .78 Nm. Using the .075 m crank as the lever arm, the maximum pushing and pulling force on the finger support was 10.4 N. This force proved to be sufficient to flex and extend the different fingers of the hand.

The crank mechanism was able to move the finger support without any major problem. The only concern was its joints, which permitted some lateral movement on their perpendicular axis, which created some unnecessary forces on the shaft of the motor and the linear guide. An improved design of the joints and the whole mechanism was proposed on the final device to reduce this problem.

The manual and automatic modes were tested on the device. Both of them worked properly and the communication between the Arduino board and LabVIEW was successful and capable of sending the commands to and from the PC. The capability of setting up the electronic limits of the device along with the mechanical stops on the rail ensured the safe operation of the system. These safety measures were tested several times and they were successful at preventing the servo motor from moving to an unwanted position.

Working with an open loop system that only relayed on the control loop of the motor for positioning the support was adequate for this initial prototype. The main reason for this was that the device's goal was to actuate the fingers in a continuous manner with full ROM movements, and this task did not require high precision. Also, the linear block moved with little friction that hardly affected the rotation of the motor and thus its final position.

Chapter 4 System Design: Final

After building the first prototype and testing its different modes of operation, a final design was proposed to achieve the following objectives:

- Exercise four fingers at the same time.
- Reduce the size of the mechanism.
- Improve the design of the finger support.
- Modify the joints of the crank mechanism.
- Reduce the device's manufacturing time.

This chapter will address the process in which these objectives were met. In addition, it is important to note that for this final design, dimensioned drawings of all the mechanical components, electronic schematics and Arduino and LabVIEW program codes can be found in the CD included in the appendix.

4.1.1 Actuators

The servo motor used for the first prototype was strong enough to move the linear block back and forward but after several cycles, one of its plastic gears was damaged due to an externally applied force. Also, the motor was only capable of moving 120°, which affected the final stroke of the support. As a result, a more robust and reliable servo was needed if the ultimate goal was to operate the four fingers. The servos that were compared for this application are presented in Table 4.1.

Servo Motor	Advantages	Disadvantages
Dynamixel **AX-12A**	Capable of setting its maximum operating torque. Several motors could be linked using a "Daisy Chain"[22] setup. Low current consumption (1.5 A).	Needs special adapter to operate. Operating voltage of 9-12 V. TTL communication interface.
Hitec **HS-7955TG**	PWM control. Operating voltage of 4.8-6 V. Titanium gears.	Higher current (3.4 A). Need external programmer to setup. High cost.
KONDO **KRS-4024S HV**	Several motors could be linked using a "Daisy Chain" setup. Capable of rotating 260 degrees.	Serial interface. Operating voltage of 9-12 V. Resin gears.

Table 4.1 - Final design servo motors

The selected digital servo was the Hitec HS-7995TG, because of its simple PWM control and its titanium gears. Since it used the same control method as the initial motor, there was no need to change the Arduino and LabVIEW applications, which were already capable of sending pulses to the motor. Also, the titanium gears offered a more robust and reliable operation without any change on the dimensions of the motor. After receiving the servos, a Hitec digital programmer was used to setup their maximum rotation angle to 180°. This resulted on a final finger support stroke of 150 mm, which complied with the initial design's requirements.

The specifications for this model are presented in Table 4.2.

[22] Wiring scheme for supplying power, data or signals to multiple devices connected in a sequence or ring.

Control System: +Pulse Width Control 1500usec Neutral
Required Pulse: 4.8-6.0 Volt Peak to Peak Square Wave
Operating Voltage Range: 4.8-6.0 Volts
Operating Temperature Range: -20° to +60° C (-68°F to +140°F)
Operating Speed (4.8V): **0.19 sec/60° at no load**
Operating Speed (6.0V): **0.15 sec/60° at no load**
Stall Torque (4.8V): **250oz/in. (18kg.cm)**
Stall Torque (6.0V): **333oz/in. (24kg.cm)**
Operating Angle: 45 Deg. one side pulse traveling 400usec
360 Modifiable: Yes
Direction: Clockwise/Pulse Traveling 1500 to 1900usec
Idle Current Drain (4.8V): 9mA at stop
Idle Current Drain (6.0V): 9mA at stop
Current Drain (4.8V): 220mA/idle and 3.4 amps at lock/stall
Current Drain (6.0V): 300mA/idle and 4.2 amps at lock/stall
Dead Band Width: 1usec
Motor Type: Coreless Carbon Brush
Potentiometer Drive: 6 Slider Indirect Drive
Bearing Type: Dual Ball Bearing MR106
Gear Type: Titanium Gears
Connector Wire Length: 7" (178mm)
Dimensions: 1.57" x 0.78"x 1.45" (40 x 20 x 37mm)
Weight: 2.29oz (65g)

Table 4.2 - Hitec HS-7955TG specifications [68]

The minimum torque of 18 kgf cm, was 2.33 times larger than the value of the first motor. This ensured a smooth operation of the device and it helped to prevent damage to the servo due to external forces acting on an opposite direction of motion.

4.1.2 Crank Mechanism

The initial crank mechanism was manufactured with 5 mm aluminium solid bars. This added unnecessary weight to the device and increased the necessary force for rotating the motor's shaft. The proposed solution was using standard 4-40 (2.84 mm) fully threaded stainless steel rods connected to custom made aluminium cranks. This type of rod is commonly used in conjunction with servo motors in RC projects because of its low weight and availability in different diameters and lengths.

The selected rods were 12 inches (304.8 mm) long, and with this length they were easily bent when a force was applied to one of their ends. In practice this is normally avoided using carbon tubes that cover the rods that provide extra strength without significantly increasing the overall weight of the mechanisms. For this project, "Cartel Triple 600" Aluminium-Carbon arrow shafts were selected because of their low weight and high strength, which exceed that of regular carbon tubes. This specialized type of arrow is used in archery because of its high stability and weight distribution in comparison with normal arrows. They consist of a 7075 aluminium core wrapped in high density carbon fibre. In addition, they were a perfect match for the 4-40 rods because of their inside diameter of 3.85 mm and their outer diameter of 5.3 mm.

For the connection between joints, 4-40 swivel ball links (Figure 4.1) were used. This reduced the weight and simplified the design because the rods and the links could be purchased instead of being manufactured in the workshop. Also, by using the included bolts and nuts their motion could be limited to rotation, and as a result this reduced the likelihood of any misalignment on the system.

