MASTERS DISSERTATION

MECHANICAL DESIGN OF A LOWER LIMB EXOSKELETON FOR REHABILITATION OF PARAPLEGIC PATIENTS

Nasiru Adamu Marafa

MASTERS DISSERTATION IN MECHATRONIC SYSTEMS
DEPARTMENT OF MECHANICAL ENGINEERING
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Masters Dissertation Submitted to the Department of Mechanical Engineering as a Partial Requirement for Obtaining the Degree of Master in Mechatronic Systems

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Dedication

This works is dedicated in its entirely to my beloved Father, Alhaji Adamu Marafa. In November 2017, while still in Brazil, I received a call from Nigeria, and was informed that my father was admitted into a hospital in my city, Bauchi, Bauchi State of Nigeria. His admission into the hospital was due to problems related to spinal cord injury (SCI), and in which he lost movements in his left leg and left arm, which were identified at that moment to be temporary. I wish you a quick and a speedy recovery Dad, In Sha Allah.

Nasiru Adamu Marafa

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I would like to thank the Brazilian Government for the opportunity given to me to study in Brazil. In 2011, I arrived in Brazil to study Mechatronics Engineering at the University of Brasilia (UnB), where I graduated as a Control and Automation Engineer. In August 2018, I also had the opportunity to get accepted as a master student in the program of "Mechatronic Systems"from the Department of Mechanical Engineering (UnB). Without the first opportunity, all the achievements I have earned in my undergraduate and graduate levels wouldn't have became possible. At this point, I would also like to extend my appreciation to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for all the financial supports they have offered me during the program which helped a lot in making my research successful. I am immensely grateful for that.

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Nasiru Adamu Marafa

RESUMO

Os exoesqueletos de membros inferiores são robôs vestíveis para membros inferiores, vestidos por operadores humanos para diversas aplicações, tais como: aumento de força, reabilitação, assistência terapêutica, entre outras. Este trabalho apresenta o projeto mecânico de um exoesqueleto de membros inferiores para reabilitação de pacientes paraplégicos. O projeto mecânico proposto pode suportar um usuário de até 1,78 m de altura e 100 kg de peso respectivamente. A estrutura final consiste em cinco graus de liberdade (5DOF) por perna (2 no quadril, 1 no joelho e 2 no tornozelo). Todos os 5DOF são feitos de juntas rotativas, duas juntas ativas (1 no quadril e 1 no joelho) e três juntas passivas (1 no quadril e 2 no tornozelo). Considerando que os usuários têm movimentos nas mãos, o uso de muletas ou andadores é necessário. Um conjunto de quatro estados de operações para o projeto final também é proposto (sentar-se, levantar-se, caminhar, parar).

O trabalho começa com uma revisão sistemática da literatura e uma análise bibliométrica, na qual os documentos com maior relevância para o tema foram analisados e escolhidos como base para o projeto. Para selecionar componentes adequados para o produto final, foram feitas análises dos cinco componentes de um sistema biomecatrônico de exoesqueletos de membros inferiores, incluindo: mecanismos, atuadores, sensores, controle e interação homem-robô, de vários projetos. Os requisitos do projeto mecânico e a seleção do material para o projeto também foram estabelecidos considerando as propriedades antropométricas do corpo humano da população brasileira, tais como: altura média, peso, velocidade entre outras. Restrições nas juntas e torques de marcha para reabilitação também foram definidos. As condições críticas do exoesqueleto, estáticas e dinâmicas foram modeladas e resolvidas analiticamente para critérios de falha estática e rigidez. Usando um software de projeto auxiliado por computador (CAD), o projeto da estrutura mecânica do exoesqueleto robótico foi subdividido em cinco partes principais, que são: suporte para as costas, atuação, elos, articulações do tornozelo e montagem do protótipo. Os resultados foram discutidos e validados. Finalmente, conclusões do projeto foram feitas e alguns trabalhos futuros foram identificados. Um dos focos principais deste projeto é uma solução de baixo custo do produto final.

Palavras Chaves: Exoesqueleto de membro inferior, Projeto mecânico, Reabilitação, Paraplégico.

ABSTRACT

Lower limb exoskeletons are wearable robots for lower limbs, won by human operators for various applications, such as: force augmentation, rehabilitation, therapeutic assistance, among others. This work presents a mechanical design of a lower limb exoskeleton for rehabilitation of paraplegic patients. The proposed mechanical design can support a user up to 1.78m in height and 100kg in weight respectively. The final structure consists of five degrees of freedom (5DOF) per leg (2 at the hip, 1 at the knee and 2 at an ankle). All the 5DOF are made of revolute joints, two active joints (1 at the hip and 1 at the knee) and three passives joints (1 at the hip and 2 at an ankle). As users are considered to have movements in their hands, the use of crutches or walkers is required. The set of operational states for the final design are also proposed to be four (Sit-down, Stand-up, Walk, Stop).

The work starts with a systematic literature review and a bibliometric analysis, in which, documents with the highest relevance to the topic were analyzed and chosen as the basis for the design. To select adequate components for the final product, analyses of the five components of a biomechatronic system of lower limb exoskeletons including: mechanisms, actuators, sensors, control and human-robot interaction, from various projects were made. Mechanical project's requirements and material selection for the design were also established considering anthropometric properties of human body of the Brazilian population such as: average height, weight, speed among others. Joints restrictions and rehabilitation gait torques were also defined. The exoskeleton's critical static and dynamic conditions were modeled and solved analytically for static failure and stiffness criteria. Using a computer aided design software (CAD), the design of the mechanical structure of the robotic exoskeleton was subdivided in to five main parts, which are: back support, actuation, links, ankle articulations and prototype assembly designs. Results were discussed and validated. Finally, project conclusions were made and some future works were identified. One of the principal focuses of this project is the low cost solution of the final product.

Keywords: Lower Limb Exoskeleton, Mechanical Design, Rehabilitation, Paraplegic.

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GLOSSARY

BDTD	Digital Library of Theses and Dissertations
BES	Bio-Electric Signal
CAD	Computer Aided Design
CAPES	National Council for Scientific and Technological Development
CE	Costumer Electronics
CG	Center of Gravity
cHTI	Cognitive Human-Robot Interaction
CNPq	National Council for Scientific and Technological Development
CTD	Catalog of Theses and Dissertations
DOF	Degree(s) of Freedom
EEG	Electroencephalogram
EMG	Electromyography
FAPDF	Federal District Research Support Foundation
FDA	Food and Drugs Administration, United States
HMI	Human Machine Interface
IBGE	Brazilian Institute of Geography and Statistics
MPSoC	Multi-Processor System on Chip
pHRI	Physical Human-Robot Interaction
RAP	Robot-Assisted Physiotherapy
SCI	Spinal Cord Injury
SEAs	Series Elastic Actuators
TD	Technical Drawings

1 INTRODUCTION

Movement is one of the most important characteristics of living organisms. Under normal circumstances, every human being is expected to move freely from one place to another without any difficulty. Whenever a person decides to move, the brain sends command signals through the spinal cord down to the nerves and down to the muscles. As a result of this signals transmission, the legs get the ability to carry out the required movements. For patients with spinal cord injuries, these signals are interrupted before reaching the muscles, and as such, they cannot complete the intended movements or cannot even begin the movements in critical conditions, resulting into a motor disability commonly known as either: *monoplegia*, *hemiplegia*, *paraplegia* and *tetraplegia*.

A motor disability is defined as a physical or motor dysfunction that can impede movement, coordination or sensation, which may be congenital or acquired. The acquired forms of motor disability are mostly caused by traffic accidents, accidents at work places, medical errors, war, violence, malnutrition and even with the increasing age. Some types of motor disabilities are the followings: *monoplegia* (paralysis of only one body member), *hemiplegia* (paralysis of half of the body), *paraplegia* (paralysis from the waist down), *tetraplegia* (paralysis from the neck down), and *amputation* (missing a body member). In this work, the main focus is paraplegia in which the patients are considered to have movements at their hands and their trunks.

According to the World Health Organisation (WHO), the number of people aged 65 or older is projected to grow worldwide from an estimated 524 million in 2010 to nearly 1.5 billion in 2050, an increase of roughly 186% and mostly in developing countries (Who, 2020). This increase in elderly population is driven by falling fertility rates and remarkable increases in life expectancy around the globe. In Brazil for example, according to the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística IBGE*),(IBGE, 2019), the life expectancy at birth for Brazilians was 76.3 in 2018, which is approximately 3 months and 4 days more than it was projected in 2017 (76 years), an increase of about 0.4%. This estimate has been growing since 1940 when the life expectancy of Brazilians at birth was only 45.5 years. Therefore, Brazilians of today live on average of 30.8 years longer than in the middle of the last century. This helps in increasing the number of people with motor disabilities in Brazil and in the World at large.

The number of paraplegic patients is increasing worldwide. For instance, in the United States alone, there are approximately 5.6 million paraplegic people, which is equivalent to 1.9% of the total US's population (Christopher & Dana, 2019). In Brazil, in 2018, about 6.7% of the Brazilian population showed some type of disability (Lailla et al., 2018), and it is our belief that, a big part of this population consists of paraplegic patients. Due to this limitation, many people have lost their work and some even lost the hope to walk again, a condition which exclude many from the real society.

To include these people back into the society, and to restore their lost hope of walking again, Therefore, there is an urgent need to provide means by which these people will be included back into the society. However, lower limb exoskeletons are wearable robots designed for lower limbs, and are worn by human operators for various purposes, such as for: (a) *human force augmentation*, (b) *rehabilitation application*, (c) *therapeutic assistance*, among others. Therefore, A mechanical structure of a lower limb exoskeleton for rehabilitation of paraplegic patients is proposed, it can later be controlled and automated.

The proposed mechanical design of the lower limb exoskeleton consists of a 5 degrees of freedom (5DOF): 2 active joints (1 at the hip and 1 at the knee) and 3 passive (1 at the hip and 2 at an ankle). As the users are considered to have movements in their hands, the use of crutches or walkers is required in order to maximize the users equilibrium. The set of operational states of the final design are also proposed and are considered to be (Sit down, Stand up, Walk, and Stop). One of the important focus of this project is the low cost solution of the design.

1.1 MOTIVATION

A literature review analysis showed a research gap in the area of Exoskeletons in Brazil. There was no domestic manufacturer found and the few academic works encountered were carried out mostly at the University of São Paulo (USP) and also at the University of Campinas (UNICAMP). Here at the University of Brasilia (UnB), this work happens to be the first initiative research on exoskeletons, and it is been funded by: FAPDF(*Fundação de Apoio a Pesquisa do Distrito Federal*), CNPq (*Conselho Nacional de Desenvolvimento Científico e Tecnológico*) and CAPES (*Coordenação de Aperfeiçoamento de Pessoal de Nível*) managed by the Brazilian Government.

Due the social impacts that exoskeletons have on humanity, especially, their rehabilitation applications for people with paraplegia, we felt very motivated to carry out this research, especially with the evolution in the area of control, instrumentation and sensing technologies. Finding good results from these researches may motivate domestic manufacturer to take the challenge of producing domestic products since the foreign ones remain expensive and not easily accessible. The first resulted prototype was developed at Laboratory of Embedded Systems and Integrated Circuits Applications (LEIA) located at the *Grupo de Automação e Controle* (GRACO) of the Faculty of Technology (FT) of the University of Brasilia, (http://www.graco.unb.br/). This prototype was designed for the lower limb application in rehabilitation context.

Some of the challenges encountered during the realization of this work migh be linked to being the initial work in the area with almost no material on ground. Another challenge was the acquisition of the necessary materials for prototyping within the Brazilian borders, such as the motor drive units among others. The Coronavirus pandemic has in some way affected the efforts in completing the first prototype as social distancing became necessary. This is because, going to the laboratory was also restricted.

1.2 GENERAL OBJECTIVE

The general objective is to design a mechanical structure of a lower limb exoskeleton for rehabilitation of paraplegic patients considered to have movements in their hands that enable them to use crutches or walkers.

1.3 SPECIFIC OBJETIVES

- To clearly define the formulated problem: that is, the mechanical design of a lower limb exoskeleton for rehabilitation of paraplegic patients, targeting Brazilian population.
- To perform a systematic literature review, in order to obtain the most relevant documents either in English or Portuguese related to the formulated problem and which include: books, articles, revised articles, dissertations, theses and online sources.
- To perform an analysis of biomechatronic components of lower limb exoskeletons, which include: mechanisms, actuators, sensors, control and human-robot interactions, in order to select adequate components of the final mechanical structure.
- To establish the exoskeleton's mechanical design requirements by analyzing the physical characteristics of the Brazilian population such as biomechanics of walking, average weight, average height, average walking speed, among others.
- To draw the mechanical design's components (back support, actuation, links, ankle articulations and final prototype assembly) using CAD software. And to also present the technical drawing of these components with their dimensions for possible prototype construction.
- To construct and test the first prototype of the mechanical structure.

1.4 PRESENTATION OF THE DISSERTATION'S CHAPTERS

This Masters Dissertation consists of seven chapters, appendixes and bibliographic references. It is written, organized and presented as follows:

- In Chapter 1, an introduction, contextualizing the subject matter, the general objective and specific objectives of this work were presented.
- In Chapter 2, a systematic literature review analysis using five databases, which are: Web of science, Scopus, IEEE Xplore, *Catálogo de Teses e Dissertações (CTD)*, and *Bibilioteca Digital de Teses e Dissertações (BDTD)* is presented. The analysis of the best "top 10": (a) most prominent research areas, (b) most highlighted research countries, (c) sources with the highest register of documents and (d) most cited documents and journals with the highest

number of publications related to the topic are discussed. Also, a bibliometric analysis is presented. in this case, a *VOSviewer* tool and *TagCrowd* are used to analyze Co-citation, Co-authorship Bibliographic coupling and Keywords Co-occurrence. Finally, some projects from the literature review are selected and discussed.

- In Chapter 3, components of the biomechatronic system of lower limb exoskeletons, such as: Mechanism, Actuators, Sensors, Control and Human-Robot Interaction are analyzed. Therefore, in Mechanism: metabolic cost, biomechanics of walking, average human walking speed, mechanics of human movements and a Denavit-Hartenberg of a human leg are discussed. In Actuators: electric motors, hydraulic or pneumatic actuators, pneumatic muscle actuators and series elastic actuators (SEAs) are analyzed. In Sensors and Control, different types of sensors and control strategies of lower limb exoskeletons are analyzed. In Human-Robot interaction, physical and cognitive human-robot interactions are discussed.
- In Chapter 4, project requirements and material selection are established. In this case: height, weight, waist diameter, links lengths, foot length and width of the final design are dimensioned. Number of degree of freedom and joint restrictions are also established. Movements at the hip, knee and at the ankle joints are analyzed. Requirements for the actuators (motors), power, torque, angular velocity, reduction ratio and power supply required to move the exoskeleton are presented.
- In Chapter 5, mechanical design of the robotic exoskeleton is presented in five subsections: back support, actuation, links, ankle articulations and final prototype assembly. In this case, a computer aided design software was used for the modeling of parts of the exoskeleton.
- In Chapter 6, discussion on the mechanical structure of the first prototype is presented.
- In Chapter 7, conclusions and some of the identified future works are presented.
- In Appendix, Other information related to this work, and technical drawings (TDs) of the mechanical structural parts are presented.

2 SYSTEMATIC LITERATURE REVIEW AND BIBLIOMETRIC ANALYSIS

2.1 INTRODUCTION

One of the most important steps in scientific research is a literature review, where the search for documents that are most relevant to a subject is raised. A systematic literature review is defined as a scientific research method that brings together relevant studies on a formulated question, using the literature database that deals with that question as a source and method for *identification*, *selection* and *systematic analysis*, in order to perform a critical and comprehensive literature review. A systematic literature review identifies, selects, and critically appraises researches in order to answer a clearly formulated question (Dewey and Drahota, 2016) and (Mariano and Rocha, 2017). In this chapter, a methodology is introduced to carry out the search process which includes the choice of databases and the use of tools such as *VOSviewer* and *TagCrowd* to perform further analyses of the documents obtained during the search process.

Over 100 years ago, many research papers that are related to rehabilitation of people with motor disabilities were published, most of which only focused on *prostheses* and *orthoses*. In recent years, robotic exoskeletons have conquered a huge space in the literature, and have led to many innovations and scientific publications from different parts of the world. Exoskeletons are used for various applications, such as for (a) human force augmentation, (b) rehabilitation or (c) therapeutic assistance. There are basically: (a) *upper limb* exoskeletons which are designed to supplement upper body member, and (b) *lower limb* exoskeletons designed to supplement lower body member. In this work, only lower limb exoskeletons are considered. The literature review focused on two main axes: (a) commercial product (which analyzed exoskeletons in the market for commercial sells) and (b) academic publications (where the search method for academic publications in the literature was applied).

The search method was applied to the question formulated as: “Mechanical Design of a Lower Limb Exoskeletons for Rehabilitation of Paraplegic Patients”. Five databases were chosen for relevant documents search which are: (1) Web of science, (2) Scopus (Elsevier), (3) IEEE Xplore, (4) *Catálogo de Teses e Dissertações (CTD)*, and (5) *Bibilioteca Digital de Teses e Dissertações (BDTD)* of CAPES (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*) managed by the Brazilian Government. All the results presented in this report were obtained on December 31, 2019 (These results must change with time as the number of publications in these databases continue). The choice of *Catálogo de Teses e Dissertações* and *Bibilioteca Digital de Teses e Dissertações* was made to explore the works done related to lower limb exoskeletons within the Brazilian Institutions. The number of selected databases does necessarily need to be five, it can be less or more depending on researchers convenience.

To make the review reproducible, updatable and continuous, a literature review protocol was created (see Appendix I). An exploratory analysis of the obtained documents (section 2.3.2), aims at exploring the general idea of the total number of publications available in the selected databases that are related to the field of rehabilitation. Results from the exploratory analysis were further refined in the secondary analysis (section 2.3.3), and are presented analyzing the best “top 10”: (a) the most prominent research areas, (b) the most highlighted research countries, (c) sources with the highest register of documents, (d) the most cited documents, and (e) journals with the highest number of publications from only *Web of science* and *Scopus* databases. In the bibliometric analysis, *VOSviewer* tool was used for *co-citation*, *co-authorship* and *bibliographic coupling* analyses while *TagCrowd* was used for *keywords co-occurrence* analysis.

2.2 COMMERCIAL PRODUCTS

A market analysis showed that, in recent years, many companies around the world are already manufacturing exoskeletons for lower limbs. From this analysis, it was observed that, different types of exoskeletons are already available for sales and are designed for various applications. It was also observed that, most of these products (exoskeletons) are intended for rehabilitation application for patients with spinal cord injuries (SCI). Some of these products are presented in figure 2.1 and include: *ATLANTE*, *Ekso GT*, *HAL*, *H-MEX*, *ReWalk*, *REX* among others.

Figure 2.1 – Exoskeletons as commercial products by different companies.

ATLANTE, developed by a French startup Wandercraft and intended for the Hip-Knee-Ankle lower body exoskeleton, it is completely autonomous, hands free and self balanced walking system. It has an intuitive controls using a sensor vest, guided by a program which enables it to navigate obstacles and provide more natural gait. Designed to restore locomotion with adjustable assistance and to enable early task-oriented motor work, promoting patient engagement and neuroplasticity. It also enables early, intensive and repeated treatment, while minimizing mental and physical burden on both the patient and therapist. It was marked as a costumer electronics (CE) in March 2019, and since then has been acquired and used in clinical practice by multiple renowned centers, willing to propose innovative rehabilitation care to their patients (Atlante, 2019).

Ekso GT, developed by Ekso Bionic, United States of America (USA). It is the first exoskeleton approved by the FDA (Food and Drugs Administration, USA) for stroke and spinal cord injury (SCI) rehabilitation, and currently available in over 270 certified rehabilitation centers worldwide. It is used to help stroke and SCI patients relearn to correctly stand and walk after stroke. Some of it's characteristics are: Actuated at the hip and knee, a variable assist controls, ability to apply power from 0 to 100% as needed on a step by step basis, adjustable on the fly assistance level and operation mode. It has different integrated control modes, including: spotter activated, user activated (button on crutches or walker), activated upon user completing weight shift, body shift and initiation of forward leg movement (the Ekso GT will provide only the necessary power to finish the step) (Ekso GT, 2019).

HAL (Hybrid Assistive Limb), designed by Cyberdyne, Japan, and considered to be the world's first cyborg-type robot. In 2013, HAL for medical use (lower limb type) became the first exoskeleton to obtain CE Marking [CE 0197] as a robotic medical device. Designed and intended to be used with patients with musculoskeletal ambulation disability such as: spinal cord injury, traumatic brain injury, brain and neuromuscular system disease etc. It uses its sensor to capture the bio-electric signal ("BES") transmitted by the brain to the muscles and uses the signals to realize the intended movement of the wearer. Some of it's characteristics are: Powered at the hip and knee but extends fully to the ground, Bio-electrical signal control, Detachable controller for physiotherapists. It executes movements in five steps: (1) First of all, think "I want to walk", (2) Receiving the signal, muscles move, (3) HAL reads signals, (4) HAL moves as the wearer intends, (5) the brain learns motion (HAL, 2019).

H-MEX, designed by Hyundai, South Korea, and first demonstrated at the CES (Consumer Electronics Show) in Las Vegas, 2017. It is also known as the Hyundai Medical Exoskeleton. Some of it's characteristics are: Powered at the hip and knee with as many as two motors per hip joint, metal frame that connects to the ground, it has adjustable frames, running speed of about 12km/h which was considered to be a very high speed for an assistive exoskeleton in 2017, rechargeable battery packs, it can support up to 40kg of wearer's total weight and has the ability to sit, stand, move, navigate stairs and run around. It comes in two variations, H-MEX for users with lower spinal cord injury and HUMA (Hyundai Universal Medical Assist) for walking assistance for those with limited muscular power (H-MEX, 2019).

ReWalk personal 6.0, developed by ReWalk, Israel, is the first exoskeleton to receive FDA clearance for personal and rehabilitation use in the United States, 2011. It is considered to be the most customizable exoskeleton designed to be used at home and in community. It provides powered hip and knee motion to enable individuals with SCI to stand upright, walk, turn, climb and descend stairs. Some of it's characteristics are: Actuated with motors at the hip and knee joints, controlled by the user using subtle changes in his/her center of gravity. A forward tilt of the upper body is sensed by the system, which initiates the first step. Repeated body shifting generates a sequence of steps which mimics a functional natural gait of the legs. It is used as a tool to augment the capabilities of regular physiotherapy by providing a high number of consistent and reproducible steps (ReWalk, 2019).

REX, developed by Rex Bionic, New Zealand, is the first commercial powered exoskeleton. A hands-free robotic device for rehabilitation, it is designed to: alleviate complications due to prolonged wheelchair use, developed for Robot-Assisted Physiotherapy (RAP), elevates users from a sitting position into a robot-supported standing position, be self-supporting and secure that can move individuals with complete spinal cord paralysis. It can independently support itself and the weight of the user. REX can shift weight from one leg to the other, walk forward and backwards, turn and capable of climbing stairs (REX, 2019).

It was observed in the commercial product review that, most of these exoskeletons are own by rehabilitation centers around the world and are extremely expensive to be acquired for personal use at homes. For instance, HAL costs approximately USD 70.000,00 and above, a price that is not affordable by many SCI patients. In an attempt to propose a viable final product in this work, it was necessary and important to perform further literature analysis, this time from academic publications, by searching relevant documents available in accredited databases at the national and international levels. To achieve this, a methodology for a systematic literature review was created and bibliometric analyses was performed as presented in the next section.

2.3 ACADEMIC PUBLICATIONS

Analyzing what was done in the academic field, the first exoskeleton found in the literature was the one developed by the General Electric Research, Schenectady, United States in 1965, dubbed “Hardiman”, intended for human *force augmentation* as described in Dollar and Herr, (2008). In 1969, the first exoskeleton for *rehabilitation application* was developed at Mihailo Pupin Institute, Belgrade, Serbia, and also at the University of Wisconssin-Madison, United States in the early 1970s as described in Huo, (2016). Since then, different projects of robotic exoskeletons for various applications were developed and published. Some of these projects may be found in: (Zoss et al., 2006), (Mcdaid Xing and Xie, 2013) and (Vinoj et al., 2019) among others.

The literature review methodology followed for this work consists of five steps: (a) *define search topic*, (b) *choose keywords*, (c) *choose database*, (d) *string construction*, and (e) *perform the search*, which include exploratory analysis and secondary analysis. In exploratory analysis, strings were constructed and used to explore the total number of documents available in the literature related to the field of rehabilitation (section 2.3.2). In the secondary analysis (section 2.3.3), results from exploratory analysis were further refined, in this caes, *Web of science* presented 297 documents, and *Scopus* presented 440 documents. From these two results, the analysis of *top 10*, that is (a) the most prominent research areas, (b) the most highlighted research countries, (c) sources with the highest register of documents, (d) the most cited documents and journals with the highest number of publications, was performed. Finally, the *VOSviewer* tool was used for the analyses of co-authorship, co-citation, bibliographic coupling, and afterward the *TagCrowd* tool was utilized for co-occurrence of keywords.

2.3.1 Methodology

It is very important to make it clear at this point that, all the results presented (from table 2.1 to 2.9 and figure 2.2 to 2.9) were collected on December 31, 2019, given that they tend to change over time as academic publications continue in the selected databases. There are many methods for a systematic literature review (Atallah and Carsto, 1998), (Martins, Thuler and Valente, 2005) and (Pereira and Bachion, 2008) among others. In this case, our methodology is to strictly follow these steps: (a) ***Define the Search Topic***: lower limb exoskeletons for rehabilitation of paraplegic patients; (b) ***Choose Keywords***: (1) exoskeleton, (2) lower limb, (3) rehabilitation, and (4) paraplegic; (c) ***Choose Databases***: (1) Web of Science, (2) Scopus, (3) IEEE Xplore, (4) *Catálogo de Teses e Dissertações* (CTD) of CAPES and (5) *Bibilioteca Digital de Teses e Dissertações* (BDTD) of CAPES; (d) ***Strings Construction***: String (1), String (2), String (3), and String (4) (see table 2.1); (e) ***Perform the Search***: exploratory analysis and secondary analysis.

Table 2.1 – The four strings used for the search of relevant documents.

S/N	String	Comentário
(1)	"Exoskeleton" OR "Prosthesis" OR "Orthosis"	This research sequence gives us the general idea of all publications madein the field of rehabilitation. All results of this research speak in one way or anotherabout "Exoskeleton" or "Prosthesis" or "Orthosis"
(2)	"Exoskeleton"	This string refines the search results from the above string (1) by removing all documents that speak about “Prosthesis” or “Bracing”, leaving only documents that speak about “Exoskeleton”,which is our topic of interest. The result of this research includes all types of exoskeleton for the lower and upper limbs.
(3)	"Exoskeleton" AND "Lower Limb" AND ("Rehabilitation" OR "Paraplegic" OR "Paralysis" OR "Deficiency")	This string further refines our search in (2) by eliminating all documents whose focus is not for rehabilitation of paraplegic people.
(4)	"Exoskeleton" AND "Lower Limb" AND ("Rehabilitation" OR "Paraplegic" OR "Paralysis" OR "Deficiency") AND ("Mechanical Design" OR "Design" OR "Project" OR "Development" OR "Modeling")	This string further refines our research in (3) by eliminating documents whose focus is not mechanical design. In this search. From these search, the inclusion and exclusion criteria are applied.

2.3.2 Exploratory Analysis

In the *exploratory analysis* using the selected databases, *String* (1), *String* (2) and *String* (3) were used to search for relevant documents. *String* (1) was used to explore the general idea of the total number of publications available in the field of *rehabilitation*, which includes the use of *exoskeletons*, *prostheses* and *orthoses*. String (2) was used to explore the total number of publications that only talk about *exoskeletons*, which include the exoskeletons for lower limbs and exoskeletons for upper limbs, while *String* (3) was used to explore documents related to the mechanical design aspect of only lower limb exoskeletons for rehabilitation applications. For *String* (1), *String* (2) and *String* (3), table 2.2 presents searching type (Search Type), number of documents (Result) and the first year of publication (1° Year Pub.) of documents in a database. In brackets are the number of documents published in the first year of publication in a database. However, *String* (4) is applied for the secondary analysis.

Table 2.2 – Search results for the String(1), String(2) and String(3) in the exploratory analysis.

		String(1)		**String(2)**		**String(3)**	
Database	**Search Type**	**Result**	**1° Year Pub.**	**Result**	**1° Year Pub.**	**Result**	**1° Year Pub.**
WoS	Topic	71.284	1945 (4)	6,753	1947 (1)	474	2006 (2)
Scopus	T.A.K	400.291	1903 (1)	9,972	1912 (1)	723	2004 (1)
IEEE	All	7480	1969 (2)	2,545	1981 (1)	304	2006 (1)
CTD	All	4751	1989 (2)	184	1990 (1)	8	2005 (1)
BDTD	All	2737	1964 (4)	90	1994 (1)	8	2009 (2)

2.3.3 Secondary Analysis

After the Exploratory analysis, still there was the need to refine the obtained results in order to get to the most relevant documents. Therefore, a secondary analysis in this case was performed. In this case, results from exploratory analysis were further refined to extract the most relevant ones. This process aims to eliminate documents that are not relevant to the topic in question. To achieve that, the objective String (4) (see table 2.3) and some inclusion and exclusion criteria were applied.

Specifically, for including documents, we have opted for: (a) relevant documents published or accepted for publication including, books, articles, review articles, dissertations and theses; (b) documents that contain our keywords in their titles; (c) documents dealing with exoskeletons for lower limbs only; (d) documents that are easily accessible, (e) all publications till October 31, 2019, and (f) all documents in English and Portuguese. More additional excluding criteria comprises: (a) documents that focus only on Prosthesis; (b) documents dealing only with upper limb exoskeletons; (c) documents that are not easily accessible, and (d) documents in other languages other than English and Portuguese. In the secondary analysis, Web of science and Scopus databases presented 297 and 440 documents respectively.

Table 2.3 – Search results for the objective String (4) in the secondary analysis.

		String(4)	
Database	**Search Type**	**Result**	**1° Year Pub.**
WoS	Topic	297	2006 (2)
Scopus	Title, Abstract, Keywords	440	2005 (1)
IEEE	All	194	2006 (1)
CTD	All	4	2005 (1)
BDTD	All	8	2009 (2)

(a) **Most Prominent Research Areas** are research areas with the highest register of documents related to the design and development of lower limb exoskeletons available in a database. Using the results in table 2.3, table 2.4 presents the top 10 prominent research areas obtained from *Web of Science* and *Scopus* respectively. It was observed that, areas like Engineering, Robotics, Computer science, Neurosciences, Automation and Control are some areas with the highest contributions.

Table 2.4 – The most prominent research areas in the *Web of Science* and *Scopus*.

S/N	**Web of Science**			**Scopus**		
0	**Subject Area**	**Result**	**% of 291**	**Subject Area**	**Result**	**% of 440**
1	Engineering	180	60.60	Engineering	309	70.23
2	Robotics	115	38.72	Computer Science	198	45.00
3	Computer Science	65	21.89	Medicine	119	27.05
4	Automation Control Systems	52	17.51	Mathematics	63	14.31
5	Rehabilitation	41	13.80	Biochemistry, Genetics and Molecular Biology	44	10.00
6	Neurosciences Neurology	23	7.74	Neuroscience	28	6.36
7	Instrument Instrumentation	13	4.37	Physics and Astronomy	25	5.68
8	Material Science	13	4.37	Chemical Engineering	24	5.45
9	Chemistry	12	4.04	Material Science	24	5.45
10	Medical Informatics	7	2.36	Health Professions	12	2.72

(b) **Most Highlighted Research Countries** are Countries with the highest register of publications in a database. Using the results in table 2.3, table 2.5 presents the top 10 most highlightet Countries with the highest register of documents in *Web of Science* and *Scopus* respectively. It was observed that Peoples Republic of China is the leading country followed by the United States. Despite not appearing in the top 10 analysis strategy, Brazil is now presenting it's interest in this field with many project from the Universiity of São Paulo (*Universidade de São Paulo-Usp*) and State University of Campinas (*Universidade Estadual de Campinas-UniCamp*).

Table 2.5 – Most highlighted research countries in the *Web of Science* and *Scopus*.

SN	***Web of Science***			***Scopus***		
0	**Country**	**Result**	**% of 297**	**Country**	**Result**	**% of 440**
1	Peoples R China	75	25.25	Peoples R China	113	25.68
2	United States	50	16.83	United States	59	13.41
3	Spain	20	6.73	Italy	32	7.27
4	Italy	19	6.39	Spain	31	7.07
5	France	18	6.06	Switzerland	23	5.22
6	Switzerland	15	5.05	France	21	4.78
7	Mexico	14	4.71	Japan	18	4.09
8	South Korea	12	4.04	India	16	3.63
9	Japan	12	4.04	Malaysia	15	3.41
10	Belgium	11	3.70	Mexico	15	3.41

(c) **Sources with the Highest Register of Documents** are sources with the highest number of documents in a database. In this case, table 2.6 and table 2.7 present the top 10 sources from the *Web of Science* and *Scopus* databases respectively. According to the result of this analysis, sources like *International Conference on Rehabilitation and Journal of NeuroEngineering and Rehabilitation Robotics (ICORR)* are two important sources for consideration for a possible article submission.

Table 2.6 – Sources with the highest register of documents in the *Web of Science*.

S/N	Source Title	Register	% of 297
1	International Conference on Rehabilitation Robotics	13	4.38
2	Journal of NeuroEngineering and Rehabilitation	11	3.70
3	Sensors	9	3.03
4	IEEE Transactions on Neural Systems and Rehabilitation Engineering	8	2.69
5	International conference on Ubiquitous robots and ambient intelligence	6	2.20
6	IEEE ASME transactions on Mechatronics	5	1.68
7	Industrial Robot: The international journal of robotics research and application	5	1.68
8	Proceedings of the IEEE RAS EMBS International Conference on Rehabilitation Robotics ICORR 2015	5	1.68
9	Proceedings of the IEEE RAS EMBS International Conference on Biomedical Robotics and Biomechatronics	5	1.68
10	Robotics and Autonomous Systems	5	1.68

Table 2.7 – Sources with the highest register of documents in the *Scopus*.

SN	Source Title	Register	% of 440
1	IEEE International Conference on Rehabilitation Robotics	31	7.05
2	IEEE Transactions on Neural Systems and Rehabilitation Engineering	16	3.63
3	Journal of NeuroEngineering and Rehabilitation	15	3.41
4	Biosystems And Biorobotics	8	1.81
5	Journal of Physics Conference Series	8	1.81
6	Industrial Robot	6	1.36
7	Ifmbe Proceedings	5	1.14
8	International Journal of Advanced Robotic Systems	5	1.14
9	Lecture Note in Computer Science Including Subseries Lecture Notes in Artificial Intelligence and Lecture Note in Bioinformatic	5	1.14
10	Plos One	5	1.14

(d) **Most Cited Documents** are documents with the highest number of citations in a database. Using the results in table 2.3 and a *VOSviewer* tool, table 2.8 and table 2.9 present the top 10 most cited documents from *Web of Science* and *Scopus* respectively. It was observed that, most of these documents are repeated in the two databases and also passed the inclusion criteria established, there by making them more relevant to this work.

Table 2.8 – The most cited documents in the *Web of Science*.

SN	Title	Aut.	Year	Cit.	Com.
1	Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-art	Dollar, A. M.	2008	619	R/I
2	Review of Assistive Strategies in powered lower-limb orthoses and exoskeletons	Yan, T.	2015	183	R/I
3	Control Strategies for active lower extremity prosthetics and Orthotics: a Review	Tucker, M. R.	2015	166	R/I
4	Preliminary Evaluation of a Powered Lower Limb Orthosis to aid walking in paraplegic individuals	Farris, R. J.	2011	136	R/I
5	State of the Art and Future Direction for Lower Limb Robotic Exoskeletons	Young, A. J.	2017	126	R/I
6	Recent Development of Mechanisms and Control strategies for robot-assisted lower Limb rehabilitation	Meng, W.	2015	113	R/I
7	Emg and App-integrated human-machine interface between the paralyzed and Rehabilitation Exoskeleton	Yin, Y. H.	2012	109	R/I
8	The H2 Robotic Exoskeleton for gait rehabilitation after stroke: early findings from a clinical study	Bortole, M.	2015	98	R/I
9	The Design and Control of a therapeutic Exercise Robot for lower limb Rehabilitation: Physiotherabot	Akdogan, E.	2011	96	R/I
10	Oscillator-based assistance of cyclical movements: model-based and model-free approaches	Ronsse	2011	83	R/I

Table 2.9 – The most cited documents in *Scopus*.

SN	Title	Aut.	Year	Cit.	Com.
1	Lower Extremity Exoskeletons and Active Orthoses: Challenges and Stste-of-the-art	Dollar, A. M.	2008	770	R/I
2	Wearable Robot: Bio mechatronics Exoskeletons	Pons, J. L.	2008	323	R/I
3	Current hand Exoskeleton technologies for rehabilitation and Assistive Engineering	Heo, P.	2012	226	IR/E
4	Control Strategies for active lower extremity prosthetics and Orthotics: a Review	Tucker, M. R.	2015	202	R/I
5	Review of Control Algorithms for Robotic Ankle Systems in Lower-Limb Orthosis, Prostheses, and Exoskeletons	Jimenez-Fabian, R.	2012	163	R/I
6	State of the Art and Future Directions for Lower Limb Robotic Exoskeletons	Young, A. J.	2017	149	R/I
7	Lower limb wearable robots for assistance and rehabilitation: A State of the Art	Huo W.	2016	105	R/I
8	Passive exoskeletons for assisting limb movement	Rahman T.	2006	93	R/I
9	Voluntary driven exoskeleton as a new tool for rehabilitation in chronic spinal cord injury: a pilot study	Aach m.	2014	92	R/E
10	Oscillator-based assistance of cyclical movements: model-based and model-free approaches	Ronsse R	2011	91	R/I

2.3.4 Bibliometric Analysis

This is a quantitative analysis of documents relevant to the topic. In this case, tools like, *VOSviewer* (Nees and Ludo, 2019) and *TagCrowd* (https://tagcrowd.com/) were used for the *co-authorship*, *co-citation*, and *bibliographic coupling* and *co-occurrence of Keyword* analyses.

2.3.4.1 Co-authorship Analysis (Authors)

In co-authorship analysis using *VOSviewer*, the closer two authors are located to each other, the stronger their relatedness. Therefore, for *Web of Science*, the minimum number of documents of an author was set to 5, the minimum number of citations of an author to 10 and from 1063 authors, 17 met the threshold (figure 2.2). And for Scopus, the minimum number of documents of an author was set to 5, the minimum number of citations of an author to 10 and in this case, from 1393 authors 37 met the threshold (figure 2.3).

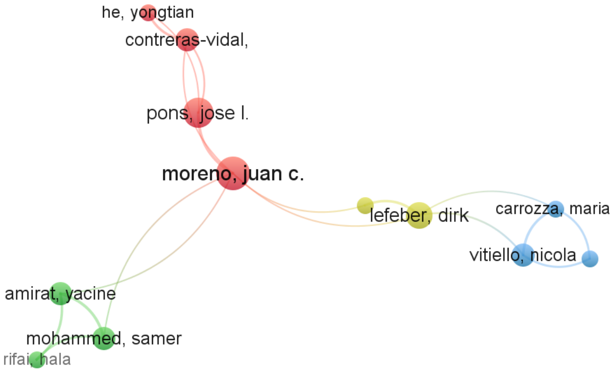

Figure 2.2 – Analysis of co-authorship based on *Web of Science* database data.