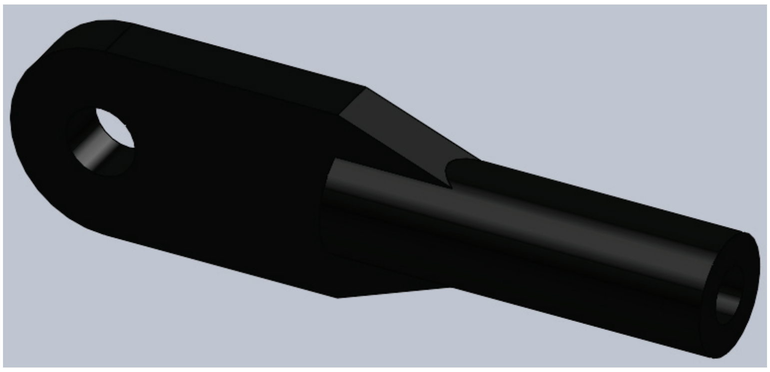

Figure 4.1 - Swivel ball link

The aluminium cranks (Figure 4.2) were manufactured using a laser cutter instead of a mill, to reduce their machining time and cost. Each had four clearance holes that were going to be fitted with screws, which fixed them to the motor's plastic horn. On their other end, they had a clearance hole to enable the connection with the rod's ball links.

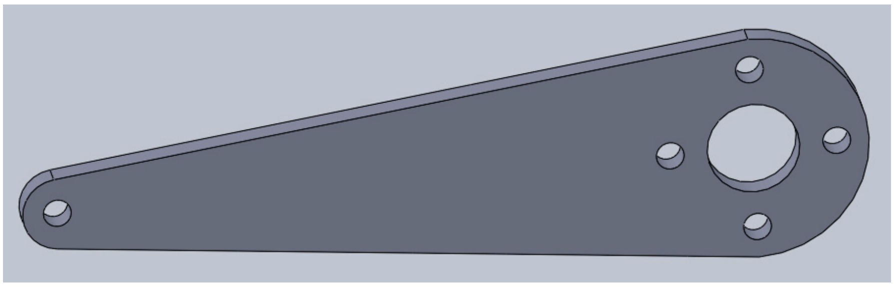

Figure 4.2 - Modified Crank

The motor was mounted in a horizontal manner to be able to fix it by its top and bottom ends. This measure was taken to hold the motor in a way that reduced the weight that was supported by the shaft due to the connected mechanism. This helped to spread the weight between two points instead of just one, as when the motor was vertically fixed. Also, the twisting moment created by the motor would be evenly distributed between these two points, decreasing the stress concentrated on the clearance holes of the servo and thus preventing the formation of premature fractures on the casing of the servo.

Figure 4.3 shows the modified crank mechanism and the motor setup for the device's final design.

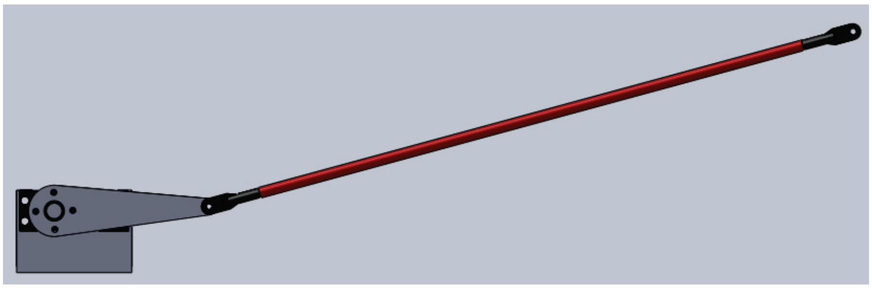

Figure 4.3 - Modified crank mechanism

40 x 40 aluminium angle bars (Figure 4.4) were used to support the motors. They were selected as a replacement of the solid blocks that were used on the first design. These angle bars were easily cut and drilled, and as a result the overall time and cost of the project was reduced. Also, in the case one of the supports became damaged, it could be easily replaced, as angle bars are widely available in hardware stores.

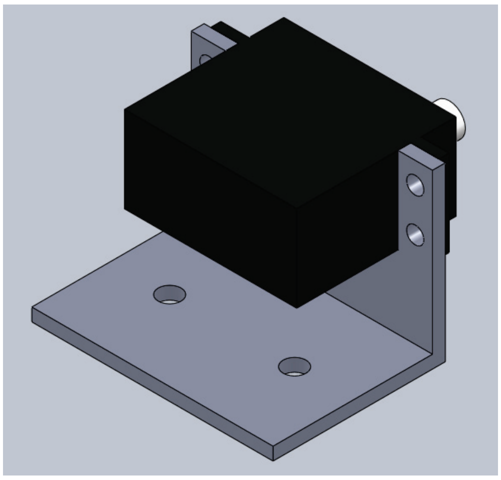

Figure 4.4 - Motor Support

4.1.3 Linear Guides

The original linear guide and block was provided by the mechanical workshop at the University of Sydney. Their operation was adequate for the requirements of the device, and they were able to move with very little friction and almost no misalignment.

Consequently, for the remaining three fingers, the same models were going to be acquired, but their high cost discarded them as a viable option.

Taiwanese guides and blocks were selected because they shared the same dimensions as the THK ones, and they were readily available in Australia at a low cost. The fact that they shared the same dimensions ensured that the designed model wouldn't have to be modified or adjusted to fit a different product.

The manufacturer was HIWIN and the models for the blocks and guides were MGN12CZ0CM and MGNR12R. Figure 4.5 shows a 3D model of one.

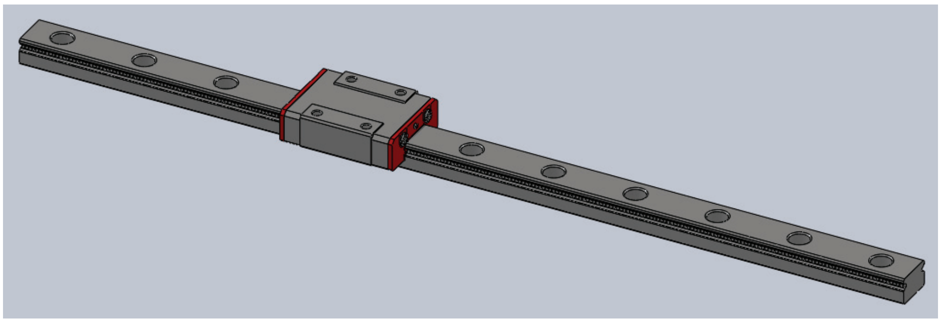

Figure 4.5 - HIWIN linear guide [69]

Instead of using columns to support the rails, Aluminium angle bars were used to reduce the manufacturing time and cost of having to produce customized parts. Two 100 x 100 angle bars (Figure 4.6) were used on each end of the rails and they were fixed by bolts to the device's base.