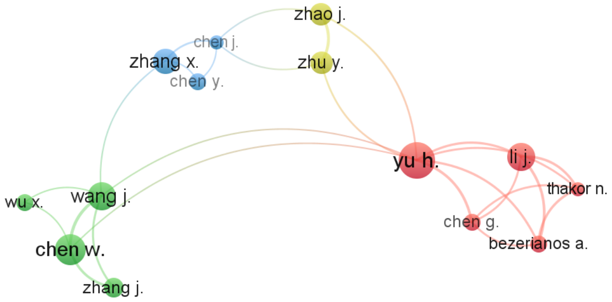

Figure 2.3 – Analysis of co-authorship based on *Scopus* database data.

2.3.4.2 Co-citation Analysis (Cited References)

In co-citation analysis using *VOSviewer*, the closer two documents are located to each other, the stronger their relatedness. The strongest co-citation links between documents are also represented by lines (Nees and Ludo, 2019). Therefore, for *Web of Science*, the minimum number of citations of a cited reference was set to 15 and from 6795 cited references, 41 met the threshold (figure 2.4). And for Scopus, the minimum number of citations of a cited reference was set to 4 and in this case, from 12047 cited references, 23 met the thresholds (figure 2.5).

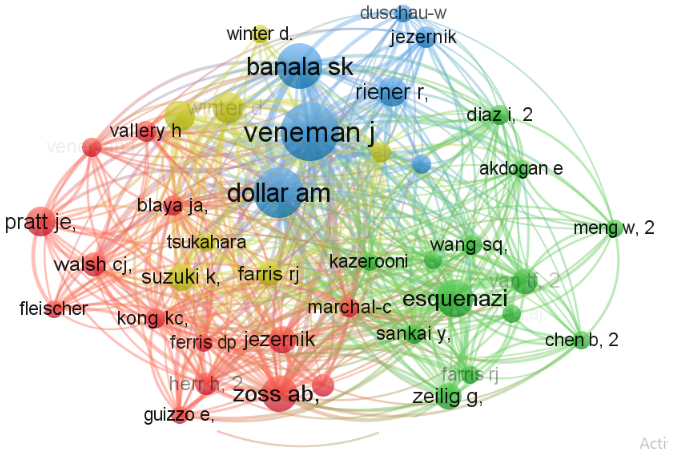

Figure 2.4 – Analysis of co-citation based on *Web of Science* database data.

Figure 2.5 – Analysis of co-citation based on *Scopus* database data.

2.3.4.3 Bibliographic Coupling (Documents)

The bibliographic coupling using *VOSviewer* tool relates the number of cited references that two publications have in common. In this case, the bigger the circle of a document, the strongest the citation of the document by others. Therefore, for *Web of Science*, the minimum number of citations of document was set to 25 and from 297 documents, 30 meet the thresholds (see figure 2.6). Otherwise, the minimum number of citations of document was set to 40, from 440 documents, 33 meet the thresholds (see figure 2.7). (Dollar and Herr, 2008) was observed to be the most cited document among both the *Web of Science* and *Scopus*.

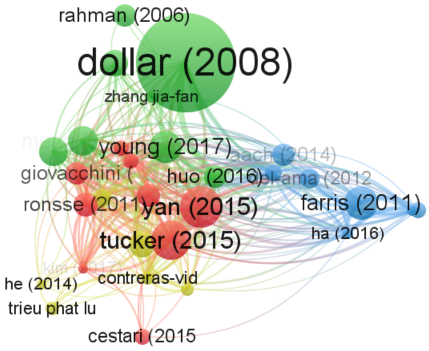

Figure 2.6 – Analysis of bibliographic coupling based on *Web of Science* database data.

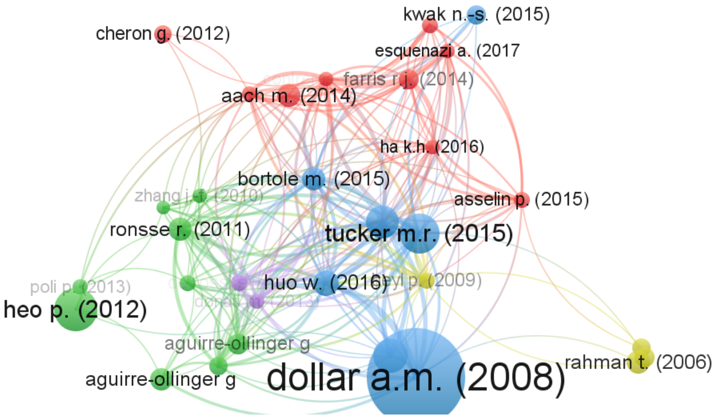

Figure 2.7 – Analysis of bibliographic coupling based on *Scopus* database data.

2.3.4.4 keyword co-occurrence (Keywords)

The keyword co-occurrence analysis using *TagCrowd* relates the occurrence of a keyword repeated in two or more documents. Figure 2.8 and figure 2.9 show this relations. In this case, the bigger the appearance of a keyword, the more number of documents it is repeated in a particular database. *TagCrowd* tool was used to analyze this relationship by using the *Web of Science* and *Scopus* data collected from the secondary analysis. The keyword **exoskeleton** appears in more documents than any other keyword in both the *Web of Science* and *Scopus* data, therefore, it appears bigger and more visible.

Figure 2.8 – Analysis of co-occurrence of keywords based on *Web of Science* database data.

Figure 2.9 – Analysis of co-occurrence of keywords based on *Scopus* database data.

2.4 SELECTED PROJECT FROM THE LITERATURE REVIEW

The General Electric's Hardiman (figure 2.10), is a full-body and hydraulically powered machine (30DOFs) mainly intended to drastically increase the strength capabilities of the wearer to approximately 25:1 where the wearer is expected to lift wearer to lift loads of 1500 pounds (680 kg) with ease. "While satisfactory results were achieved with the arm amplifying aspects of the prototype, problems with the lower limb components were never resolved and the full-bodied device. Was reportedly never even powered up with a human inside. Perhaps the most important contribution of the Hardiman project was identifying many of the most challenging aspects of the exoskeleton design such as power supply and human/machine interface as well as convincing the research community that the creation of effective exoskeleton devices is extremely difficult" (Dollar, 2008).

Figure 2.10 – The first exoskeleton developed by the General Electric and named Hardiman.

Zoss, A. B. et al. (2006) presented the Berkeley Lower Extremity Exoskeleton (BLEEX) project. Intended for force augmentation, BLEEX comprises two powered anthropomorphic legs, a power supply and a backpack-like frame on which a variety of heavy payloads can be mounted and carried over rough, unstructured, and uncertain terrains (figure 2.11). It has 7DOF per leg which are purely rotary joints (3 at the Hip, 1 at the Knee and 3 at the ankle), 4 of which are powered by linear hydraulic actuators. In this project, appropriate size of actuators was determined analytically using an equation for the actuator's torque capabilities.

(a) Simplified Model

(b) Final Design

Figure 2.11 – The Berkeley Lower Extremity Exoskeleton (BLEEX) (Zosh, 2006).

Hybrid Assistive Limb (HAL) (figure 2.12), developed by Tsukuba University and the robotics company Cyberdyne in Japan is intended to support and expand the physical capabilities of its users, particularly people with physical disabilities. There are two primary versions of the system: HAL 3, which only provides leg function, and HAL 5, which is a full-body exoskeleton for the arms, legs, and torso. HAL 3 has 7DOF, motorized and uses its sensor to capture the bio-electric signal ("BES") transmitted by the brain to the muscles and uses the signals to realize the intended movement of the wearer. Crutch or Walker is necessary.

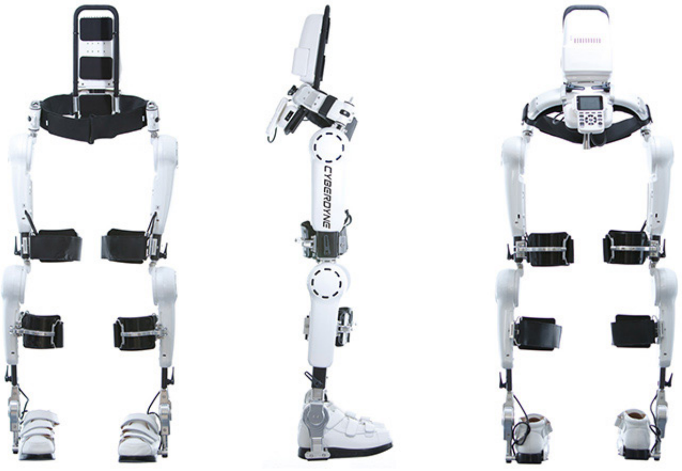

Figure 2.12 – The Hybrid Assistive Limb (HAL) developed by Cyberdyne in Japan.

Hyundai Medical Exoskeleton (H-MEX) (figure 2.13), is an 18kg (40 pounds) exoskeleton with an adjustable aluminum frames that straps to the user's feet, legs, and back, with hinges at the knee and waist capable of supporting up to 40kg of wearer's total weight. Electrically motorized, H-MEX has the ability to sit, stand, move, navigate stairs and run around. The user needs canes (Crutches) to maintain balance and to trigger the next action: step, sit, or climb.

Figure 2.13 – The Hyundai Medical Exoskeleton (H-MEX) developed by Hyundai in South Korea.

REX (figure 2.14), Designed to work with users of different size (it is adjustable), motion is generated by 10 custom designed linear actuators which provide the power to move the REX and a user of up to 100Kg. The wide foot plates provide stability and ease of movement across flat surfaces and there is no need of the use of crutches or walker by the wearer since the equipment is robust enough to control the center of gravity regardless of the user. A Joystick is used for navigation control.

01 Motion is generated by 10 custom designed linear actuators which provide the power to move REX and a user of up to 100Kg.

02 The custom carbon fibre pelvis provides the strength and stiffness required to support the user whilst minimising the weight of the system.

03 Half a million lines of proprietary code control 27 onboard microprocessors that manage the actuator systems – forming the core of a custom movement control system which has been developed to ensure stability throughout all phases of the movement cycle.

04 REX is designed to work with users of different heights. The device leg length can be readily adjusted enabling precise and accurate alignment to the user's joints. Adjustment can be quickly and easily performed between different patient sessions in a clinic.

05 The harness and abdominal straps help support the user and hold them upright. They are also fully adjustable to provide maximum user comfort.

06 Wide foot plates provide stability and ease of movement across flat surfaces.

07 Powered by rechargeable, interchangeable batteries. The REX lithium-polymer battery (29.6V, 16.5Ah) carries a charge sufficient for approximately sixty minutes of normal use. Two batteries are provided ensuring continuous use.

08 Custom designed carbon fibre cuffs, with double tethered straps, hold the legs firmly but without creating pressure points. The removable foam padding allows easy maintenance and compliance with infection control regimens.

Figure 2.14 – The REX developed by Rex Bionic in New Zealand.

Aguillar-Sierra et al. (2015) (figure 2.15), showed the advantages of using two types of actuators (DC motor with harmonic unit and a pneumatic artificial muscles) at the hip and knee joints respectively. The harmonic drive actuator has high torque, high precision positioning and relatively small dimensions which are ideal properties for gait rehabilitation. A sample survey of 600 people was used to create the mechanical structure of the device. This survey was instrumental in establishing the adjustable mechanical structure that can be used by many within a target population.

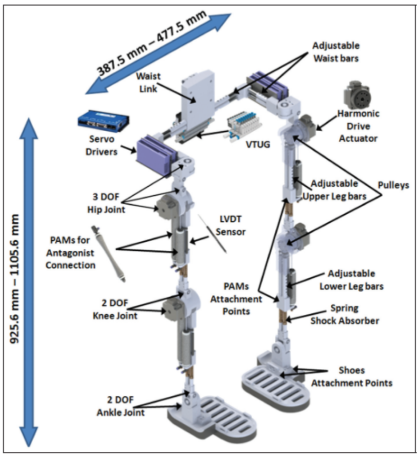

Figure 2.15 – Exoskeleton using two types of actuators (Aguillar-Sierra, 2015).

(Dos Santos, W. M. et al. 2016) developed an exoskeleton consisting of a tubular low-weight structure and the coupling between the links and mounting brackets that provide a modular feature of the system (figure 2.16). This feature allows the exoskeleton is adapted to assist the movement of one or more joints of the patient. The performance of the exoskeleton is also modular and can be performed passively by means of springs and shock absorbers, or actively by actuators, especially elastic actuators in series. One important thing with this work was how the project was divided in to its components and later joint together to generate a final exoskeleton structure.

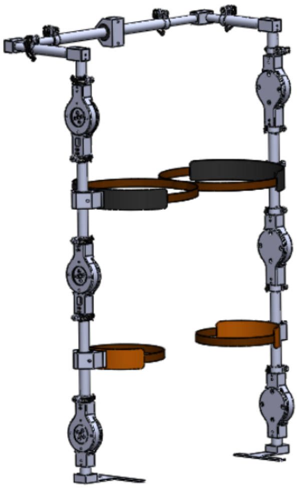

Figure 2.16 – Designing links using tube to make it adjustable (Dos Santos,2016).

In his Dissertation approach, Dos Santos, D. P (2015) presented a mechanical design of an exoskeleton subdividing the device system into four main components: Actuators, Ankle articulation, links and back support (figure 2.17). Each of the components was developed individually and later integrated as one for the prototype construction. We adapt this division of strategy in our development.

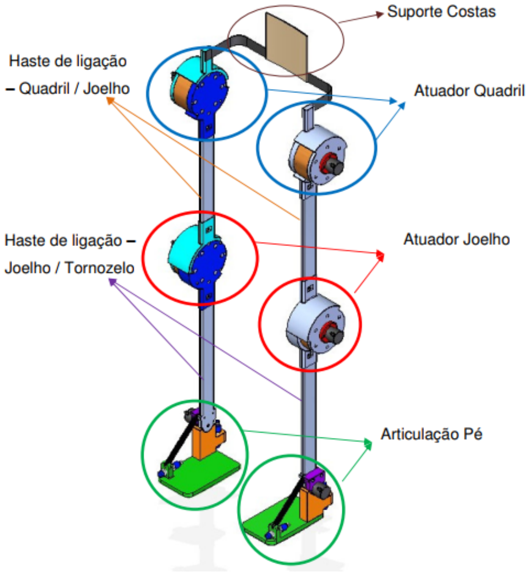

Figure 2.17 – Dividing the exoskeleton's project into sub projects (Dos Santos, (2015).

It is possible to measure the Center of Pressure (CoP) or Zero Moment Pressure (ZMP) of an exoskeleton using force sensors as shown by J. H. Kim et al. (2012). This measurement technique can be used to check stability while an exoskeleton is being used by a patient or even to estimate their human intention to walk. One of the main focuses of this work was the minimization of user discomfort where the exoskeleton was designed with 7 degrees of freedom in each leg (3 hips, 1 knee and 3 ankles) with only joint, hip and knee juices activated in the sagittal plane. Denavit-Hartenberg (DH) was adopted to model the exoskeleton kinematics.

Rehabilitation exoskeletons often help patients to walk based on fixed gait paths. Y. Long et al. (2016) presented a hybrid training mode for unilateral paraplegics. The main idea is to train the leg with movement problem based on healthy leg behavior. With two modes of operation (passive training mode and active assistance mode). In passive training mode, used before recovery, the problem leg is trained based on healthy leg trajectory information. In active assistance mode it is used after recovery of the problem leg. The most interesting part of this project is the use of single leg actuators and the total project weight was 18.5kg.

One of the critical steps of exoskeleton design is actuator selection, in this direction U. Onen et al. (2014) presented the critical design criteria to be considered in the mechanical development and selection of exoskeleton actuators. Criteria such as comfort and ergonomic design, high maneuverability, light and strong structure, adaptability to different users, user safety for development of mechanical structure of the exoskeleton were established.

2.5 LITERATURE REVIEW CONSIDERATIONS

The methodology presented here starts by providing information on the general idea of the number of publications in a particular field in question. This was achieved by the use of String (1), where the general idea of when and what was published in the field of rehabilitation (from day one) was presented in all the databases selected. String (2), String (3) and Sting (4) were used to refine these results further. However, choice of right keywords, databases and a good strings construction are very important in guaranteeing the quality of the results. In this sense, Heo, P. (2012) was exclude because it only talked about Hand Exoskeleton (Upper Limb) and becomes irrelevant by the exclusion criterion (b). Farris, D. P. (2005) was excluded because of not been easily accessible and becomes irrelevant by exclusion criterion (c) and also for not talking about lower limb exoskeletons. It was observed that, the method applied was efficient, and from the top 10 most cited documents in Web of Science and Scopus, six (6) are found common to both databases and only two documents in all were rejected leaving twelve (12) relevant documents, which can be found in tables 2.8 and table 2.9.

3 BIOMECHATRONIC SYSTEMS ANALYSIS OF LOWER LIMB EXOSKELETONS

3.1 INTRODUCTION

Biomechatronics can be regarded as a bio-inspiration used in (a) designing, (b) modeling, and (c) controlling mechatronic systems. A biomechatronic system is a system that mimics how the human body works and can be considered to have five components: (1) mechanisms, (2) actuators, (3) sensors, (4) control, and (5) human-robot interaction which can either be Physical Human-Robot Interaction (pHRI) or Cognitive Human-Robot Interaction (cHRI) (Pons, 2008).

In this section, an analysis of biomechatronic system's components of lower limb exoskeletons is presented given examples of some of their applications in various project found in the literature. Firstly, mechanisms, kinematics and dynamics of lower limb exoskeletons are analyzed explaining the concepts of biomechanics of walking, human walking speed, mechanics of human walking, and a Denavi-Hartenberg model of a human leg. Secondly, actuators, analysis of different types of actuators used in designing lower limb exoskeletons is presented, these actuators include: electric motors, series elastic actuators (SEAs), hydraulic, pneumatic actuators and pneumatic muscle actuators. Afterwards, sensors and control, analysis and examples of different types of sensors used in different control strategies of lower limb exoskeletons are presented, these sensors include: force sensors, position sensors, electromyography (EMG) and electroencephalogram (EEG) sensors among others. Finally, Human-Robot Interaction, a physical human-robot interaction and a cognitive human-robot interaction are discussed analyzing the Human-Robot interfaces that support them. Figure 3.1 shows the analogy between the human body components and a biomechatronic system's components of wearable robots (Pons, 2008).

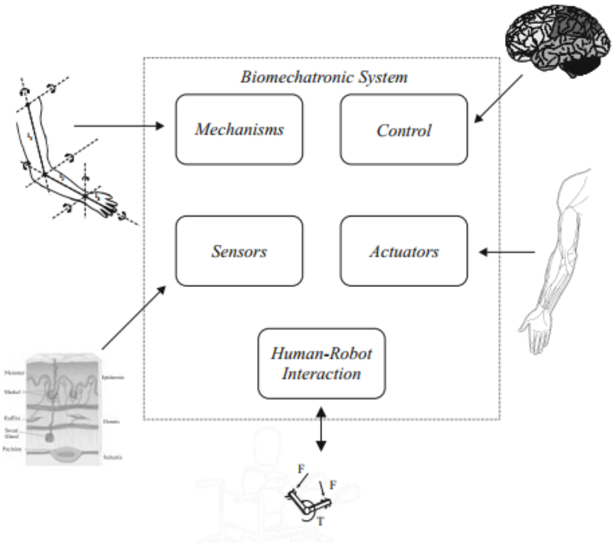

Figure 3.1 – Biomechatronic system's components (Pons, 2008).

3.2 MECHANISMS

3.2.1 Metabolic Cost

One of the main objectives of designing lower limb exoskeletons, especially for augmentation performance, is to significantly minimize the metabolic cost of the intended user. Therefore, to determine the effectiveness or whether the device is significantly assistive or not, there is the need to compare the required human metabolic cost needed to perform a task with or without the use of the exoskeleton. This calculation can be done by measuring and comparing the rate of oxygen consumption, carbon dioxide production and urinary nitrogen excretion while performing the task using the exoskeleton and without using the exoskeleton (Huo, 2016).

There are many other methods for this calculations as shown in (Griffin, 2003), (Winter, 2015) and (Donelan, 2002). However, changing the user's walking speeds may complicate this comparison. In Seethapathi and Srinivasan (2015), the method for measuring a metabolic energy cost of walking when changing speed is presented, it was also estimated that, the cost of this changing speeds represents 4–8% of the daily walking energy budget. Initial tests of metabolic cost were performed on some exoskeletons with varied results showing an increase metabolic expenditure in some projects such as in MIT exoskeleton (valiente, 2005) and in other cases showing a decrease metabolic expenditure such as in (Sawicki, 2009).

3.2.2 Biomechanics of walking

Human walking is accomplished with a strategy called the double pendulum. During forward motion, the leg that leaves the ground swings forward from the hip, this sweep is considered the first pendulum and then, the leg strikes the ground with the heel and rolls through to the toe in a motion described as an inverted pendulum. The motion of the two legs is coordinated so that one foot or the other is always in contact with the ground. The process of walking recovers approximately sixty per cent (60%) of the energy used due to the pendulum dynamics and the ground reaction force.

It was observed from the literature review that, normally, the human leg has 7 DOF (3 at the hip, 1 at the knee and 3 at the ankle) for a proper and comfortable motion. In the design and control of lower limb exoskeletons, understanding human walking gait is fundamental. It was also observed that, human gait cycle was represented by the periodic repetition of two phases, the stance phase and the swing phase (figure 3.2). The stance phase (when the foot is on the ground) occupies around 60% of the gait cycle and occurs between two events: the heel strike and the toe-off (same foot) while the swing phase (when the foot is in the air) occupies only around the 40% of gait cycle and starts with the toe-off event and ends whit the ext heel strike (Luca, 2015).

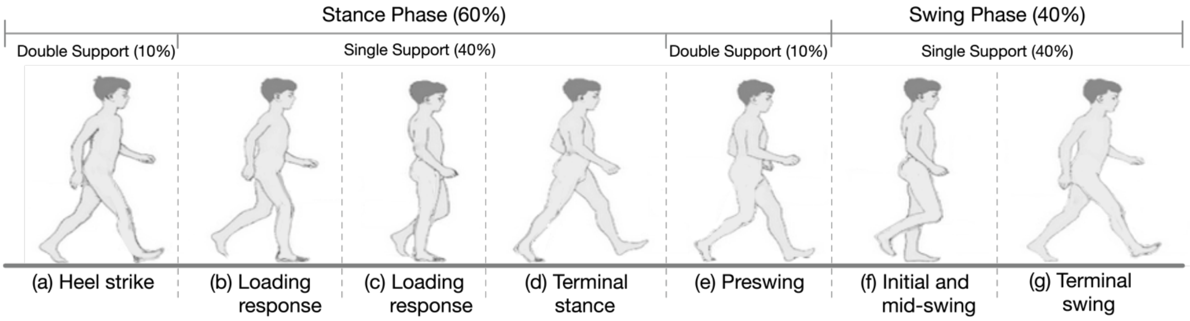

Figure 3.2 – Human walking gait cycle, adapted from (Luca, 2015).

Figure 3.3 shows an experiment carried out on a normal, healthy individual (82 kg, 0.99 m leg-length, 28-year-old male) walking at 1.27 m/s, showing joint angle, moment, and power for hip, knee, and ankle flexion/extension motions during level-ground walking (Dollar, 2008). It is important to know the power required by each joint when designing exoskeletons. From this experiment, it is noted that, at low speed, power at the hip is positive or near zero, it is negative at the knee, and evenly split between negative and positive at the ankle. It can also be noted that, at a steady state, the net mechanical power of the individual as a whole should be close to zero, since there is no net work done and also resistance to motion is small.

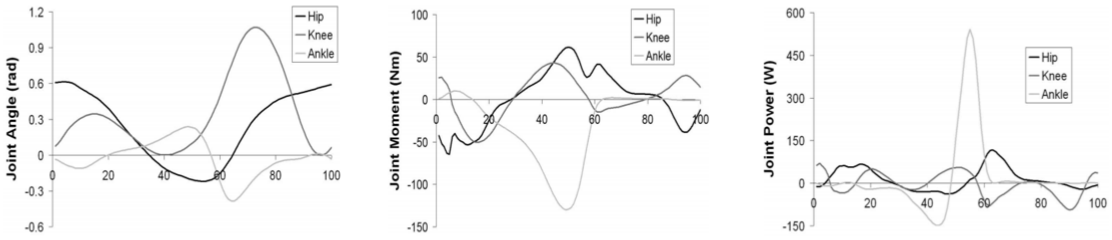

Figure 3.3 – Joint angle(rad), moment(Nm) and power(W) for the hip, knee and ankle during a normal walking (Dollar, 2008).

3.2.3 Human walking speed

Human walking speed is another important aspect to be considered when designing and controlling lower limb exoskeletons. People walk with different speeds depending on factors like, height, weight, age, gender, terrain, surface, load, effort, fitness, and cultural believes. A study carried out at Portland State University in 2005, and later reviewed in 2009, showed that the average human walking speed at crosswalks is about 1.4 m/s or 5 km/h (Cery and Aspelin, 2009). In Brazil, (Miranda, Dourado and Novaes, 2011) studied the gait speed among Brazilians aged above 40 years old and their study showed that the average speeds of the Brazilian population were around 1.26 m/s or 4.54km/h among men and 1.16 m/s or 4.18km/h among women. It was also observed that, gait speed and step length were very important considerations of many projects when designing and controlling of lower limb exoskeletons for rehabilitation application.

3.2.4 Mechanisms of Human Movement

The anatomical planes of human motion as described in medicine are (a) *sagittal* or *lateral plane* which divides the body into right and left parts (b) *transversal* or *Axial plane* which divides the body into upper and lower parts and (c) *coronal* or *frontal plane* which divide the body into anterior and posterior parts (figure 3.4).

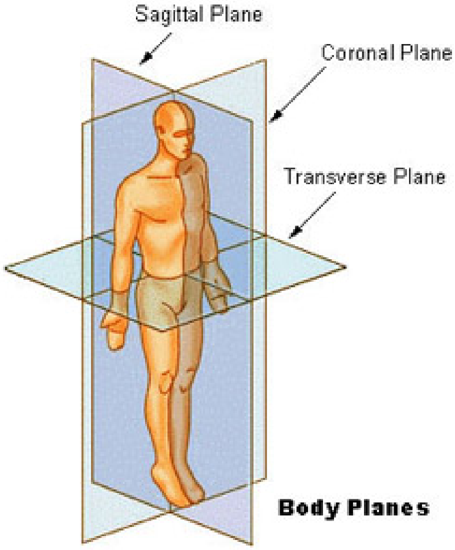

Figure 3.4 – Human anatomical planes (Planes, 2019).

Considering the above body planes, movement in the sagittal plane include *flexion*, *extension* and *hyperextension*, *dorsiflexion* and *plantarflexion*. Movement in the coronal plane include *abduction* and *adduction*, *lateral flexion*, *elevation* and *depression*, *inversion* and *eversion radial* and *ulnar deviation*. Movement in the transverse plane include *left* and *right rotations*, *medial* and *lateral rotations*, *supination* and *pronation*, *horizontal abduction* and *adduction*. To establish the number of degree of freedom for this work, movement at the *Hip*, *Knee* and *Ankle* joints were analyzed.

3.2.4.1 Movements at the Hip Joint

The hip joint is a multiaxial ball-and-socket synovial joint which behaves as a spherical joint. It moves in different cardinal reference planes that pass through the joint center allowing three possible degree of freedom (3DOF). All the 3DOF are important for stable locomotion of an individual, and even in a straight line (Pons, 2008). As presented in (Hall, 2015), at the hip, these movements include: Flexion–extension, Abduction–adduction and Medial–lateral rotation.

(a) **Flexion–extension**

Hip joint flexion and extension (figure 3.5) are movements at the hip joint that occur in the sagittal plane. Flexion is the rotating motion of the hip joint that brings the thigh forward and upward while extension is just the opposite of flexion. Flexion is accomplished by the muscles: *iliopsoas*, (iliacus and psoas major), *tensor fasciae latae*, *rectus remoris*, *pectineus*, *sartorius* and *adductor muscles*. Extension is accomplished the by muscles: *gluteus maximus*, *semitendinosus*, *semimembranosus*, *biceps femoris* and *adductor magnus*. The range of hip flexion is up to 120° and that of extension is up to 20°, (Pons, 2008).

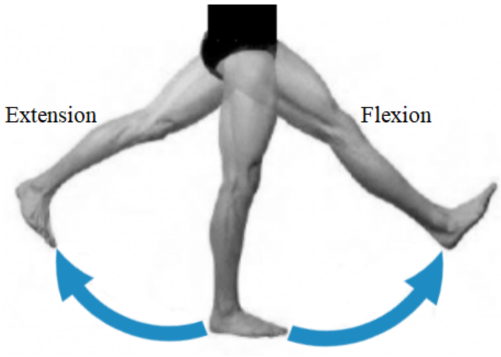

Figure 3.5 – Flexion–extension, hip movement in the sagittal plane (Clinical gait, 2020).

(b) Abduction–adduction

Hip joint abduction and adduction are movements at the hip joint that occur in the frontal or coronal plane (figure 3.6). Abduction is the movement of lower limb away from the mid-line of the body while the adduction is just the opposite of abduction. Abduction is accomplished by lateral muscles such as the: *gluteus medius*, *gluteus minimus*, *tensor fasciae latae*, *sartorius*, *piriformis* and *obturator externus*. Adduction is accomplished by the muscles: *adductors (magnus, longus and brevis)*, *pectineus* and *gracilis*. The range of abduction is up to 40° and that of adduction is between 30° and 35°, (Pons, 2008).

Figure 3.6 – Abduction–adduction, hip movement in the frontal plane (Hall, 2015).

(c) Medial–lateral rotation

Hip joint medial–lateral rotation is the rotation at the hip joint that occur in the transverse plane (figure 3.7). It is the rotation around the long axis of the femur. Medial rotation is accomplished by the muscles: *tensor fasciae latae*, *gluteus medius* and *gluteus minimus*. Lateral rotation is accomplished by the muscles: *obturator internus* and *gemelli*, *obturator externus*, *quadratus femoris*, *piriformis*, *gluteus maximus* and *sartorius*. The range of medial rotation is only from 15° to 30° and that of lateral rotation is up to 60°, (Pons, 2008).

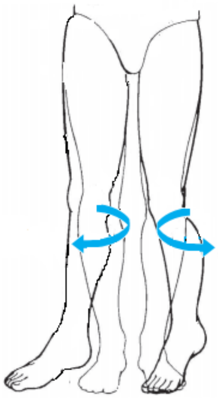

Figure 3.7 – Medial–lateral rotation, hip movement in the transverse plane (Hall, 2015).

3.2.4.2 Movements at the Knee Joint

The knee joint is a synovial hinge joint which behaves just like ellipsoidal. It is formed by the bones: *the femur*, *the tibia* and *fibula*, and *the patella*. In (Moore, 1992), it is described to have two parts: the *femoro-patellar* joint and the *femoro-tibial*, and it moves in different cardinal reference planes that pass through the joint center allowing two possible degree of freedom (2DOF) which include: (a) *Flexion–extension* and (b) *Medial–lateral rotation*. One of these 2DOF (*Flexion–extension*) is the most important joint which allows stable locomotion of an individual.

(a) **Flexion–extension**

Just like in hip joint, flexion and extension are movements at the knee joint that occur in the sagittal plane. In flexion, the shank approaches the thigh while the femur and tibia remain in the same plane while the extension is just the opposite of flexion. Knee flexion is accomplished by the muscles: *semimembranosus*, *semitendinosus*, *biceps femoris*, *sartorius*, *gracilis* and *gastrocnemius*, while knee extension is accomplished the by muscles: *rectus femoris* and the *vastii* (*medialis*, *lateralis* and *intermedius*). The range of knee flexion is up to 120° when the hip is extended, 140° when the hip is flexed and 160° when the knee is flexed passively, and the range of knee extension is from 0–10°, (Pons, 2008).

(b) **Medial–lateral rotation**

Knee joint medial-lateral rotation is the rotation at the knee joint that occurs in the transverse plane. Medial rotation is an internal rotation that occurs during the final stage of extension that brings the knee to the locked position for maximum stability, while Lateral rotation occurs during the early stage of flexion. The knee medial rotation is accomplished by the muscles: *sartorius*, *gracilis* and *semitendinosus*, whith the knee lateral rotation is accomplished by the muscle *biceps femoris*. The range of the knee medial rotation is limited to 10° with 30° of flexion and is limited to 15° when the knee is fully flexed, while the range of the knee lateral rotation is limited to 30° with 30° of flexion and to 50° with 120° of flexion, (Pons, 2008).

3.2.4.3 Movements at the Ankle Joint and Foot Articulations

The ankle is a hinge-type synovial joint located at the inferior part of the lower extremity which is involved in lower limb stability. The ankle and foot together contain 26 bones connected by 33 joints, and more than 100 muscles, tendons and ligaments (Pons, 2008). The foot plays an important role in supporting the weight of the body and in locomotion. It can be divided into three parts – hindfoot, midfoot and forefoot – formed by the following bones: talus, calcaneus, navicular, cuboid and cuneiforms, metatarsal and phalanges. The ankle comprises basically two joints: the talocrural joint and the talocalcaneal joint (Moore, 1992). However, in biomechanical modelling it is usually treated as a single joint.

(a) **Dorsal flexion and Plantar flexion**

Dorsal and plantar flexion are movements at the ankle joint in sagittal plane (figure 3.8). Dorsal flexion is the movement that brings the foot dorsally to the anterior surface of the leg, while plantar flexion is the just the opposite of dorsal flexion. Dorsal flexion is accomplished by the muscles: *tibialis anterior*, *extensor hallucis longus*, *extensor digitorum longus* and *fibularis tertius*, while plantar flexion is accomplished by: *gastrocnenius*, *soleus* and *plantaris*. The range of motion in dorsal flexion is up to 20°, while the range of motion in plantar flexion is from 40° to 50°, (Pons, 2008).

Figure 3.8 – Dorsal-plantar flexion movement of an ankle (Hall, 2015).

(b) **Inversion and Eversion (heel and forefoot)**

Inversion and eversion are movements at the ankle joint that occur in frontal plane (figure 3.9). Inversion involves moving the heel and forefoot towards the mid-line of the body, bringing the footsole towards the median plane while eversion consists of moving the heel and forefoot laterally placing the sole of the foot away from the median plane. Inversion is accomplished by the muscles: *tibialis posterior* and *tibialis anterior*, while eversion is accomplished by the muscles: *fibularis longus* and *fibularis brevis*. The range of motion for inversion is between 30° and 35°, while the range of motion for eversion is between 15° and 20°, (Pons, 2008).

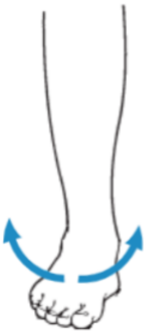

Figure 3.9 – Inversion-eversion movement of an ankle (Hall, 2015).

(c) **Pronation and Supination**

Pronation is a combination of forefoot inversion and abduction, while supination is a combination of forefoot inversion and adduction. Pronation is accomplished by the muscle *fibularis longus*, while supination is accomplished by the *tibialis* muscles.

3.2.5 The Kinematic Modelling

Kinematics is the branch of mechanics that deals with the description of the motion of points, bodies, or systems of bodies, without considering the forces that produce them. Referring to lower limb exoskeletons, it deals with the analysis of the motion of each robot link with respect to a reference frame. It also involves an analytical description of motion as a function of time, and the nonlinear relationship between the robot's end-effector position, orientation and configuration.

Kinematics can either be a forward or an inverse kinematics, depending on what parameters are to be determined. A forward kinematics consists in determining the body configuration and the position and orientation of the end-effector on the basis of the known angles and displacements of the links, while, an inverse kinematics consists in determining the angles and displacements on the basis of the known position and orientation of the end effector.

In this work, the forward kinematics approach is applied, and the human body segments are therefore considered to be a chain of rigid links. In this case, any linear displacement is not taken into consideration. The structural segments of the exoskeleton were also considered to strongly imitate the human counterparts in terms of degrees of freedom (DoFs) and range of motion (ROMs). The end-effector is placed at the tip of the longest toe.

In figure 3.10, the Denavit–Hartenberg model is presented. In this case, coordinate (X_0, Y_0, Z_0) represents a reference frame. At the hip joint, (X_1, Y_1, Z_1) represents the medial and lateral rotation coordinate while (X_2, Y_2, Z_2) represents flexion–extension coordinate. At the knee joint, (X_3, Y_3, Z_3) represents flexion–extension coordinate. At the ankle, (X_4, Y_4, Z_4) represents dorsiflexion–plantarflexion coordinate while (X_5, Y_5, Z_5) represents inversion–eversion coordinate. The end-effector is placed at the tip of the longest toe and is referenced as (X_6, Y_6, Z_6) coordinate. The Denavit–Hartenberg parameters are shown in table 3.1.

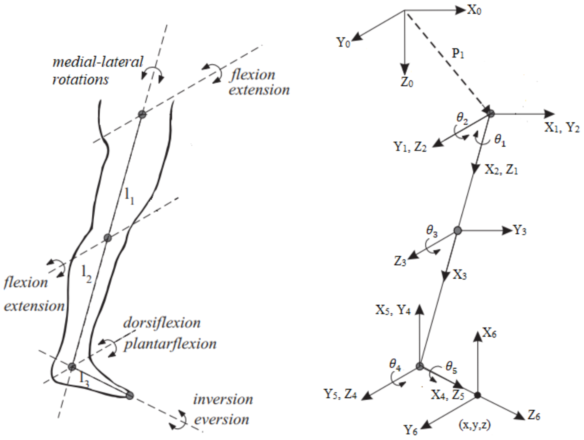

Figure 3.10 – Denavit–Hartenberg model for a human leg, adapted from (Pons, 2008).

Table 3.1 – D–H parameter for leg segment (Pons, 2008).

Joint	β_i	**Number**	α_i	a_i	d_i	θ_i
Base	0	$1_{(0\to1)}$	0	a_0	d_0	0
Hip	(-30) medial rotation/lateral rotation (+60)	$2_{(1\to2)}$	-90°	0	0	β_1 + 90°
Hip	(-20) extension/flexion (+120)	$3_{(2\to3)}$	0	l_1	0	β_2
Knee	(0) extension/flexion (+135)	$4_{(3\to4)}$	0	l_2	0	β_3 + 90°
Ankle	(-40) plantarflexion/dorsiflexion (+20)	$5_{(4\to5)}$	+90°	0	0	β_4 + 90°
Ankle	(-35) inversion/eversion (+20)	$6_{(5\to6)}$	0	0	l_3	β_5

3.2.6 The Dynamic Modelling

3.2.6.1 The body motion equation

In the dynamic analysis, the main focus are the forces and moments in the joints that cause the movements of the legs. It can be deducted based on the Lagrangian-Euler formulation that, the body motion can be expressed by equation 3.1.

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta}) + K(\theta) = \tau, \tag{3.1}$$

where θ is the vector of joint coordinates, $\dot{\theta}$ is the vector of joint velocities and $\ddot{\theta}$ is the vector of joint accelerations; all three are functions of time. $M(\theta)$ is a square inertial matrix and represents the effect of joint acceleration on the generalized torque, $C(\theta, \dot{\theta})$ is the vector of centrifugal and Coriolis forces and $K(\theta)$ is a vector of gravity related forces.

3.2.6.2 Double compound Pendulum Modeling

Since the active and the only two motorized joints rotate on the same anatomical plane, the motion performed by the exoskeleton is therefore restricted to two dimensions. In this case, the concept of a double compound pendulum can be applied to model the behavior of the movements performed by these joints whenever a force is applied. Figure 3.11 shows this relationship.

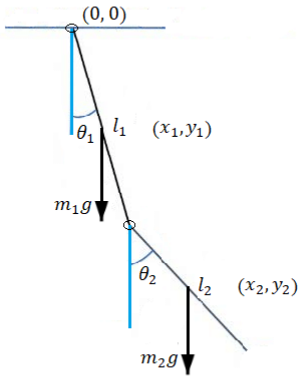

Figure 3.11 – Double pendulum implementation.