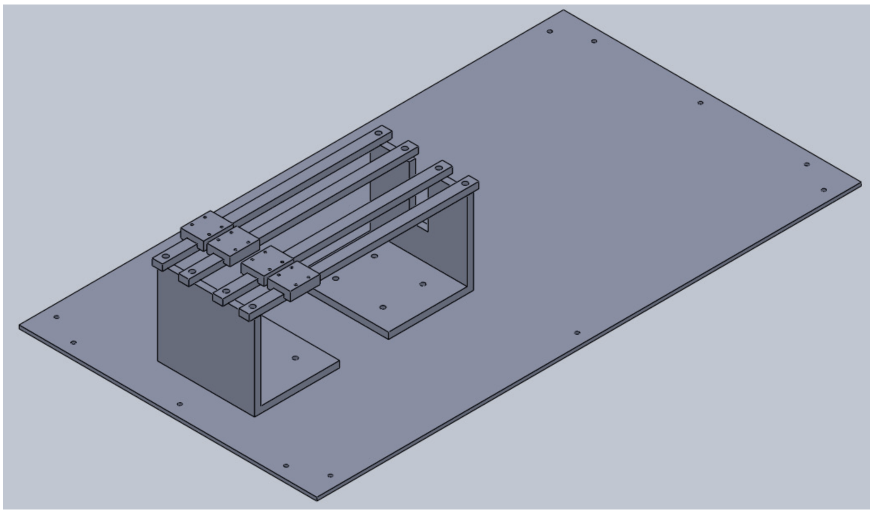

Figure 4.6 - Linear guides support

4.1.4 Fingers' Supports

The fingers' supports were modified to reduce their size and permit the simultaneous parallel motion of the four fingers. The main constraint to achieve this was the distance between fingers' edges, which in this case was based on anthropometry data of U.S. Army Personnel [61] and the designer's hand. The proposed distance between fingers' edges was 5 mm. This value represented a great challenge to the design of the fingers' supports, as there would have to be a really small gap between them.

The new design (Figure 4.7) was based on the previous support but the overall shape and components were simplified to allow manufacture from a single block of aluminium. On its base there were clearance holes to fit bolts that would fix it to the linear block, and it also had a lateral hole that would allow the ball link from the rod to be connected to it.

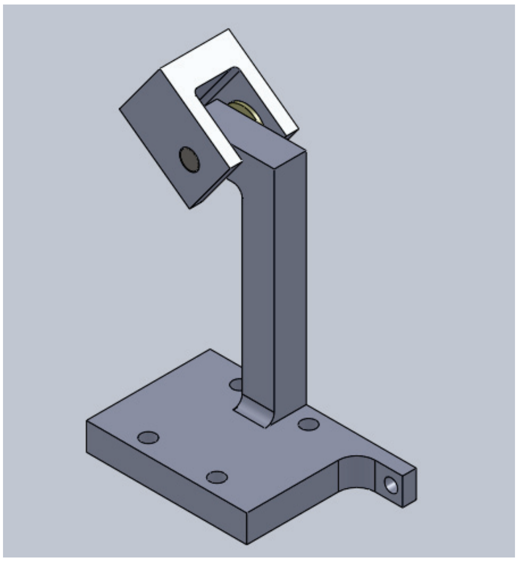

Figure 4.7 - Modified Finger Support 3D View

The tip support was elevated to avoid any contact between the patient's hand and the mechanism. A steel rod served as the connection link between the tip and the main support, and it was fixed by a set screw that held the rod in place. Between the aluminium parts, two steel washers were fitted to reduce the friction between them and to ensure smooth operation. A front view of this part is shown in Figure 4.8.

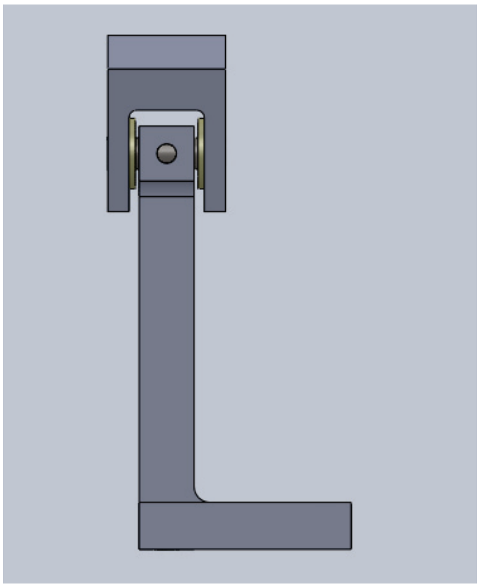

Figure 4.8 - Finger support front view

The area of the tip and the Velcro straps used in the previous system were unchanged, as they proved to be adequate to hold and support the fingers. The modified design allowed the finger to rotate a maximum of 180°, and as a result it increased the flexion angles of the involved joints somewhat compared to the previous design.

Four different parts (Figure 4.9) were produced for this system. Two of them were originals and the other two where only mirror images that enabled a connection to the ball link on the other side of their base. Their different shapes were created to maintain the 5 mm gap between fingers and to attach themselves to the linear guides. Also, to avoid stress concentrations due to sharp edges, a small radius was added to some of the corners of the parts.

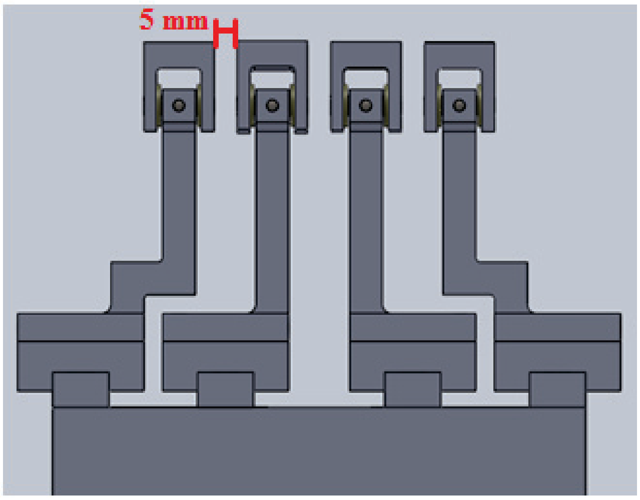

Figure 4.9 - Four supports (with 5 mm gap between them)

Due to their three dimensional outline, the parts were manufactured using a CNC (Computer Numerical Control) process instead of using ordinary tools from the workshop. This decision was made due to the complexity of fabricating these parts by hand, which at the end would result on a higher cost and production time for the system.