For the double pendulum implementation, if the origin of the Cartesian coordinate system is taken to be at the point of suspension of the first pendulum, then the center of mass of the first pendulum is located at point (x_1, y_1) as represented by equations (3.2 and 3.3).

$$x_1 = \frac{l_1}{2} sin\theta_1 \tag{3.2}$$

$$y_1 = -\frac{l_1}{2} cos\theta_1 \tag{3.3}$$

It can also be observed that, the center of mass of the second pendulum is located at the point (x_2, y_2) as presented by equations (3.4 and 3.5).

$$x_2 = l_1 sin\theta_1 + \frac{l_2}{2} sin\theta_2 \tag{3.4}$$

$$y_2 = -l_1 cos\theta_1 - \frac{l_2}{2} cos\theta_2 \tag{3.5}$$

To find the moment of inertia of each link, if the mass is evenly distributed, then the center of mass of each link is at its midpoint, and the limb has a moment of inertia at equation 3.6.

$$I_i = \frac{1}{12} m_i l_i^2 \tag{3.6}$$

However, the Lagrangian L can be expressed as the potential energy subtracted from the kinetic energy as expressed by the equation 3.7.

$$L = KineticEnergy - PotentialEnergy \tag{3.7}$$

$$= \tfrac{1}{2}m_1v_1^2 + \tfrac{1}{2}m_2v_2^2 + \tfrac{1}{2}I_1\dot{\theta}_1^2 + \tfrac{1}{2}I_2\dot{\theta}_2^2 - m_1gy_1 - m_2gy_2$$

$$= \tfrac{1}{2}m_1(\dot{x}_1^2 + \dot{y}_1^2) + \tfrac{1}{2}m_2(\dot{x}_2^2 + \dot{y}_2^2) + \tfrac{1}{2}I_1\dot{\theta}_1^2 + \tfrac{1}{2}I_2\dot{\theta}_2^2 - m_1gy_1 - m_2gy_2$$

From this equation, it is deducted that, the first and second terms are the linear kinetic energy of the center of mass of the bodies, the third and fourth terms are the rotational kinetic energy around the center of mass of each rod, and the last two terms are the potential energy of the bodies in a uniform gravitational field.

When simplifications were applied by substituting the coordinates above and rearranging, equation 3.8 is obtained.

$$L = \frac{1}{6}L^2(m_2\dot{\theta}_2^2 + m_1 4\dot{\theta}_1^2 + m_1 3\dot{\theta}_1\dot{\theta}_2 cos(\theta_1 - \theta_2)) + \frac{1}{2}gl(m_1 3cos\theta_1 + m_2cos\theta_2) \tag{3.8}$$

It is observed that, there is only one conserved quantity (the energy), and no conserved momentum. Therefore, the two generalized momentum may be written as equations 3.9 and 3.10.

$$p\theta_1 = \frac{\partial L}{\partial \dot{\theta}_1} = \frac{1}{6}m_1L^2(8\dot{\theta}_1 + 3\dot{\theta}_2 cos(\theta_1 - \theta_2) \tag{3.9}$$

$$p\theta_2 = \frac{\partial L}{\partial \dot{\theta}_2} = \frac{1}{6}m_2L^2(2\dot{\theta}_2 + 3\dot{\theta}_1 cos(\theta_1 - \theta_2) \tag{3.10}$$

These two equations above may be inverted to obtain equation 3.11 and 3.12.

$$\dot{\theta}_1 = \frac{6}{m_1L^2}\frac{2p\theta_1 - 3cos(\theta_1 - \theta_2)p\theta_2}{16 - 9cos^2(\theta_1 - \theta_2)} \tag{3.11}$$

$$\dot{\theta}_2 = \frac{6}{m_2L^2}\frac{8p\theta_2 - 3cos(\theta_1 - \theta_2)p\theta_1}{16 - 9cos^2(\theta_1 - \theta_2)} \tag{3.12}$$

3.3 ACTUATORS

Lower limb exoskeletons actuations are analogous to human leg joints, they provide and regulate the joint angles needed to move the exoskeleton wearers from one place to another. There were many types of actuators used for the construction of exoskeletons adopted by several projects from the literature and these include: Electric Motors, Hydraulic Actuators, Pneumatic Actuators, Pneumatic Muscle Actuators, and Series Elastic Actuators (SEAs). Each of these actuators can be chosen based on the project's requirements.

In (Aguillar-Sierra et al., 2015), two actuators (DC motor with harmonic unit and pneumatic artificial muscle) were used for the hip and knee joints and took the advantage of the harmonic drive actuator's, high torque, high precision positioning and relatively small dimensions and the electric motor's high torque to weight ratio, reduced noise, and reliability. Stepper motors and servo motors are capable of very advanced position-based control which is much more difficult to achieve with pneumatic or hydraulic systems. Pneumatic or hydraulic actuators have high ratio of actuator power to actuator weight. series elastic actuators have special characteristics such as highfidelity, extremely low impedance, low friction and others. The first walking active exoskeleton developed by Prof. M. Vukobratovic and his team at Mihailo Pupin Institute was pneumatically actuated. The General Electric Research's full-body powered exoskeleton prototype was actuated using a hydraulic unit. In 1974, the first known example of active exoskeleton actuated using electrical motors was designed. However, in recent years, DC electric motors, linear pneumatic and hydraulic actuators are mostly used. Since early 1990s, researchers started to develop SEAs which are now playing an important role in actuation design.

3.4 SENSORS

Sensors have been playing a significant role in controlling lower limb exoskeletons. They are the main source of information in the cognitive human-robot interaction and are mostly used to regulate force and position of the assistive device. Most of the sensors used in control of exoskeletons are: force sensor, pressure sensor, encoders, Hall effect sensor, pose sensor, electromyography (EMG) sensor and electroencephalogram (EEG) sensor. In table 3.2, Some of the sensors used in several exoskeletons are presented. Some of the projects found in the literature used more than one type of sensor for controlling the lower limb exoskeletons such as in (Onen et al., 2014), (Sankai, 2006) and other while some used only one sensor for this control such as in (Vinoj, Jacob and Menon, 2015) and (Aguilar-Serra et al., 2015). Figure 3.2 shows some of the characteristics of exoskeletons designs based on literature analysis.

Table 3.2 – Characteristics of exoskeletons designs based on literature analysis.

SN	Reference	Actuator	Sensor	DOF
1	(Van Der Kooijl, 2006) (Veneman et al., 2007)	DC Servomotor	EMG + Force sensors in the feet.	8
2	(Winfree et al., 2011) (Winfree et al., 2011)	DC Motor	Joint Encoders + Knee and hip load cells + pressure sensors in the soles of the feet.	3
3	(Onen et al., 2014) (Onen et al., 2014)	DC Servomotor	Motor encoders + force sensors at the sole of the feet.	3
4	(Beyl, 2010) (Beyl, 2010)	Linear Pneumatic Actuator	Pressure Sensors + foot force sensors + knee and hip encoders.	2
5	(Kawamoto, 2003), (Sankai, 2006	DC Motor	EMG + encoders (knee and hip) + Pressure and Force Sensors on the soles of the feet	3
6	(Sankai, 2006), (Sankai, 2010)	DC Motor	EMG + encoders (knee and hip + arms and trunk) + Pressure and force sensors on the soles of the feet.	
7	(Kim et al., 2004), (Zoss et al., 2006)	Linear Hydraulic Actuator	16 accel erometers + 10 encoders + 8 feet sensors + 6 force sensors + 1 load cell +1 in clinometer + 6 servo hydraulic valves	7
8	(Vinoj et al., 2019),	DC Motors	EEG sensor + angular + pressure sensor	3
9	(Aguiler-Sierra, 2015)	DC Motors + Pneumatic Artificial Muscles.	EMG sensor + pressure + linear motion sensors	7
10	(Long et al., 2016)	DC Motor + gear pair transmission + ball screw with a slide nut	Gyroscope + position + force + posture sensor	7

3.5 CONTROL

It was observed that, the control strategies vary widely from one project to another. The two common forms of control strategies applied in controlling lower limb exoskeletons are the, Force-based control and Position-based control strategies. The Forced-based control strategy is commonly applied to exoskeletons for human performance augmentation. It involves the application of force/torque value based on the assumed portion of the gait cycle. The Position based control strategy is usually applied when the user has little ability to interact with the exoskeleton (Young, A. J.; Daniel P. F., 2017)[33], it is commonly applied to exoskeletons for rehabilitation applications. In Mcdaid, A. J. et al (2013) and Vinoj, P. G. et al. (2019), the exoskeletons are controlled by the brain waves of the user using an electroencephalogram (EEG) headset based on human intention to move. In this case, the headset used by the wearer is capable of capturing brain signals and sending them to a microcontroller for motion execution. In the automatic control strategy, the exoskeleton is set to mimic normal human walking in a repetitive way.

3.6 HUMAN-ROBOT INTERACTION

Human-Robot Interaction is the interaction between the wearer and the robotic exoskeleton. This interaction can be physical human–robot interaction or cognitive human–robot interaction. “The interaction between the wearable robot and the human is a critical factor for ensuring smooth and efficient control strategies that will be based on the estimation of the wearer’s motion intention” (Huo et al, 2016).

3.6.1 Physical Human-Robot Interaction

In physical human-robot interaction (pHRI), the interaction between the human body and the mechanical structure of lower limb exoskeletons is considered. The key role of a robotic exoskeleton in a pHRI is the generation of supplementary forces to empower and overcome human physical limits. This limits can either be natural or even the result of a disease or trauma. Therefore, there is a direct flux of power between both actors (exoskeleton and the user). However, pHRI are designed according to the interaction forces between the user and the exoskeleton.

In pRHI, the anthropometry of human body which is the basis of exoskeleton design is considered. This is done during the mechanical design phase, by proper establishment of the structural requirements such as the material to be use, number of degree of freedom, number of actuated joints, joints restriction, type of actuator to be used, weight of the robot, height of the links and waist diameter among others. It was also observed that, there were different types of actuators used by different projects. For instance, (Sankai et al, 2006) used electric motors, (Beyl et al., 2010) used linear pneumatic actuators, (Zosh et al., 2015) used hydraulic actuators and (Aguiler-Sierra et al., 2015) used the combination of two types of actuators.

3.6.2 Cognitive Human-Robot Interaction

In the cognitive human-robot interaction (cHRI), the cognitive process involves reasoning, planning and execution of a previously identified goal. Here, the main objective is to create a cognitive system that reflects the wearer's intent to move. In this case, the human–robot interaction is designed in such a way that, there is some kind of direct communication between the robot and human biological aspects such as EMG and EEG signals. These signals are measured from the human body and reflect the human motion intention directly, which can be fully estimated without information loss and delay. Based on these two types of signals, corresponding control strategies have also been developed to assist the users to ensure daily living activities and rehabilitation exercises. On the other hand, one of the crucial roles of a cHRI is to make the human aware of the possibilities of the robot while allowing him to maintain control of the robot at all times.

In (Aguilar-Serra et al., 2015), the human-machine interface (HMI) uses the EMG sensors which are put on several muscles of human lower limb to capture its movements, generate a base of gait patterns and send EMG signals to a computer via a wireless connection. In (Vinoj et al., 2019), the EEG sensor has 16 electrodes incorporated in its structure, where two electrodes act as the measurement references. It also uses a noninvasive method to collect brain signals from the scalp of the person. The signal is then converted into digital data which is given as an input to a microcontroller. It is applied in (Kawamoto et al., 2003), (Van Der Kooij et al., 2006), (Sankai et al, 2006), (Aguiler-Sierra et al., 2015) and (Vinoj et al., 2019).

4 PROJECT REQUIREMENTS AND MATERIAL SELECTION

4.1 INTRODUCTION

From the literature analyses, it was observed that, generally, lower limb exoskeletons have common characteristics such as: height, weight, actuation type, sensors, number of degree of freedom and material used for the mechanical structural development. Therefore, to design a lower limb exoskeleton that is compatible with the target populations heights and weights (i.e., Brazilian population's height and weight), it was necessary to analyze the standard properties of human body and some relevant characteristics of this population in order to establish and select the project requirements, which include: (a) *exoskeleton's structural components dimensions*, (b) *number of degrees of freedom*, (c) *actuator type*, and (d) *material for the the mechanical structure*.

In *exoskeleton's structural components dimensions*, anthropometric proportions of human body, average height and weight of the Brazilian population were analyzed. From these analyses, exoskeleton's: height, weight, waist diameter, links lengths, foot length and foot width were established. To make the structure compatible to different size within the established minimum and maximum ranges, the components are dimensioned to be adjustable.

In *number of degrees of freedom*, mechanisms of human movement and lower limb joints articulations were analyzed, in this scenario, movements at the hip joint, knee joint and ankle joint were analyzed. From these, number of degrees of freedom for each joint was established. The selection of the number of the degrees of freedom is made to provide a normal and comfortable movement to the user.

In *actuator type*, all analyses made on different types of actuation from the literature were considered, and for this work, a Maxon motor and a plenary gearhed were selected as the actuation unit. Characteristics of this actuation unit were also established, which include: power, torque, angular velocity, reduction ratio and power supply required to move the exoskeleton and the load (user) from one point to another (see Appendix II). However, it was also noticed that, to transmit the motor's torques to the links, some additional components need to be designed.

In *materials for the mechanical structure*, some materials were analyzed which include: two steel type (Steel 1020 and Steel 1045), two aluminum type (Aluminum 6000 and Aluminum 7000), a Brass metal and plastics. They are necessary for the links design, foot articulation design and additional components for the actuation unit designs. These materials were chosen to be analyzed considering their suitability for this work and also their availability in close markets which facilitate their acquisition and consequently reduce the production time and cost.

4.2 EXOSKELETON'S STRUCTURAL COMPONENTS DIMENSIONS

4.2.1 Average Height and Weight of the Brazilian Population

Height and weight are two important properties to be considered when designing a mechanical structure of lower limb exoskeletons. In this work, the data that provides the information about the average height and average weight of the Brazilian population was obtained from the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística IBGE*) based on a survey carried out in the year 2008.

According to the survey, almost half of the Brazilian population (49%) aged 20 or over is overweight. This data is part of the study of anthropometry and nutritional status of children, adolescents and adults in Brazil ("*Antropometria e estado nutricional de crianças, adolescentes e adultos no Brasil*") released in 2009 and which was part of the 2008/2009 family budget survey. The survey showed that, from 20 to 24 years of age, the medians of height and weight of the Brazilian men were 1.73m in height and 69.4kg in weight while that of women were 1.61m in height and 57.8kg weight (see table 4.1). It was also observed that, the number of overweight men jumped from 18.5% in 1974-1975 to 50.0% in 2008-2009, in women, this increase was observed to be from 28.7% to 48%. (G1, 2010).

The study assesses the nutritional status of the population from the height, weight and Body Mass Index (BMI) for each age. Body Mass Index is obtained by dividing the weight in kilogram by height in meter square. More than 188.000 people of all ages were interviewed between May 2008 and May 2009. People with BMI of 25kg/m2 and less than 30kg/m2 are considered overweight, people with BMI equal to or greater than 30kg/m2 are considered obese and people with BMI below 18.5kg/m2 are considered to have a weight deficit. According to the IBGE, the survey points out that, in addition to almost half of Brazilian adults' overweight, another 14.% are obese and only 2.7% are underweight. Obesity is higher among women aged 20 years and above (16.9%) than among men (12.5%) while overweight, on the other hand, is registered mostly among men (50.1%) than among women (48%), (G1, 2010) (table 4.1).

Table 4.1 – Average height and weight of Brazilian population of 18 years and above (Ibge, 2020).

Age and Age Interval	**Average Height (mm)**		**Average Weight (kg)**	
	Men	**Women**	**Men**	**Women**
18 years	1726	1611	65.3	55.4
19 years	1720	1612	65.9	56.2
20 to 24 years	1730	1611	69.4	57.8
25 to 29 years	1730	1607	72.7	60.5
30 to 34 years	1716	1600	74.2	62.0
35 to 44 years	1710	1594	74.6	63.8
45 to 54 years	1699	1583	74.6	65.1
55 to 64 years	1682	1566	73.1	65.3
65 to 74 years	1669	1550	70.3	63.4
75 years and above	1657	1528	66.8	59.2

4.2.2 Anthropometric Proportions of Human Body

Anthropometry of human body is the basis of exoskeletons design since the devices are aimed to corporate with the human body parts. Table 4.2 shows some of the properties of human body segments such as the mass, length, center of gravity. In this table, the weight of body segments are expressed as % of total body weight, the length of body segments are expressed as % of total body height, and the gravitational center (GC) locations are expressed in % of segment lengths; measured from the proximal ends of segments.

Table 4.2 – Some properties of human body segments, weight, length and CG, (Hall, 2015).

Body Segment	**Males**			**Females**		
	Weight	**Length**	**CG**	**Weight**	**Length**	**CG**
Head and neck	08.26	10.75	55.00	08.20	10.75	55.00
Trunk	46.84	30.00	63.00	45.00	29.00	56.90
Upper arm	03.25	17.20	43.60	02.90	17.30	45.80
Forearm	01.87	15.70	43.00	01.57	16.00	43.40
Hand	00.65	5.75	46.80	00.50	05.75	46.80
Thigh	10.50	23.20	43.30	11.75	24.90	42.80
Lower Leg	04.75	24.70	43.40	05.35	25.70	41.90
Foot	01.43	04.25	50.00	01.33	04.25	50.00

In (Hall, 2015), it is shown how to use a segmental method to determine total-body center of mass location based on the masses and center of gravity (CG) of the individual body segments. This procedure takes the advantage that, the body is composed of individual segments and that each segment has it's individual CG, therefore, the location of the total-body CG is a function of the locations of the respective segmental CGs. However, some body segments are more massive than others and as such have a larger influence on the location of the total-body CG. By this method, the total-body CG is calculated by the, sum of the product of each body segment's CG and its mass divided by the sum of all segmental masses, see equation 4.1.

$$\frac{\sum_{i=1}^{n} CG_i M_i}{\sum_{i=1}^{n} M_i} \tag{4.1}$$

As presented in many exoskeleton project developments such as in Aguillar, (2015), Dos Santos, (2016) and many others, in this work also, the technique of anthropometry was also used for dimensioning the: (a) waist diameter, (b) links heights, (c) foot length, and (d) foot width. For this dimensioning, the average height from table 4.1 was used for the calculations. Figure 4.1 shows some standard properties of human body.

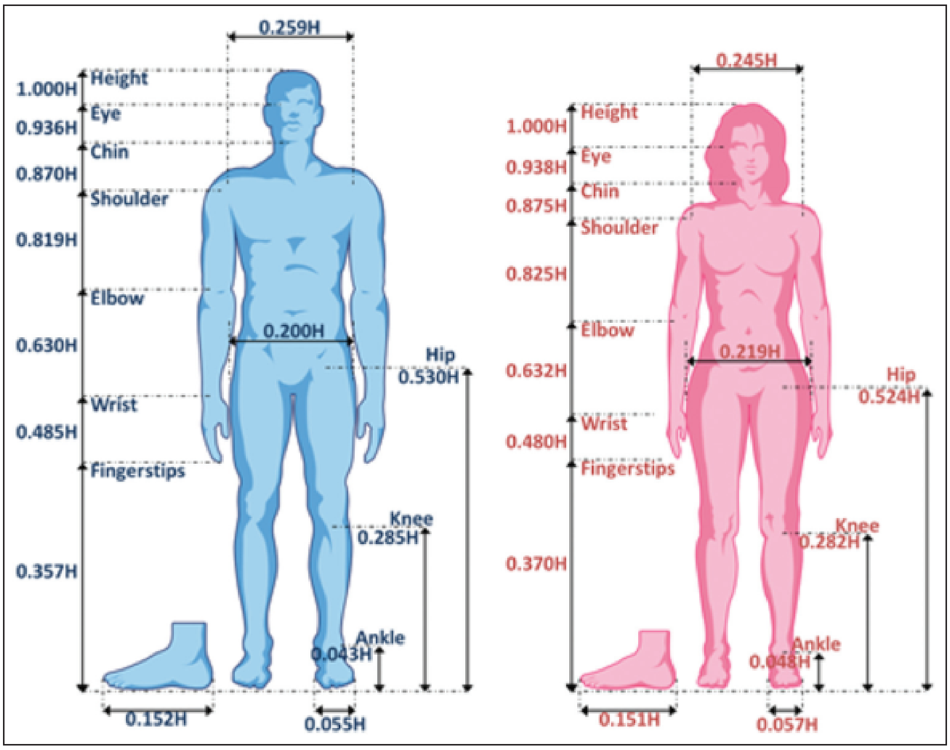

Figure 4.1 – Standard properties of human body (Aguillar, 2015).

Based on the standard properties of human body (figure 4.1), the structural components dimensions of the exoskeleton's: (a) *Waist diameter*, (b) *Upper link length*, (c) *Lower link length*, (d) *foot length* , and (e) *foot width* were calculated. For this calculations, average height of Brazilian men was taken as 1730mm and that of Brazilian women as 1612mm respectively. The age for possible users of the exoskeleton was considered to be 18 years and above. From table 4.1, the weight interval of the user considering both the men and women is from 55.4kg – 74.6kg. Therefore, the mechanical structure of the final design must support a user of 74.6kg.

If i stands for an individual (men or women) and H_i is height, WD_i is the waist diameter, HN_i is the hip to knee length, NA_i is the knee to ankle length, AG_i is the ankle to ground length, FL_i is the foot length, and FW_i is the foot width, then;

Waist Diameter Exo (WE)

$$WE_i = H_i \; . \; WD_i \tag{4.2}$$

$$WD_{men} = 1730(0, 200) = 346mm$$

$$WD_{women} = 1612(0, 219) = 353.028mm$$

Hip to Knee Height Exo (HNE)

$$HNE_i = H_i \; . \; HN_i \tag{4.3}$$

$$HNE_{men} = 1730(0,530 - 0,285) = 424mm$$

$$HNE_{women} = 1612(0,524 - 0,282) = 390.104mm$$

Knee to Ankle Height Exo (NAE)

$$NAE_i = H_i \ . \ NA_i \tag{4.4}$$

$$NAE_{men} = 1730(0,285 - 0,043) = 418mm$$

$$NAE_{women} = 1612(0,282 - 0,048) = 377.208mm$$

Ankle to Ground Height Exo (AGE)

$$AGE_i = H_i \ . \ AG_i \tag{4.5}$$

$$AGE_{men} = 1730(0,043) = 74.39mm$$

$$AGE_{women} = 1612(0,048) = 77.376mm$$

Foot Length Exo (FLE)

$$FLE_i = H_i \ . \ FL_i \tag{4.6}$$

$$FLE_{men} = 1730(0,152) = 262.96mm$$

$$FLE_{women} = 1612(0,151) = 243.412mm$$

Foot Width Exo (FWE)

$$FWE_i = H_i \ . \ FW_i \tag{4.7}$$

$$FWE_{men} = 1730(0,055) = 95.15mm$$

$$FWE_{women} = 1612(0,057) = 91.884mm$$

In table 4.3, components dimensions to be considered during the design of the exoskeleton are presented. These dimensions were calculated considering the standard properties of human body and the data collected from IBGE (average height and weight). The adapted dimensions were chosen in such a way that, the final structure is adjustable in three regions: (a) *Waist diameter*, (b) *Upper link length* and (c) *and Lower link length* of each leg. All adjustment were done individually.

Table 4.3 – Exoskeleton’s components dimension

Design Parameters	Men	Women	Adapted Dimension
Height (mm)	1730	1612	1550 – 1780 (Possible Use)
Weight (kg)	74.6	65.3	56 – 100 (Possible Use)
Waist diameter (mm)	346	353	320 – 375 (Adjustable)
Upper link height (mm)	424	387	360 – 450 (Adjustable)
Lower link height (mm)	418	374	350 – 440 (Adjustable)
Ankle to Ground height (mm)	74.4	77.38	75
Foot Length (mm)	263	243	290
Foot Width (mm)	95	92	150

4.3 NUMBER OF DEGREES OF FREEDOM

4.3.1 Joints Restrictions

To establish joint restriction angles, different choices of joint restrictions adapted by various projects in the literature were analyzed. This analysis provided us with an idea of how important it is to understand the target populations biomechanics in order to establish comfort angles for the mechanical design of our project. The problem of joint constraints of an anthropomorphic exoskeleton may be easily solved by the use of similar constraints of anatomical joints of the user. This type of approach aims to enable full equivalence to the set of possible movements described by the human body. However, some designers questioned the real need this wide range of movements given the current state of development and purpose of their projects, as well as restrictions imposed by the types of activities used (Wehner et al., 2013). Table 4.4, table 4.5 and table 4.6 present some of the joint restriction for the hip, knee and ankle joints respectively, adapted by some projects from the literature.

Table 4.4 – Hip joint restriction of some project from the literature.

Project	Flexion	Extension	Abduction	Adduction	Media Rotation	Lateral Rotation
HAL	120°	20°	-	-	-	-
BLEXX	121°	10°	16°	16°	-	-
WSE	100°	17°	-	-	-	-
MindWalker	110°	18°	17°	19°	10°	10°
(Long et al.,2016)	120°	30°	45°	20°	50°	40°
ExoSuit	035°	10°	-	-	-	-

Table 4.5 – Knee joint restriction of some Project from the literature.

Project	Flexion	Extension
HAL	120°	6°
BLEXX	121°	0°
WSE	100°	0°
MindWalker	120°	1.5°
(Chen et al. 2016)	90.5°	0°
(Long et al.,2016)	150°	0°
KIT-EXO 1	65°	0°
ExoSuit	60°	5°

Table 4.6 – Ankle joint restriction of some project from the literature.

Project	Dorsal Flexion	Plantar Flexion	Inversion	Eversion	Pronation	Supination
BLEXX	45°	45°	-	-	20°	20°
MindWalker	-	-	-	-	20°	20°
(Chen et al. 2016)	20.8°	38.8°	-	-		
(Long et al.,2016)	20°	40°	35°	20°	35°	20°
KIT-EXO-1	25°	45°	7°	7°	-	
Exosuit	10°	25°	-	-	-	

Table 4.7 – Comfort angles of lower limb joints (Aguillar, 2015).

Joint	Movement	Range
Hip	Hyperextension Flexion	0–45° 0–130°
Knee	Flexion	0–135°
Ankle	Dorsiflexion Plantarflexion	0–20° 0–40°

4.4 MATERIAL SELECTION

For the sake of easy accessibility within the Brazilian borders, some materials (metals) were selected and analyzed for the exoskeleton's structural development. In this case, five materials were selected and analyzed, they are: two of Steel types (Steel 1020 and Steel 1045), two of Aluminum types (Aluminum 6000 and Aluminum 7000) and a Brass metal. These five materials were chosen to be analyzed considering their suitability for this project and also, for their availability within the Brazilian markets, thereby facilitating acquisition and subsequently reducing the production cost.

4.4.1 Steel 1020

Steel 1020 (GGD 1020 steel) presents an excellent plasticity and weldability. It is used in mechanical components such as gears, shafts, crankshafts, camshafts, guide pins, gear rings, columns, ratchets, covers. Is one of the most common carbon steels used as cementation steel with an excellent cost-benefit ratio compared to more alloyed steels for the same purpose. It has excellent plasticity and weld ability. After carburizing it is benefited, but it has less hardening capacity, compared to GGD 8620 for example.

4.4.2 Steel 1045

Steel 1045 (GGD 1045 steel) presents a good relationship between mechanical strength and fracture resistance. Generally used in the manufacture of general-purpose components where a mechanical strength higher than that of conventional low-carbon steels is required. Mainly applied to axles in general, pins, cylinders, bolts, screws, clamps, nails, columns, among others.It is a steel for processing with low temper ability, that is, low penetration of hardness in the cross section, its use is not recommended for sections greater than 60 mm. It is generally used with hardness's of 180 to 300 HB. For large sections, use standard heat treatment.

4.4.3 Aluminum 6000

6000 series are aluminium alloys with magnesium and silicon as the major alloying elements. 6000 series alloys present good corrosion resistance and formability. They are moderate strength alloys, achieved by either heat treating or cold working. For a heat treatable grade, they have excellent spot and fusing weldability and can be furnace brazed. They can also be easily anodized. Some of the applications of 6000 series aluminium alloys are found in the manufacture of: window and door parts, architectural applications, hardware, furniture parts, rings, fuses, electrical conductors, screw machine parts, among other.

4.4.4 Aluminum 7000

7000 series are aluminium alloys with the highest strength of all the series. Zinc is the primary alloying element. Most 7000 series alloys include magnesium and copper as well. 7000 series alloys have excellent fatigue properties. In the T6 condition fracture toughness can be inferior to other alloys. Alloys in series can be spot welded but not fusion welded. If corrosion is a concern, 7000 series alloys should be anodized, primed, painted or protected with some type of chemical film. Some of the applications of 7000 series aluminium alloys are found in: fin stock and applications requiring high strength.

4.4.5 Brass

Brass is commonly used in applications which require low friction where corrosion resistance and low friction is required, such as locks, hinges, gears, bearings, ammunition casings, zippers, plumbing, hose couplings, valves, and electrical plugs and sockets. The composition of brass, generally 66% copper and 34% zinc, makes it a favorable substitute for copper based jewelry as it exhibits greater resistance to corrosion. Figure 4.8 and figure 4.9 show safety factors and characteristics of the discussed materials.

Table 4.8 – Safety factors and characteristics.

Material	Massa Ind.	Dimension Ind.	Static SF	FS Fadiga ASME	FS Fadiga ABNT
Steel 1020	0.226 kg	50 x 24 x 12 mm	14.86	14.63	11.14
Steel 1045	0.226 kg	50 x 24 x 12 mm	12.14	11.33	9.10
Alum. 6000	0.078 kg	50 x 24 x 12 mm	3.82	3.80	2.86
Alum. 7000	0.078 kg	50 x 24 x 12 mm	4.08	3.97	3.05

Table 4.9 – Characteristics of the selected metals.

	Steel 1020 Normal	Steel 1045 Normal	Aluminum 6000 Hardness H14	Aluminum 7000 Hardness H12
Modulus of elasticity:	200.0 Gpa	200.0 Gpa	70.0 GPa	75.0 Gpa
Rigidity Module:	79.3 Gpa	80.0 Gpa	26.5 GPa	28.5 GPa
Flow Limit:	295.0 Mpa	310.0 MPa	95.0 MPa	105.0 Mpa
Breaking Limit:	420.0 Mpa	565.0 MPa	130.0 MPa	135.0 MPa
Poisson's ratio:	0.24	0.29	0.33	0.33
Density:	7870 kgm3	7870 kgm3	2725 kgm3	2710 kgm3
Brinell hardness:	111 HB	163 HB	26 HB	28 HB

However, for the mechanical structural development, for this project, **6063 aluminium alloy** was selected. This is because, it offers medium strength and high corrosion resistance. It is readily suited to welding and can be easily anodised. and also, for it's availability in the Brazilian markets. A Brass was also selected for the intermediate rotator construction. Figure 4.10 shows a summary of the project requirements.

Table 4.10 – Mechanical design requisites.

S/N	**Component**	**Requisite Established**
1	Height (mm)	1550 – 1780 (Range of Use)
2	Weight (kg)	50 – 100 (Range of Use)
3	Waist diameter (mm)	320 – 375 (Adjustable)
4	Upper height (mm)	360 – 450 (Adjustable)
5	Lower height (mm)	350 – 440 (Adjustable)
6	Ankle-Ground height (mm)	75 (Fixed Value)
7	Foot length (mm)	290 (Fixed Value)
8	Foot width (mm)	150 (Fixed Value)
9	Number of Degree of freedom Hip Joint	2DOF
10	Number of Degree of freedom Knee Joint	1DOF
11	Number of Degree of freedom Ankle Joint	2DOF
12	Hip Joint Angular Range (flexion/extension)	– 20° to 120° (Active)
14	Hip Joint Angular Range (medial/lateral rotation)	– 30° to 60° (Passive)
15	Knee Joint Angular Range (flexion/extension)	0° to 135° (Active)
16	Ankle Joint Angular Range (Plantar/Dorsiflexion)	– 40° to 20° (Passive)
17	Ankle Joint Angular Range (Inversion/Eversion)	– 35° to 20° (Passive)
18	Material for the links and Actuation	6063 Aluminum Alloy
19	Complement Materials for Actuation	Brass

5 MECHANICAL DESIGN OF THE LOWER LIMB EXOSKELETON

5.1 INTRODUCTION

After the literature review analysis, there was the need for the mechanical project design of the robotic exoskeleton. In this case, the kinematic and the dynamic analyses for lower limb exoskeletons were applied. However, since the proposed final product in this, contains only two active joints that produce flexion/extension movements in the sagittal plane at the hip and at the knee joints respectively, a Denavit–Hartenberg method was adapted for the kinematic modeling, while a double pendulum method was applied for the dynamic modeling. The required joints torques to move the user and the exoskeleton were also calculated, and a 3D modeling of components was also performed using a computer aided design software (CAD). In this case, the general structure was divided into components: links, actuation, and foot articulations. Integrated together, the first prototype was modeled for visualization, analysis and a possible future remodeling.

5.2 JOINT TORQUE CALCULATION

Since there are two active joints per leg (one at the hip, and one at the knee), there is the need to calculate the required torques at the hip and knee joints respectively, that are sufficient to swing the user's limb and exoskeleton's limb simultaneously. In this case, torques at swing phase of the human gait cycle (figure 3.2(g)) are calculated. By using a free body diagram of one leg, it was possible to calculate the required torque at each joint as shown by the following equations. However, since the user is required to use crutches, it is assumed in this work that the use of the crutches will supplement the motor's torques when standing up. Therefore, the calculated torques at the knee and hip joints are sufficient for operation. The method for the torque calculation was adopted from (Shaari et al., 2015).

5.2.1 Hip Torque Equation

At swing phase, the hip joint is expected to require more torque than the knee joint, since it carries more weight than the knee joint. The equation for the required torque at the hip was obtained considering the force acting on the entire leg during walking as the leg moves through an angle θ (i.e. from hip down). Figure 5.1 shows these forces. Solving for torque at the hip joint, equation 5.1 is obtained.

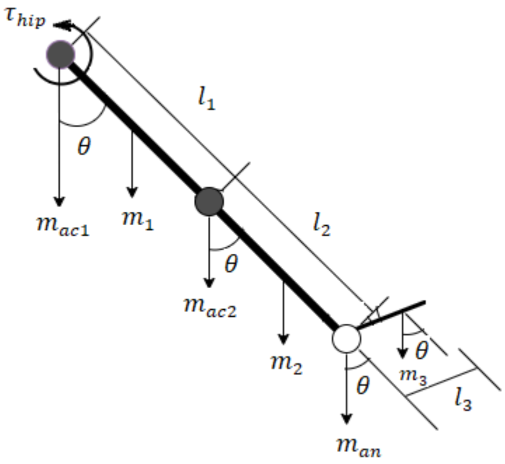

Figure 5.1 – Free body diagram showing forces acting on the hip joint.

$$\tau_{hip} = sin\theta g\left[m_1\left(\frac{l_1}{2}\right) + m_{ac2}l_1 + m_2\left(l_1 + \frac{l_2}{2}\right) + (m_{an} + m_3)(l_1 + l_2)\right] + cos\theta\left[m_3 g\left(\frac{l_3}{2}\right)\right] \tag{5.1}$$

5.2.2 Knee torque Equation

Similarly for the knee joint, the equation for the torque considers the forces acting on the leg from the knee joint down as shown in figure 5.2. Solving for torque at the knee joint, equation 5.2 is obtained.

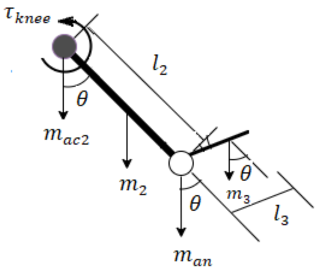

Figure 5.2 – Free body diagram showing forces acting on the knee joint.

$$\tau_{knee} = sin\theta g\left[m_2\left(\frac{l_2}{2}\right) + (m_{an} + m_3)\,l_2\right] + cos\theta\left[m_3 g\left(\frac{l_3}{2}\right)\right] \tag{5.2}$$

To calculates these torques, data on weights of body segments from table 4.2 were used.

mass of Thigh = 5.9kg, mass of Shank = 2.7kg; mass of foot = 0.72kg;

mass of Hip link = 0.3kg, mass of Knee link = 0.3kg;

m_1 = mass of thigh + mass of Hip link = 6.2kg;

m_{ac1} = mass of actuator at the Hip joint = 1.5kg;

m_2 = mass of shank + mass of Knee link = 3kg;

m_{ac2} = mass of actuator at the Knee joint = 1.5kg;

m_3 = mass of the foot + mass of foot link = 0.8kg;

m_{an} = mass of articulation at the ankle = 0,3kg;

l_1 = length of the Hip link = 0.45m;

l_2 = length of the Knee link 0.44m;

l_3 = length of the Foot link = 0.29m; and $g = 9.81m/s^2$

Using the above values in equation 5.1 and equation 5.2, the required torques at the Hip joint and at the Knee joints are calculated respectively as

$$\tau_{hip} = 31Nm \text{ and } \tau_{knee} = 7Nm$$

Therefore, the set of a motor and reducer should produce torque which is greater than 31Nm at the hip joint, and greater than 7Nm at the knee joint in order to be able to move the user and the exoskeleton. However, to stand-up from sitting, it is assumed in this work that the use of the crutches will supplement the motor's torques.

5.3 ACTUATOR SELECTION

Since this work aims at designing of a rehabilitation exoskeleton for use with SCI patients, the torques in the frontal and transverse planes can be neglected. That simplification is based in two considerations. First, the exoskeleton will only provide motion in the sagittal plane. Second, the user will not apply any extra loads or torques to the structure, except the ones caused by the inertia and weight of the leg. From the calculation above, the torque required at hip joint is 31Nm, at the knee joint is 7Nm.

Since the torque required by the exoskeleton is significantly high, reducers were selected to decrease the output speed of the motors and to increase the output torque. In this case, a brushless DC motor and reducer set selected consist of a Maxon EC90-flat motor 90W with code 323772 and a Maxon GP52C planetary gearbox with code 223095 (figure 5.3). The motor's power is sufficient for operation. For more details, see Appendix II. However, some important characteristics of this motor and the plenary gearbox are presented in table 5.1. The planetary gearbox has a reducing power of ratio 113:1, this amplify the motor's output torque by 113 times.

(a) Maxon motor

(b) Maxon plenary gearhead

Figure 5.3 – Selected actuator, (a) Maxon motor and (b) Maxon plenary geared.

Table 5.1 – Characteristics of the used motor and the reducer.

Characteristics of the Motor and the Reducer Used			
Dimension	**Weight**	**Velocity**	**Torque**
Using tape measure the motor and reducer assembled has a length of 13cm and a max. width 10.5cm	Motor and reducer assembled weigh is 1.37kg according to the datasheet of both products.	Without load, the max. speed reached by the motor and reducer is 44 RPM and with the load, the max. allowed by the reducer is 26RPM.	A max. continuous torque of 30Nm and a max. peak of 45Nm.

5.4 DC MOTOR MODELING

In this work, a MAXON set that combines a EC90 motor drive and a GP52 planetary gearhead was chosen as driving unit. As shown in (Aguilar-Sierra, 2015), here also, each motor system was divided into electrical and mechanical subsystems. The electrical system equation was obtained using Kirchhoff's voltage law as shown in equation 5.3.

$$U_i = L_i\dot{I}_i + R_iI_i + K_b\dot{\theta}_i, \tag{5.3}$$

where, U stands for the input voltage, I_i for armature current, R_i and L_i are the resistance and inductance of the armature respectively, K_b is the back emf constant, and θ_i is the angular velocity. Compared to R_iI_i and $K_b\dot{\theta}$, the term $L_i\dot{I}_i$ is small, and can be safety neglected. However, the mechanical subsystem is presented in the equation 5.4.

$$\frac{1}{K_g}(J_i\ddot{\theta} + B_i\dot{\theta}) = \tau_i, \tag{5.4}$$

where, K_g is the gear ratio, J_i is the effective moment of inertia, B_i is the viscous friction coefficient, and τ_i is the torque produced at the motor shaft. The electrical and mechanical subsystems are coupled to each other through an algebraic torque equation 5.5.

$$\tau_i = K_iI_i, \tag{5.5}$$

where, K_i stands for the torque constant of the motor. Assuming that there is no backlash or electric deformation in the gears, the work done by the load shaft equals the work done by the motor shaft, $\tau_m = (1/K_g)\tau_i$. So, the DC motor model is presented by equation 5.6.

$$\frac{R_i J_i}{K_i K_g}\ddot{\theta} + \left(K_b + \frac{R_i B_i}{K_i K_g}\right)\dot{\theta} = U_i. \tag{5.6}$$

5.5 EXOSKELETON DESIGN AND PROTOTYPE CONSTRUCTION

In this part of the project development, the mechanical design of the robotic exoskeleton was modeled using a computer aided design software (CAD), subdividing the structure in to five components, which are: Actuation Design, Back Support Design, Links Design, Ankle Articulation Design and a Prototype Assembly. The use of CAD tools is to facilitate redrawing of parts, enables solid modeling, generate a 3D model for analysis and to create technical drawings (TDs) for possible components fabrication (Appendix III to VI). All the technical drawings are presented in appendix II. However, for its symmetry, only the right leg components are presented, the left leg components are imagined to be the mirrored of the individual right leg components.