Because of the relatively low forces involved, it was decided that FEA[23] analysis of the stress in these components would not be necessary.

4.1.5 Cover and Base

The cover was made of clear acrylic to permit the user and therapist to look inside the system. This also helped to show the mechanism running while a patient was being rehabilitated, giving a clearer understanding of the parts and elements involved on the motion of the device. Figure 4.10 shows a 3D model of the part.

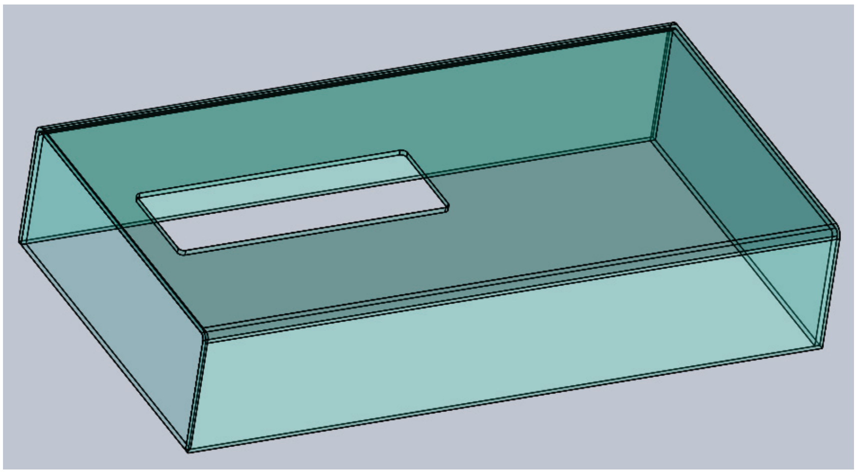

Figure 4.10 - Modified Cover

The cover consisted of three parts: the formed top and two side panels. The formed top was made from a single sheet of acrylic that was bent to create a strong single piece that would hold the arm of the patient. It also had a hole from which the fingers' supports would emerge to connect to the patient joints. The hole was the same length as the stroke of fingers' supports and the same width as the four parallel guides. Consequently, the arm and other parts of the patient's body would be isolated from the mechanism, reducing the chances of injury due to parts coming in contact with the crank and connecting rod.

[23] Finite Element Analysis

The side panels where glued on the inside of the cover top to add support and distribute the arm’s weight along different points of the assembly. As the workshop was not equipped to work with acrylic, all of the assembly was outsourced to a company that specialized on creating plastic products.

The base (Figure 4.11) was created using a 4 mm aluminium plate, which was strong enough to support the cover and the patient’s arm weight. On the edges of the base, 20 x 20 aluminium angle bars were fitted to hold the cover in place and to avoid misalignments due to external forces applied to the box. The angle bars were secured using bolts and nuts that fixed them to the base, and rubber feet were fitted on the bottom of the base to avoid any contact between the fasteners and the table onto which the device was to be positioned.

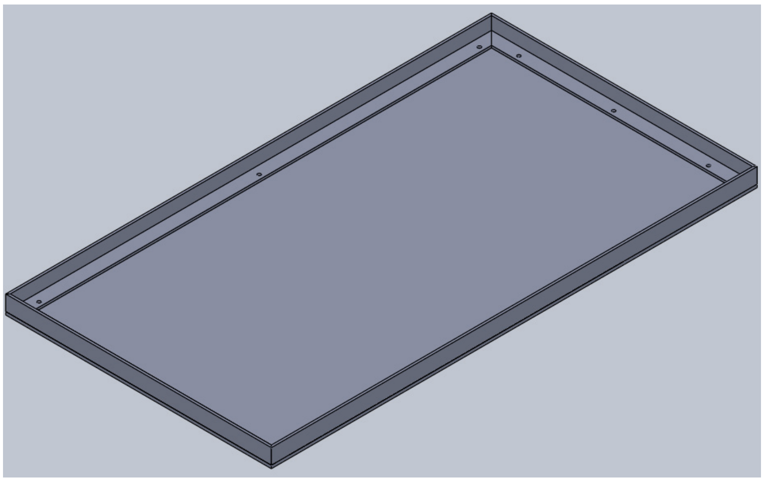

Figure 4.11 - Modified Base

The base and all of the angle bars were manufactured at the ACFR (Australian Centre for Field Robotics) mechanical workshop, and after they were finished, the whole system was assembled. A 3D model of the system’s final assembly is shown in Figure 4.12.

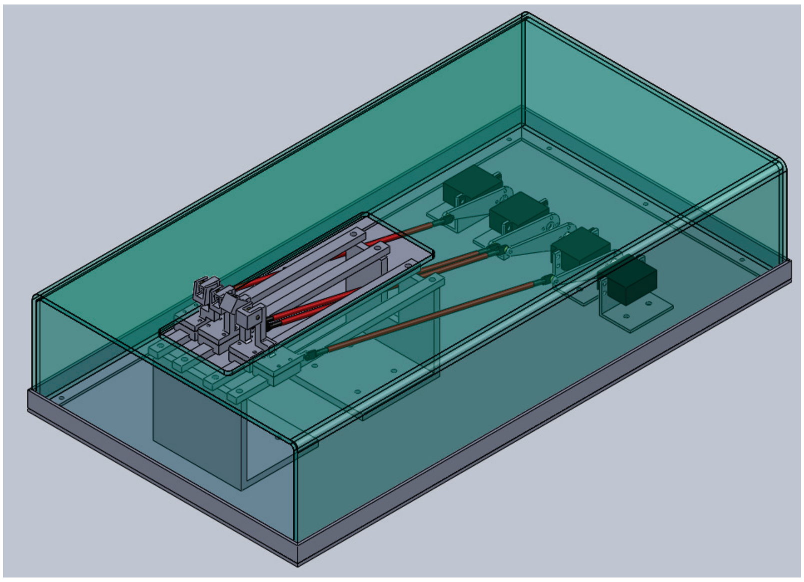

Figure 4.12 - 3D model Final Assembly

4.1.6 Software

As in the first prototype, LabVIEW was used to control the final design. As the number of motors was increased, the original program was modified to accommodate for these changes.