5.5.1 Actuation Design

After the selection of the electric motor and plenary gearhead (*actuation unit*), it was necessary to create some additional components in order to facilitate torque transmission from the actuation unit to other parts of the exoskeleton. In this case, an *outer arm* (figure 5.4g) and *inner arm* (figure 4.6h) were modeled to connect the actuation unit to the links. The *inner arm* component connects the motor shaft and the distal link bar, acting as the effective rotation unit. The *outer arm* connects the gearhead coupler to the proximal link bars and was also designed as a mechanical limiter that restricts the rotation angle to the established range criterion of the actuation mechanically. The use of *outer arm* (mechanical limiter) helps to avoid any possible damage to the user, thus, making the structure safer.

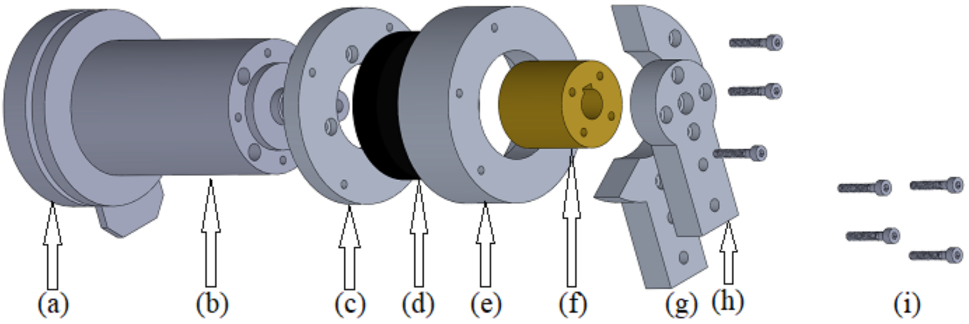

Figure 5.4 – Components for a complete actuation design

The materials for the construction of these components were chosen considering factors such as strength/density ratio and ductility. Therefore, characteristics of exoskeletons designs were preferred for most components. The *inner arm*, *outer arm* and actuation couplers were built with the 6063 aluminium alloy, prizing its superior strength. The *intermediate rotator* with golden color (figure 5.4f) was built with brass, and is the safety piece aimed to deform in case of overload. The last piece in the actuation unit is the bearing SKF 6008-2Z model, with black color (figure 5.4d). figure 5.5 shows a complete *actuation unit* mounted with the *outer arm* ready to be connected to the link bars.

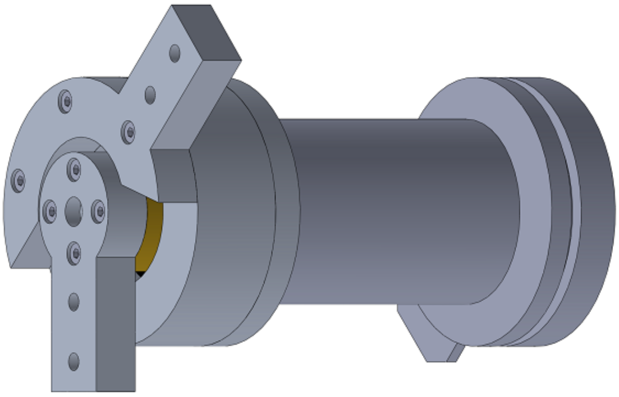

Figure 5.5 – Actuation mounted.

5.5.2 Back Support Design

The *back support* is the structure located at the superior part of the exoskeleton and used to fix the user's trunk to the equipment. It provides support to the user and can also serve as the housing to the electronic command circuit. It is designed adjustable depending on the user's waist size in the established waist range. To achieve this, three components were modeled as shown in figure 5.6: (a) is the adjustable bar and 1DOF joint, (b) is the two legs connector and (c) is the rigid frame. With these three components, it is possible to assemble a complete back support suitable for the user of the exoskeleton.

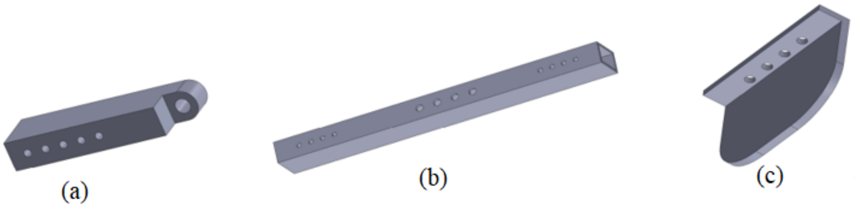

Figure 5.6 – Back support components.

The design was simplified and parts can be easily remodeled in case of damage or adaptation. Adjustable straps can also be attached to the back support which can be fastened around the user's back. The adjustable straps can be made from A-grade polyester automotive belts. Figure 5.7 shows the back support assembled.

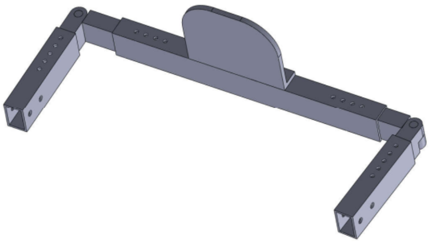

Figure 5.7 – *Back support*.

5.5.3 Upper and Lower Links Design

The *upper link* (figure 5.8a) connects the hip actuation to knee actuation and the *lower link* (figure 5.8b) connects the knee actuation to ankle articulation. The only difference between the two links is their heights 450mm for the hip and 440mm for the knee, (see table 4.10). Each link was designed to be 5cm adjustable and can easily be remodeled. However, the geometric profile chosen for the structural links was a rectangular tube in aluminum 6063. The rectangular tube's dimensions, such as wall width, were defined based on the system's analytical solution to ensure standard safety factors. Therefore, transverse section of the rectangular tubes are 20mm height, 30mm width and 2mm wall thickness geometry was chosen for the link construction. The lengths for the hip and the knee links are 450mm and 440mm respectively.

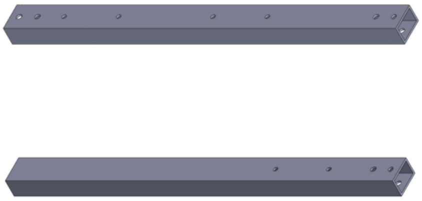

Figure 5.8 – Exoskeleton's links (a) *Upper link* and *lower link*.

5.5.4 Ankle Articulations Design

The *ankle articulation* design consists of two degrees of freedom which are all passive. To provide these 2DOF, it was necessary to design four different components: a *sleeper* (figure 5.9a), *comp1* (figure 5.9b), *comp2* (figure 5.9c) and *comp3* (figure 5.9d).

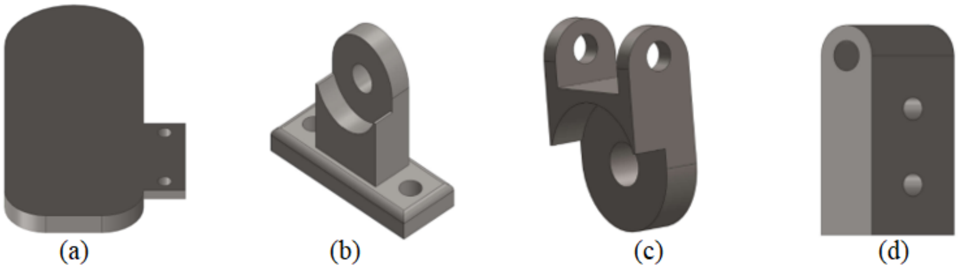

Figure 5.9 – Feet components (a) *Sleeper*, (b) *Comp1*, (c) *Comp2* and (d) *comp3*.

A *sleeper* is the most inferior part of the exoskeleton and on which a user places his foot, the combination of *comp1* and *comp2* provide the dorsal flexion and planter flexion. The combination of *comp2* and *comp3* provides inversion and eversion (figure 5.10). A strap ill be used to tight the user's foot to the sleeper.

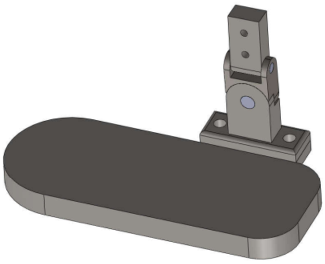

Figure 5.10 – Components of the *ankle articulations* assembled.

5.5.5 Prototype Assemble

With the five components designed, the prototype was assembled to visualize the final structure of the exoskeleton (figure 5.11). This phase is important because it indicates any modeling problem committed during individual components designs.

Figure 5.11 – Prototype Assembly

6 DISCUSSIONS, CONCLUSIONS AND FUTURE WORKS

6.1 DISCUSSIONS

In order to initiate the validation process of the final mechanical structural, the first prototype consisting of only one leg and a back support was constructed. The complete components for the actuation drive and the first prototype were developed, manufactured and assembled at the laboratory of automation and control (Grupo de Automação e Controle - GRACO) of the University of Brasilia (http://graco.unb.br/). The construction was sponsored by the Laboratory of Embedded Systems and Integrated Circuits Applications (LEIA), also located in the above mentioned group.

However, the first prototype consisting of a *back support* (or *lumber support*) and a right leg without the ankle articulations was assembled. Therefore, the constructed prototype consists of the following components: (a) back support (lumber support), (b) two DC motors, (c) two links and (d) screws for the links and joints fixation. This combination weighed approximately 13.1kg. The other set, which is the unassembled left leg is expected to approximately weight additional 5.6 kg, thereby taking the final prototype with the two legs to a total weight of approximately 18.7kg. For this exoskeleton model configuration, figure 6.1 shows the constructed prototype.

Figure 6.1 – Prototype for actuation validation.

After the first prototype was built, testing was performed and the testing protocol was divided into three parts as presented below:

- The first test performed aimed at setting the experimental setup parameters and testing a simple motion control of the two motorized joints. In this case, the two actuation drives were tested individually to reach their maximum acceleration without reaching the mechanical limiters.
- The second test aimed at checking the effective power of the actuation unit with all the losses of the coupling components, and also the deflection level of the anthropomorphic links with the critical level of external loads for which the project was designed. In this case, the exoskeleton was loaded on the hip and knee links with the equivalent weigh of the leg to replicate the maximum torque reached in rehabilitation gait condition.
- The final test aimed at creating a motion control pattern in which both joints would move simultaneously to replicate a rehabilitation gait pattern. Such test indicated if the exoskeleton's structure could stand the combined multiarticular movement loads and induced moments without significant deflections.

With respect to the number of degrees of freedom (DOF), 5DOF configuration was adopted (2DOF at the hip, 1DOF at the knee and 2DOF at the ankle). With this configuration, the mechanical structure developed provided the required normal movements in the joints which are essential for rehabilitation gait condition. This configuration can therefore be considered sufficient for the rehabilitation application.

6.2 CONCLUSION

In this work, a mechanical design of a lower limb exoskeleton for rehabilitation of paraplegic patients was presented through some sequential steps of a design methodology. These steps include: a literature review analysis, study of fundamentals of exoskeletons, establishment of the mechanical project requirements, designing of parts using CAD software, prototype construction, testing of prototype and result presentation. These steps were followed to facilitate when redesigning and remodeling of the final product is required. However, the division of the project design into four sections as presented in chapter 4 was aimed to facilitate visualization, analysis and redesigning of parts.

The experimental trials presented satisfactory results. Despite being simple, the control strategy was able to replicate a rehabilitation gait pattern without reaching the mechanical limits established. In the second and third testing phases, the exoskeleton's structure showed mechanical robustness and low levels of load induced deflection, while it could move the critical user's equivalent load without reaching the actuator's peak torque.

Due to its focus on robustness, the exoskeleton project was made aiming at its capacity to support a non-standard critical user, thereby making it useful to someone with the same physical characteristics even from outside the target population. The prototype constructed met the prerequisites successfully, and proved capable of acting in the area of rehabilitation application.

6.3 FUTURE WORKS

Some questions that might arise with respect to the tested prototype are if the model will still have the same results: (a) when assembled with both the two legs, and (b) in an eventual gait trial with the user on board. For the first case, it is believed that the deflections would only be higher at the hip and lumbar linkage, since an induced moment would appear due to dynamical variations to be introduced by the antagonist leg. However, to counter an excessive deflection, the lumbar column structure should be reinforced. For the second case, the deflections in all links are expected to be higher, and there is also a possibility of reaching critical deflection or stresses. This is possible since the user could intentionally or not, increase its muscular stiffness beyond the limits for which this exoskeleton was designed. That situation could lead to an overload of the actuation drive and parts of the structure, depending of the stimulated muscle. To counter that problem, the exoskeleton's mechanical structure should be reinforced, and also, the electronic command should monitor current and interrupt the motor drive when reaching pre-established thresholds values.

However, considerations were also made on implementing suitable control strategies to be applied on the final mechanical structure. Some of these strategies are control by applying the concept of: instrumentation, Brain-Machine Interface (BMI) with the help of Electromyography (EMG) or Electroencephalography (EEG) signals for operational control. The mechanical structure can also be redesigned in such a way that, the links and the waist structures can become adjustable with more precise adjustments, thereby increasing the range of users' size and making the structure compatible to more users with different sizes even outside the target population.

In relation to the number of DOF, the mechanical structure developed in this work considers that, the user has certain movements at the hip, as such, 5DOF per leg was considered sufficient for normal movements. However, these numbers can also be increased in future works even if some of them are designed as passive, in order to replicate de DOFs of a more natural gait.

There are possibilities of developing control systems based on MPSoC (Multi-Processor System on Chip) architectures. In this case, the system design may involve a control system embedded in FPGA based platforms. It is also considered, designing of dedicated hardware architectures for the sensor processing, aiming to improve the estimation of variables based on stochastic techniques, such as Kalman Filters (FK, EKF and UKF) and Particle Filters.

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Appendices

I. PROTOCOL FOR THE SYSTEMATIC LITERATURE REVIEW

I.1 OBJECTIVE OF THE LITERATURE REVIEW:

Identify, Analyze and Interpret all relevant references (documents) that are related to the formulated question "mechanical design of a lower limb exoskeleton for rehabilitation of paraplegic patients".

I.2 RESEARCH QUESTIONS:

1. *What are the bibliographic research databases?*
2. *Which of these bases are most relevant to our research?*
3. *How will systematic research be done?*
4. *What will be the inclusion and exclusion criteria?*

I.3 SOURCE SELECTION:

The sources should be available via the web, preferably in scientific databases in the area. Papers available in other media may also be selected, provided they meet the requirements of the Systematic Review.

I.4 KEYWORDS:

English: "Exoskeleton", "Lower Limb", "Mechanical Design", "Rehabilitation", "Paraplegic".

Portuguese (Brazil):"Exoesqueleto", "Membro Infereior", "Projeto Mecânico", "Reabilitação", "Paraplégico".

I.5 LIST OF THE DATABASES CONSULTED (ACCESS PROVIDED BY CAPES, BRAZIL):

1. *Web of Science*
2. *Scopus (Elsevier)*
3. *IEEE Xplore*
4. *Catálogo de Teses e Dissertações (CTD) of CAPES*
5. *Biblioteca de Teses e Dissertações (BDTD) of CAPES*

I.6 DOCUMENTS TYPE:

Papers published in journals, conferences, proceedings, symposium, Master's Dissertations and Doctoral Theses available easily accessible in these databases or online will be considered.

I.7 DOCUMENTS LANGUAGE(S):

English and Portuguese.

I.8 DOCUMENTS INCLUSION AND EXCLUSION CRITERIA:

I.8.1 Inclusion Criteria:

(a) *Relevant document published or accepted for publication including books, articles, and revised articles;*

(b) *Documents that contain keywords in their titles;*

(c) *Documents dealing with exoskeletons for lower limbs;*

(d) *Documents that are easily accessible;*

(e) *All publications till 2019;*

(f) *All documents in English and Portuguese.*

I.8.2 Exclusion Criteria:

(a) *Documents that focus only on Prosthesis;*

(b) *Documents dealing only with upper limb exoskeletons;*

(c) *Documents that are not easily accessible;*

(d) *Documents in other languages other than English and Portuguese.*

I.8.3 Quality Criteria for Primary Studies:

The work should have been published in peer-reviewed journals or event proceedings when referring to articles or approved by an examining board for course, master's or doctoral work. To evaluate the articles will be used the following criteria: population considered in the evaluation and statistical methods.

I.8.4 Primary Study Selection Process:

TStrings will be constructed with the keywords and their synonyms. The strings will be submitted to search engines. After reading the abstract and applying the inclusion and exclusion criteria, the paper will be selected if confirmed by the main reviewer (student). If there is doubt of relevance the other reviewers will be consulted.

I.9 INFORMATION EXTRACTION STRATEGY:

Once defined the definitive works, they will be read in full. The reviewer will summarize each of them, highlighting the methods used for the assessment and the parameters considered, as appropriate.

T"Data extraction forms" will be completed for each text, considered valid for RS, read in full. In addition to the basic information (bibliographic data, date of publication, abstract, among others), these forms should contain the synthesis of the work, written by the researcher who will conduct the SR and personal reflections on the content and conclusions of the study.

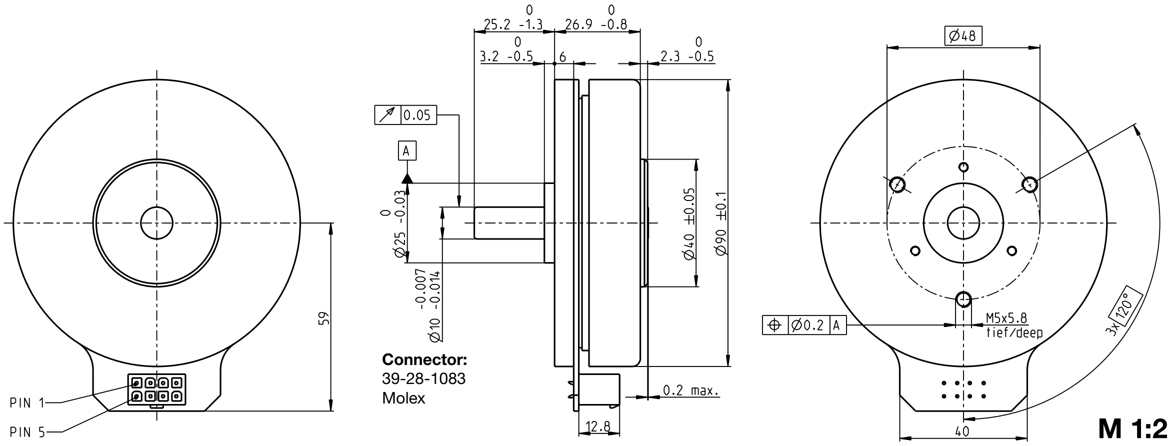
I.9.1 Summery of Results:

TAfter reading and summarizing the selected works, a technical report will be prepared with a quantitative analysis of the works. A qualitative analysis will also be developed to define the advantages and disadvantages of each method.

Attributes to be extracted from the included articles: name of technique, number of users participating in the evaluation, stereoscopy technique used, haptic device, statistical techniques employed, technique application domain.