On the main window (Figure 4.13) a number of buttons were added to control the ON or OFF state of the different motors. This enabled an independent control of the servos, regardless of the selected mode of operation. A “Ready” indicator was also included to alert the therapist at the exact moment in which the device became available to use after pressing the “Start” button. In addition, the servos could still be reset to their centre position and the device and the application could still be turned off from this main window, using the “Restart”, “OFF” and “Exit Application” buttons, respectively.

Figure 4.13 - Main window LabVIEW

The status indicator (Figure 4.14) was also modified to include the new motors and their current values (Pulse Width, Angle, Max. and Min.). The manual and automatic steps and the current mode of operation were also displayed to indicate the general state of the device.

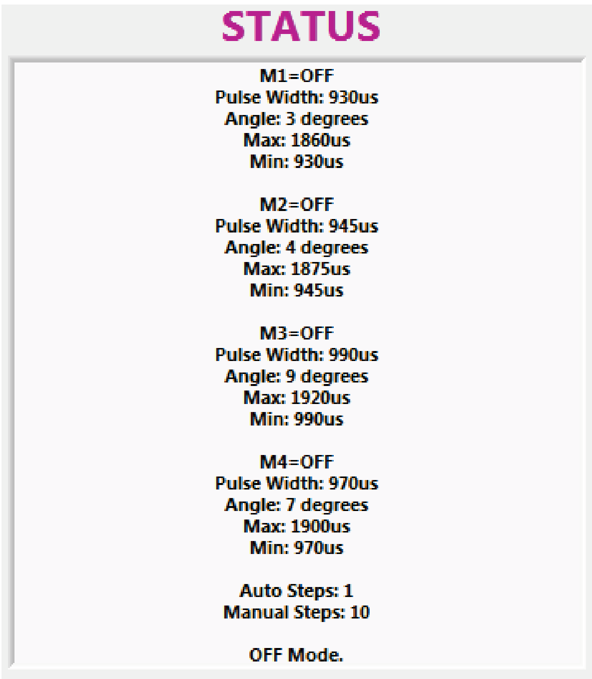

Figure 4.14 - Modified Status indicator

The Setup tab remained unmodified and the maximum and minimum limits of each servo could be set depending on the servos that were activated at the time of pressing the “Set Max” or “Set Min” buttons. Each servo could be programmed to different and independent limits, to make the device’s motion consistent with the length of the user’s fingers.

The Manual tab was not modified, and the position of each servo could still be changed by pressing the “Increase and Decrease” buttons. In addition, the “Manual Steps” could still be customized if the therapist wanted to move the fingers faster or slower, depending on each patient’s condition.

The Automatic tab (Figure 4.15) remained the same except for two new modes that were included in the program, the “1-2-3-4” and the “4-3-2-1” mode. Instead of moving all the fingers at the same time as with the Automatic Mode, these routines enabled the therapist to select the order in which the fingers will move. On the “1-2-3-4” mode, the index finger started moving first and the other fingers would follow in an orderly manner, separated by a distance set by the Arduino program. After the index finger reached its maximum limit, its controlling servo was halted to wait for the next finger to arrive to its limit and so on. After all the fingers had reached their maximum limit, the index finger started to move towards the minimum limit and the other fingers followed one by one. The “4-3-2-1” did exactly the same but the little finger was the first one to move and the others followed, again, each separated from the next one by a value set on the Arduino board.

The Automatic Steps could still be modified to increase the velocity of the linear carts depending on the user’s needs. And a default maximum and minimum limit for these steps was programmed in the Arduino board to prevent the therapist from using the automatic modes in a speed that could potentially damage the patient’s fingers.

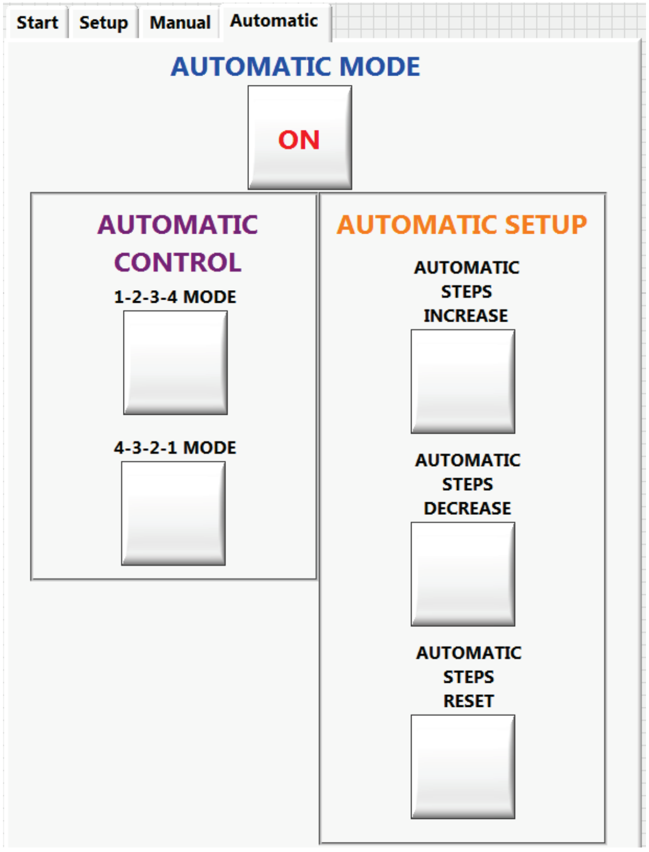

Figure 4.15 - Modified Automatic Tab

4.1.7 Electronic Components

As a result of having three more servos, the number of digital outputs from the Arduino was increased and the current capacity of their power source was augmented. The new power source was capable of delivering 30 amperes at 5 Volts, this was sufficient to control the motors, as the maximum current consumption of all the servos was 14 amperes. All of the motors were still controlled by PWM and powered by an external source.

The general electrical schematic is shown in Figure 4.16.

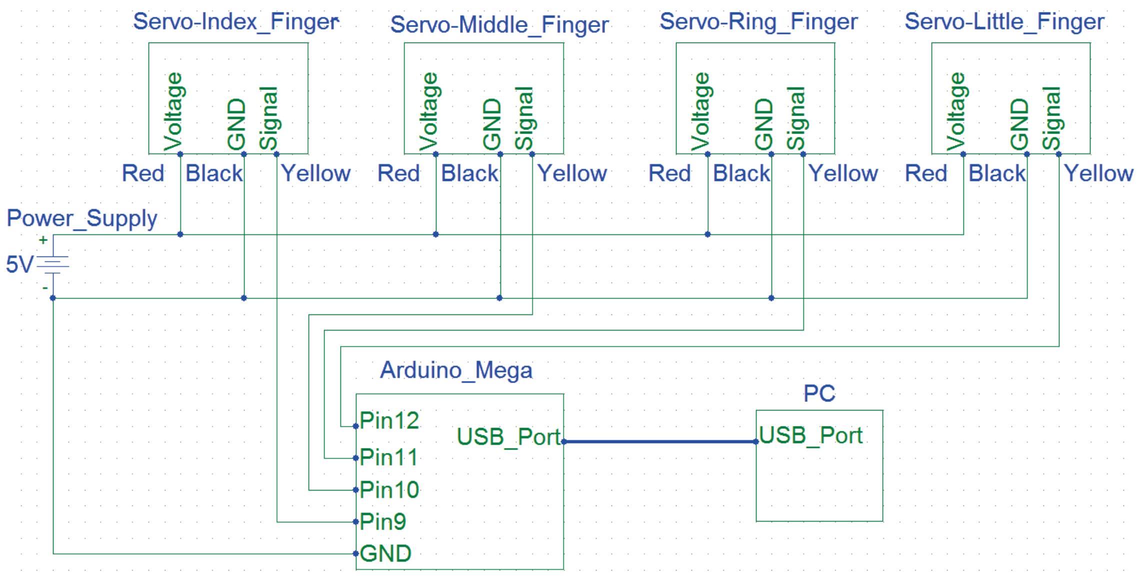

Figure 4.16 - New Electrical Schematic

The power source and all the connectors were placed outside of the device to prevent any disconnection and to avoid any electrical discharge if a cable touched the patient's arm.

Chapter 5 Results and Discussion

As with the first prototype, the device was tested on the designer's hand. All of the fingers except for the thumb were attached to the supports to operate the device on its different modes. Figure 5.1 shows the final prototype.

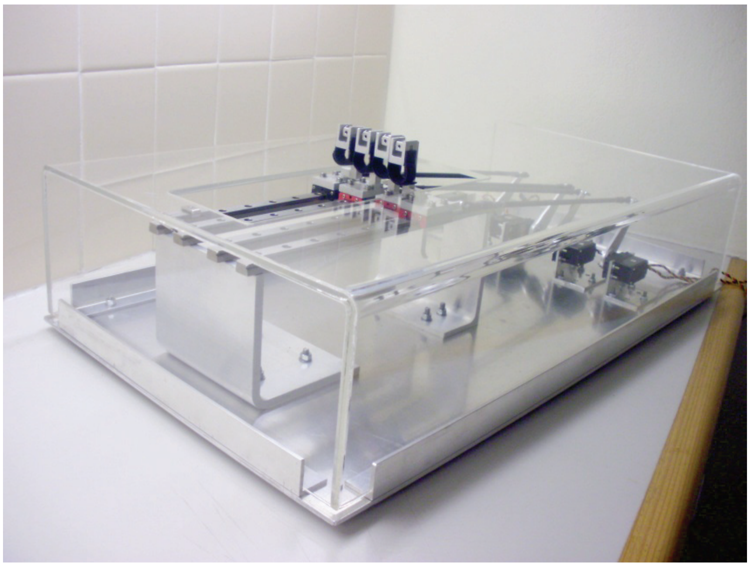

Figure 5.1 – Final design

Figure 5.2 shows a top view of the device.

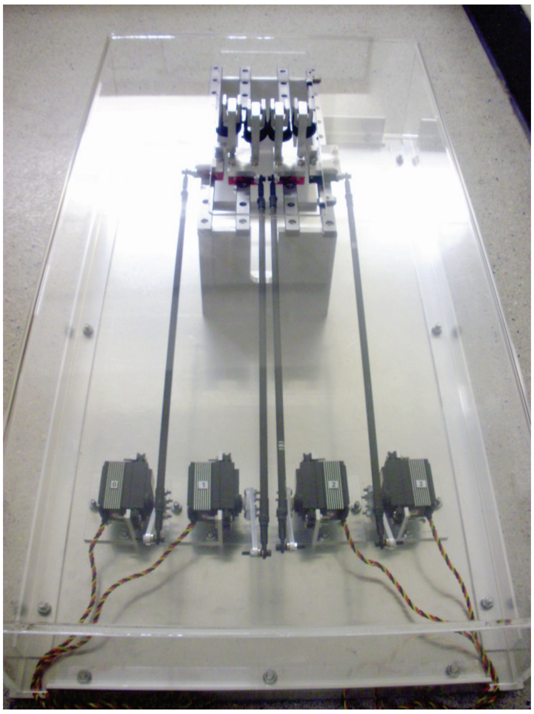

Figure 5.2 - Top view final design

As the device does not actuate the thumb, the user is able to attach their right or left hand without any modification to the mechanical components. This enables possible rehabilitation of the two hands with only one device, giving more flexibility to its functionality. Figure 5.3 shows a front view of the rehabilitation device.

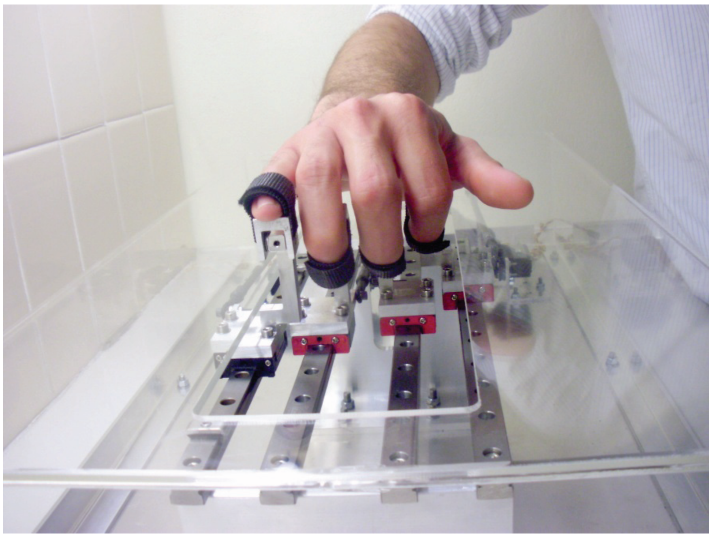

Figure 5.3 - Front view final design

The arm was still rested on foam blocks (sitting on the device's cover), which served as a support for the forearm (Figure 5.4). The cover was manufactured from clear "Perspex" to enable the user and therapist to see the inside of the device, making it easier for them to understand the way the fingers are actuated and to assure them of the safety and simplicity of rehabilitating the extremity with an orthotic device of this type.

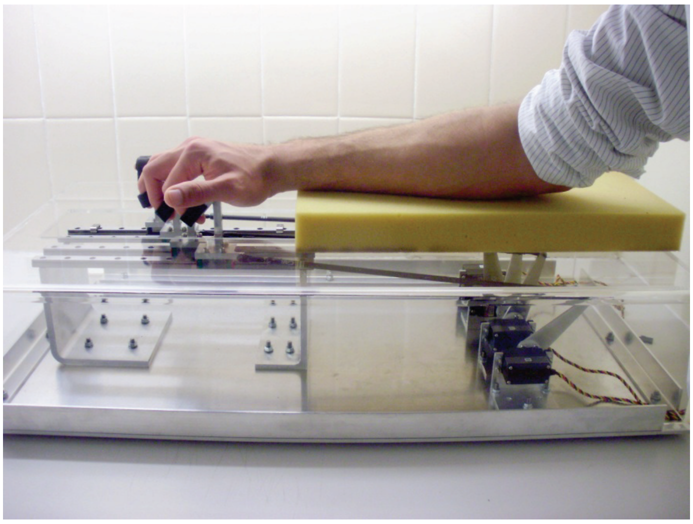

Figure 5.4 - Supported forearm and fingers

The slot in the cover from where the finger's supports were able to stand out had an appropriate size for the supports to complete their full stroke without crashing against the cover (Figure 5.5). Also, as its dimensions were the same as the total rails' widths and lengths, the possibility of foreign objects interfering with the fingers motion was reduced.

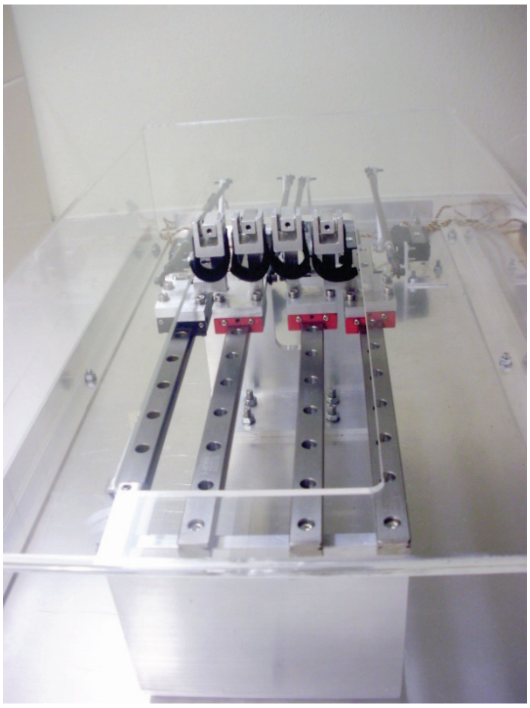

Figure 5.5 - Final Cover

The cables from the servos exited the device trough the space between the base and the cover, eliminating the need to create a new hole in the cover to serve the same purpose. This was done to reduce the chances of stress concentration around that hole due to the weight of the arm.

After being programmed the digital servos were capable of moving 180°, achieving a maximum final stroke of 152.36 mm on each finger. As a result of the dimensions of the offset crank mechanism, the complete 180° was not used. After 168°, the cart started to reverse as the push rod started to pull instead of pushing. This was an expected behaviour as the mechanics of the crank were studied on the Solid Works model. The only way to reduce this effect would be to use a simple crank mechanism or to change the height difference between the servos and the rails. These options were not feasible, as the current height difference prevented the push rods interfering with the cover, and the mechanism dimensions were already the optimal ones for this design.

As the minimum and maximum limits for the pulse width of the motors were 900 and 2100 microseconds, this resulted in a total stroke requirement of 1200 microseconds. The Arduino's digital output resolution by default was 1 microseconds and because a 180° motion was now possible, the minimum motor step increased to 0.15°.

At 5 volts each motor was capable of exerting a maximum torque of 1.84 Nm. Using the 0.075 meter crank as the lever arm, the maximum pushing and pulling force on the finger supports was 24.53 N. This force proved to be sufficient to flex and extend the different fingers of the hand simultaneously or independently.

While testing the device the total current consumption was measured to be 5A, even when a force was applied to prevent the carts from moving. As a result, the power source capacity could be reduced if future testing on disabled patients proved the same effect.

The maximum flexion angles that were achieved on the different fingers are presented in Table 5.1. These angles were measured by analysing different images of the fingers in motion using Solid Works. It is important to note that all of these angles are approximations and are subject to visual error while analysing the images. Also, depending on the size of the patient's fingers and arm these values could vary. Consequently, in the future a more accurate method to measure these values should be developed to ensure more reliable results.

Joint	ROM joint limits (Degrees) [57]	First Prototype Index finger achieved flexion (Degrees)	Final Prototype Index finger achieved flexion (Degrees)	Final Prototype Middle Finger achieved flexion (Degrees)	Final Prototype Ring Finger achieved flexion (Degrees)	Final Prototype Little Finger achieved flexion (Degrees)
MCP	90	**25**	54	59	57	45
PIP	115	**85**	88	86	83	87
DIP	90	**45**	35	28	26	42

Table 5.1 - Flexion angles four fingers

As shown in the table the MCP joint increased by more than twice its flexion angle, compared to the first design. The PIP values remained almost the same and the DIP value decreased. All these variations are a result of the fingers' supports design, which for the final device were capable of rotating 180° instead of the original 130°. This increase resulted in more flexion for the MCP joint as predicted by the 3D model. However, the DIP was still below its maximum angle, but this could be improved by increasing the rotation angle of the fingers' supports further. In the future, if the support was capable of achieving 270°, the flexion of all the joints would be closer to their maximum values. Figure 5.6 shows how the four fingers are actuated simultaneously using the Automatic Mode.

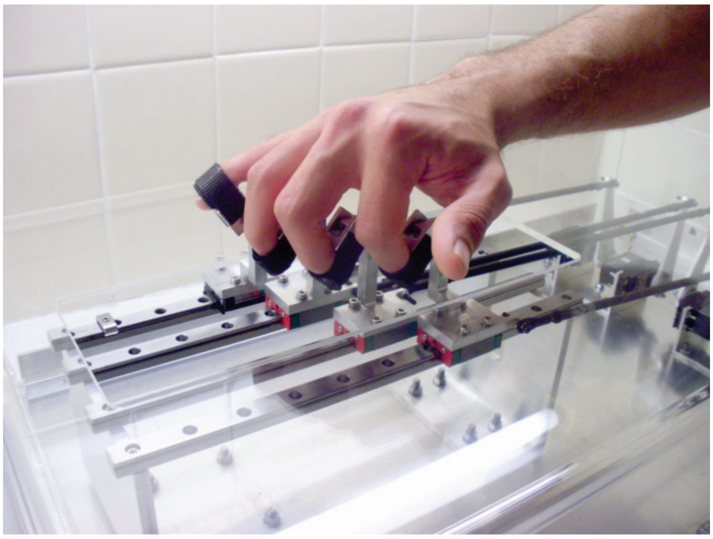

Figure 5.6 - Four fingers actuated at the same time

The ball links operated with minimum friction and misalignment. Consequently, this permitted the smooth operation of the device and continuous movement of the finger supports. Also, the carbon shafts prevented any bending of the rods even when the maximum torque was transmitted from the motors to the carts. Figure 5.7 shows a detailed view of these components.

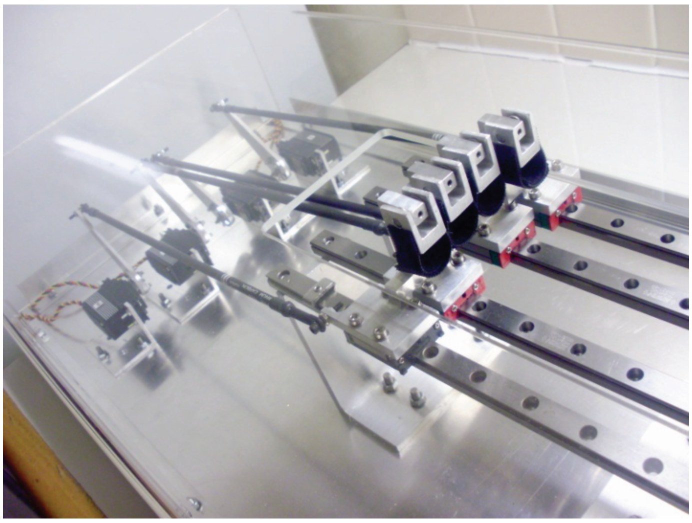

Figure 5.7 - Push rods and ball links

All of the functionalities and modes of the device were tested to ensure a safe operation of the system. All of the fingers were attached to the device using Velcro straps that proved to be sufficient to hold them in place and actuate them (Figure 5.8). As with the first prototype, moving the fingers without reading any feedback from their position, proved to be sufficiently accurate for the proposed motion of the fingers, as the overall finger motion from a minimum to a maximum limit was the main focus of the project.

Figure 5.8 - Velcro finger supports

Chapter 6 Conclusions and future work

Creating a low cost rehabilitation device for the hand was the main purpose of this thesis. This objective was successfully met, as the final design was capable of independently actuating four fingers that consequently permitted the flexion and extension of their joints. Also, the speed of the servos could be modified depending on the user's needs, and the supports' Velcro straps were capable of attaching fingers with different shapes and sizes, allowing men and women to be rehabilitated with the same device.

The system was tested in a healthy subjected and all of the modes worked as expected, the future challenge would be to test the device in disabled patients that should have less mobility on their joints and to investigate the impact of using this system on their recovery process.

One of the main advantages of this design was that the patient could potentially rehabilitate either hand without the need to change the device's configuration. Nevertheless, a thumb actuator would need to be implemented if the system was to be used to rehabilitate the whole hand of disabled patients. This would add more complexity to the design as the actuator would have to be relocated or reconfigured ever time a patient changed from left to right hand or vice versa.

The constraint of building a low cost system was one of the main factors that affected the final design of the orthotic device. As a result, a crank mechanism was implemented as the driving method because of its simplicity and ease to manufacture. However, without such a constraint, a linear actuator could reduce the overall size of the device and decrease the number of joints and elements of the system. Consequently, it could ensure a direct mean of actuating the device without the need of using rods and cranks. Also, the linear actuator could connect to the Arduino board to read the current position of the carts without the need of acquiring linear transducers or rotating encoders.

The wrist and arm support would need to be modified before going into testing in a hospital environment. At the moment of completion the foam blocks were not capable to prevent the patient from moving their upper extremity in such a way that could disconnect the fingers from their moving supports.

Force sensing resistors were going to be used but because of time constraints, they could not be implemented on the final prototype. These sensors should be part of the future design to enable the implementation of an Active and Interactive mode. These modes could use the efforts of the patients, to move their fingers with the aid of the servos, allowing a more complete rehabilitation program and possibly increasing the chances of recovery. Also, if these new modes were to be implemented a position feedback element needs to be installed to be able to read and use the location of the fingers to ensure closed loop behaviour of the system.

The LabVIEW program needs to be modified to handle the possible errors due to malfunctions of the system. In addition, a complete plan to deal with these errors needs to be created to prevent user injuries or permanent damage to the equipment. Also, the new modes need to be programmed in both the Arduino and LabVIEW program to enable their modified functionalities and inputs.

In terms of the electronic components and controllers, the following changes should be applied to the future design, to ensure a safer operation:

- Include at least three “Emergency Stop” buttons that could potentially disconnect the system from its power source and prevent the servos from moving any further. Two of these buttons should be located on both sides of the device, for easy access if the patient needed to activate them. And the other one should be next to the therapist operating the device, in case he needed to suddenly stop the operation of the system.
- Create a circuit board to distribute the power and signals to the servos in a permanent way, instead of using temporary connectors.
- Contain the circuit board, power source, cables, and Arduino in a custom plastic box to prevent any disconnection or hazards to the user.
- Acquire or create a small power source capable of delivering the necessary power to all of the electronic components.
- Install a “Ground” cable connected to the device’s cover and base to prevent any shock hazard.
- Install a fuse to protect the electronics of the system.

Overall the functionality of the device was satisfactory and it proved to be a starting point for creating an upper limb robotic rehabilitation system. These device and thesis could serve as an example of the introduction of automation technologies in the health industry that could potentially lead to a technological revolution, which could use the benefits of these “Biomechatronic” systems to increase the rate of success of rehabilitation programs applied all around the world.

Chapter 7 Appendix

A CD-ROM is attached to this thesis. It includes:

- Mechanical drawings.
- 3D models.
- LabVIEW programs.
- Arduino programs.
- Photos and Videos of the prototypes.
- Electrical schematics.

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