II. MOTOR’S AND PLANETARY GEARHEAD INFORMATION

EC 90 flat Ø90 mm, brushless, 90 Watt



Connector:
39-28-1083
Molex

🟥 Stock program
☐ Standard program
▨ Special program (on request)

Part Numbers

		323772	429271	244879
with Hall sensors		🟥	☐	🟥
Motor Data				
Values at nominal voltage				
1 Nominal voltage	V	24	36	48
2 No load speed	rpm	3190	3120	2080
3 No load current	mA	544	348	135
4 Nominal speed	rpm	2590	2510	1610
5 Nominal torque (max. continuous torque)	mNm	444	560	533
6 Nominal current (max. continuous current)	A	6.06	4.76	2.27
7 Stall torque	mNm	4940	7480	4570
8 Stall current	A	70	69	21.1
9 Max. efficiency	%	84	87	85
Characteristics				
10 Terminal resistance phase to phase	Ω	0.343	0.522	2.28
11 Terminal inductance phase to phase	mH	0.264	0.625	2.5
12 Torque constant	mNm/A	70.5	109	217
13 Speed constant	rpm/V	135	88	44
14 Speed/torque gradient	rpm/mNm	0.659	0.423	0.462
15 Mechanical time constant	ms	21.1	13.6	14.8
16 Rotor inertia	gcm^2	3060	3060	3060

Specifications

Thermal data

17 Thermal resistance housing-ambient	1.91 K/W
18 Thermal resistance winding-housing	2.6 K/W
19 Thermal time constant winding	46 s
20 Thermal time constant motor	283 s
21 Ambient temperature	-40…+100°C
22 Max. winding temperature	+125°C

Mechanical data (preloaded ball bearings)

23 Max. speed		5000 rpm
24 Axial play at axial load	< 15 N	0 mm
	> 15 N	0.14 mm
25 Radial play		preloaded
26 Max. axial load (dynamic)		12 N
27 Max. force for press fits (static)		183 N
(static, shaft supported)		8000 N
28 Max. radial load, 5 mm from flange		68 N

Other specifications

29 Number of pole pairs	12
30 Number of phases	3
31 Weight of motor	600 g

Values listed in the table are nominal.

Connection

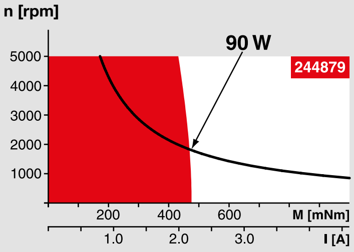
Pin 1	Hall sensor 1
Pin 2	Hall sensor 2
Pin 3	V_{Hall} 4.5…18 VDC
Pin 4	Motor winding 3
Pin 5	Hall sensor 3
Pin 6	GND
Pin 7	Motor winding 1
Pin 8	Motor winding 2

Wiring diagram for Hall sensors see p. 43

Cable

Connection cable Universal, L = 500 mm	**339380**
Connection cable to EPOS2, L = 500 mm	**354045**

Operating Range



Comments

🟥 **Continuous operation**
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

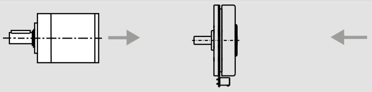
☐ **Short term operation**
The motor may be briefly overloaded (recurring).

— **Assigned power rating**

maxon Modular System

Overview on page 28–36

Planetary Gearhead
Ø52 mm
4 - 30 Nm
Page 351



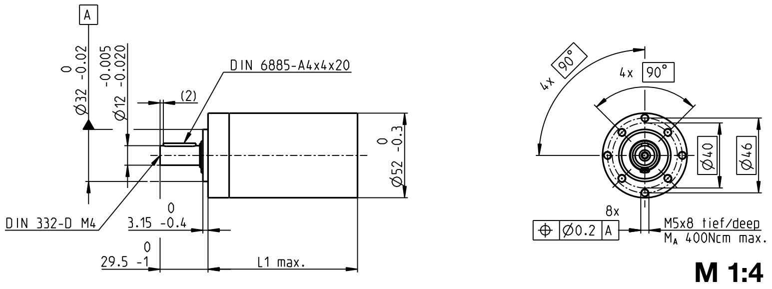
Encoder MILE
512 - 6400 CPT,
2 channels
Page 390

Recommended Electronics:

Notes	Page **32**
ESCON Mod. 50/4 EC-S	427
ESCON Mod. 50/5	427
ESCON 50/5	428
ESCON 70/10	428
DEC Module 50/5	430
EPOS2 24/5, 50/5, 70/10	435
EPOS2 P 24/5	438
EPOS4 Module/CB 50/5	442
EPOS4 Module 50/8	443
EPOS4 Comp. 50/8 CAN	443
MAXPOS 50/5	447

Planetary Gearhead GP 52 C ∅52 mm, 4.0–30.0 Nm

Ceramic Version

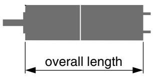


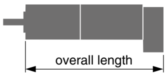
Technical Data

Planetary Gearhead	straight teeth
Output shaft	stainless steel
Bearing at output	preloaded ball bearings
Radial play, 12 mm from flange	max. 0.06 mm
Axial play at axial load < 5 N	0 mm
> 5 N	max. 0.3 mm
Max. axial load (dynamic)	200 N
Max. force for press fits	500 N
Direction of rotation, drive to output	=
Max. continuous input speed	6000 rpm
Recommended temperature range	-15…+80°C
Extended range as option	-40…+100°C
Number of stages	1 2 3 4
Max. radial load, 12 mm from flange	420 N 630 N 900 N 900 N

🟥 Stock program
☐ Standard program
▨ Special program (on request)

			223080	223083	223089	223094	223097	223104	223109
Gearhead Data									
1	Reduction		3.5 : 1	12 : 1	43 : 1	91 : 1	150 : 1	319 : 1	546 : 1
2	Absolute reduction		$^{7}/_{2}$	$^{49}/_{4}$	$^{343}/_{8}$	91	$^{2401}/_{16}$	$^{637}/_{2}$	546
10	Mass inertia	gcm^2	20.7	17.6	17.3	16.7	17.3	16.8	16.4
3	Max. motor shaft diameter	mm	10	10	10	10	10	10	10
	Part Numbers		223081	223084	223090	223095	223099	223105	223110
1	Reduction		4.3 : 1	15 : 1	53 : 1	113 : 1	186 : 1	353 :1	676 : 1
2	Absolute reduction		$^{13}/_{3}$	$^{91}/_{6}$	$^{637}/_{12}$	$^{338}/_{3}$	$^{4459}/_{24}$	$^{28561}/_{81}$	676
10	Mass inertia	gcm^2	12	16.8	17.2	9.3	17.3	9.4	9.1
3	Max. motor shaft diameter	mm	8	10	10	8	10	8	8
	Part Numbers			223085	223091	223096	223101	223106	223111
1	Reduction			19 : 1	66 : 1	126 : 1	230 : 1	394 : 1	756 : 1
2	Absolute reduction			$^{169}/_{9}$	$^{1183}/_{18}$	126	$^{8281}/_{36}$	$^{1183}/_{3}$	756
10	Mass inertia	gcm^2		9.5	16.7	16.4	16.8	16.7	16.4
3	Max. motor shaft diameter	mm		8	10	10	10	10	10
	Part Numbers			223086	223092	223098	223102	223107	223112
1	Reduction			21 : 1	74 : 1	156 : 1	257 : 1	441 : 1	936 : 1
2	Absolute reduction			21	$^{147}/_{2}$	156	$^{1029}/_{4}$	441	936
10	Mass inertia	gcm^2		16.5	17.2	9.1	17.3	16.5	9.1
3	Max. motor shaft diameter	mm		10	10	8	10	10	8
	Part Numbers			223087	223093		223103	223108	
1	Reduction			26 : 1	81 : 1		285 : 1	488 : 1	
2	Absolute reduction			26	2197/27		15379/54	4394/9	
10	Mass inertia	gcm^2		9.1	9.4		16.7	9.4	
3	Max. motor shaft diameter	mm		8	8		10	8	
4	Number of stages		1	2	3	3	4	4	4
5	Max. continuous torque	Nm	4	15	30	30	30	30	30
6	Max. intermittent torque at gear output	Nm	6	22.5	45	45	45	45	45
7	Max. efficiency	%	91	83	75	75	68	68	68
8	Weight	g	460	620	770	770	920	920	920
9	Average backlash no load	°	0.6	0.8	1.0	1.0	1.0	1.0	1.0
11	Gearhead length L1	mm	49.0	65.0	78.5	78.5	92.0	92.0	92.0

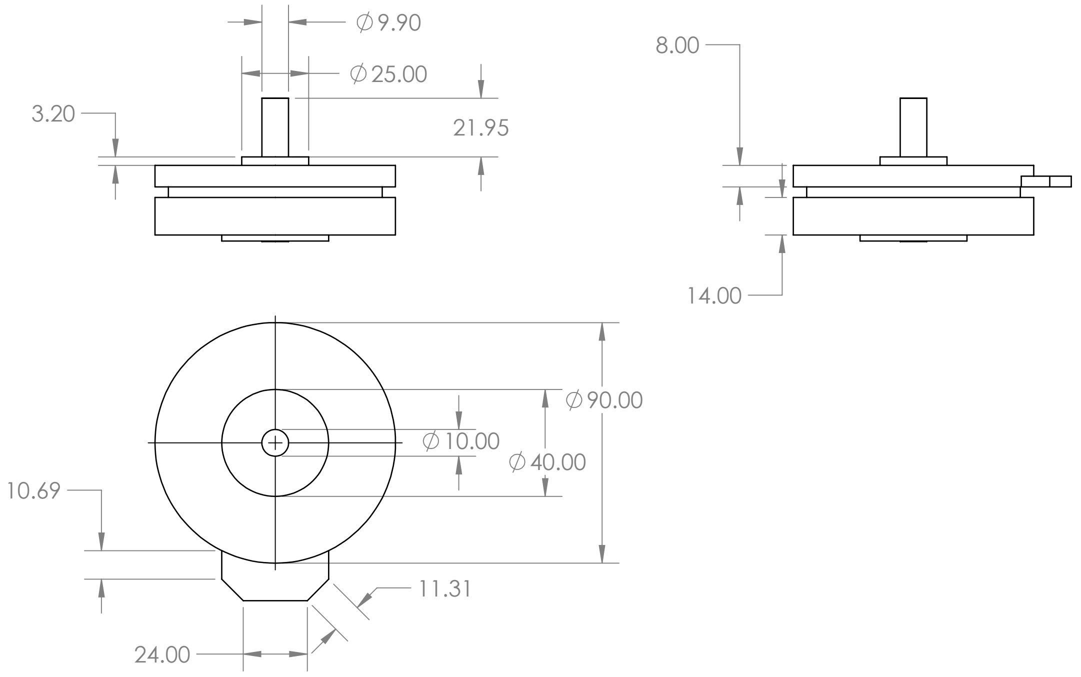


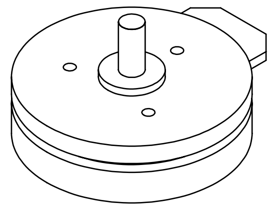


maxon Modular System

+ Motor	Page	+ Sensor	Page	Brake	Page	**Overall length [mm]** = Motor length + gearhead length + (sensor/brake) + assembly parts						
RE 40, 150 W	132					120.1	136.1	149.6	149.6	163.1	163.1	163.1
RE 40, 150 W	132	MR	420			131.5	147.5	161.0	161.0	174.5	174.5	174.5
RE 40, 150 W	132	HED_ 5540	429/432			140.8	156.8	170.3	170.3	183.8	183.8	183.8
RE 40, 150 W	132	HEDL 9140	436			174.1	190.1	203.6	203.6	217.1	217.1	217.1
RE 40, 150 W	132			AB 28	480	156.2	172.2	185.7	185.7	199.2	199.2	199.2
RE 40, 150 W	132			AB 28	481	164.2	180.2	193.7	193.7	207.2	207.2	207.2
RE 40, 150 W	132	HED_ 5540	429/432	AB 28	480	173.4	189.4	202.9	202.9	216.4	216.4	216.4
RE 40, 150 W	132	HEDL 9140	436	AB 28	481	184.6	200.6	214.1	214.1	227.6	227.6	227.6
RE 50, 200 W	133					157.1	173.1	186.6	186.6	200.1	200.1	200.1
RE 50, 200 W	133	HED_5540	430/432			177.8	193.8	207.3	207.3	220.8	220.8	220.8
RE 50, 200 W	133	HEDL 9140	437			219.5	235.5	249.0	249.0	262.5	262.5	262.5
RE 50, 200 W	133			AB 44	484	219.5	235.5	249.0	249.0	262.5	262.5	262.5
RE 50, 200 W	133	HEDL 9140	437	AB 44	484	232.5	248.5	262.0	262.0	275.5	275.5	275.5
EC 40, 170 W	213					129.1	145.1	158.6	158.6	172.1	172.1	172.1
EC 40, 170 W	213	HED_5540	430/432			152.5	168.5	182.0	182.0	195.5	195.5	195.5
EC 40, 170 W	213	Res 26	439			156.3	172.3	185.8	185.8	199.3	199.3	199.3
EC 40, 170 W	213			AB 32	482	171.8	187.8	201.3	201.3	214.8	214.8	214.8
EC 40, 170 W	213	HED_5540	430/432	AB 32	482	190.2	206.2	219.7	219.7	233.2	233.2	233.2

III. TECHNICAL DRAWINGS: ACTUATION





UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH:
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FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Maxon Motor

DWG NO.

Motor

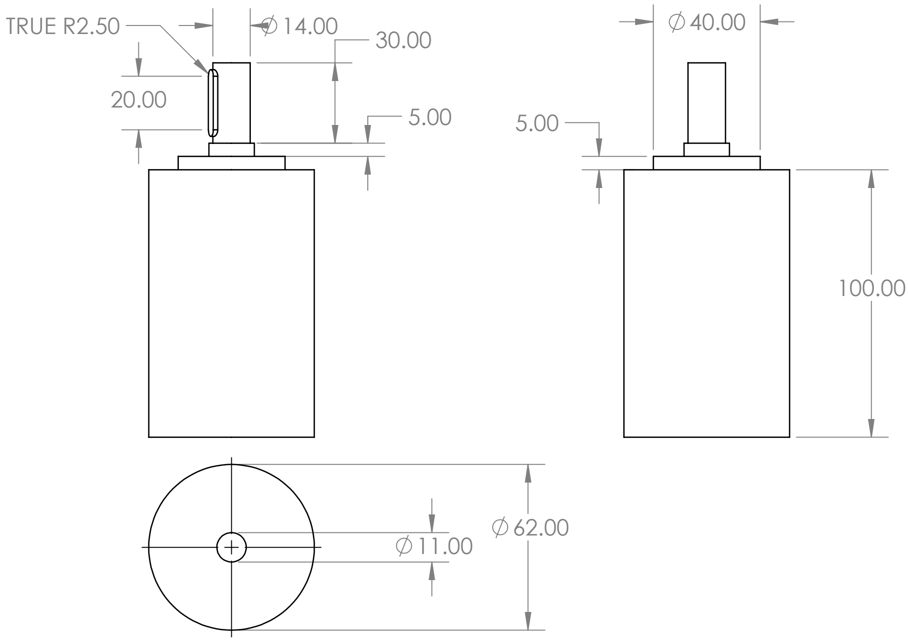
A4

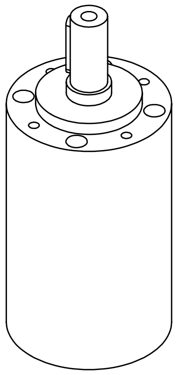
SCALE:1:2

SHEET 1 OF 1

6 5 4 3 2 1

D C B A





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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Planetary Gearhead

MATERIAL:

DWG NO.
PlanetaryGearhead

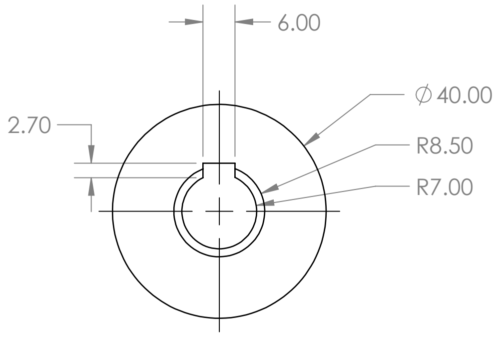
A4

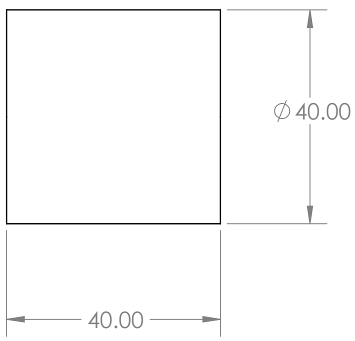
WEIGHT:

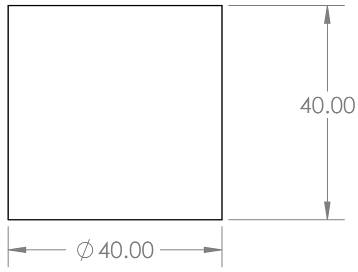
SCALE:1:2

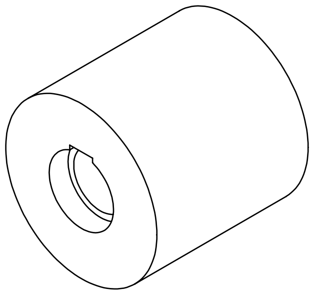
SHEET 1 OF 1

6 5 4 3 2 1









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June 2020

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REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Intermediate Rotator

MATERIAL:

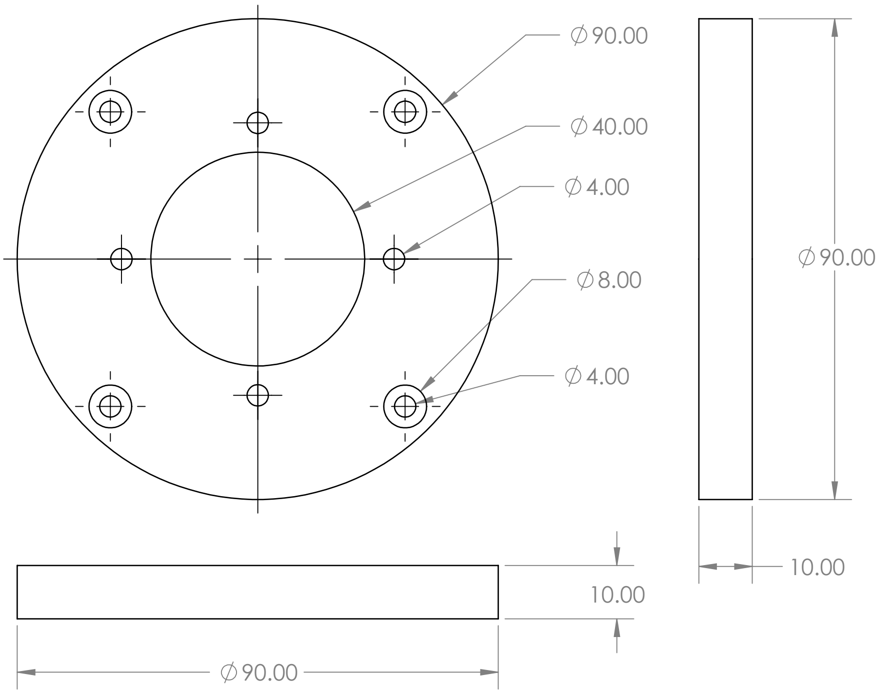
DWG NO.
Rotator

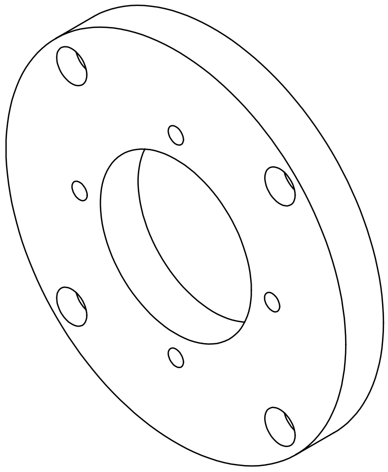
A4

WEIGHT:

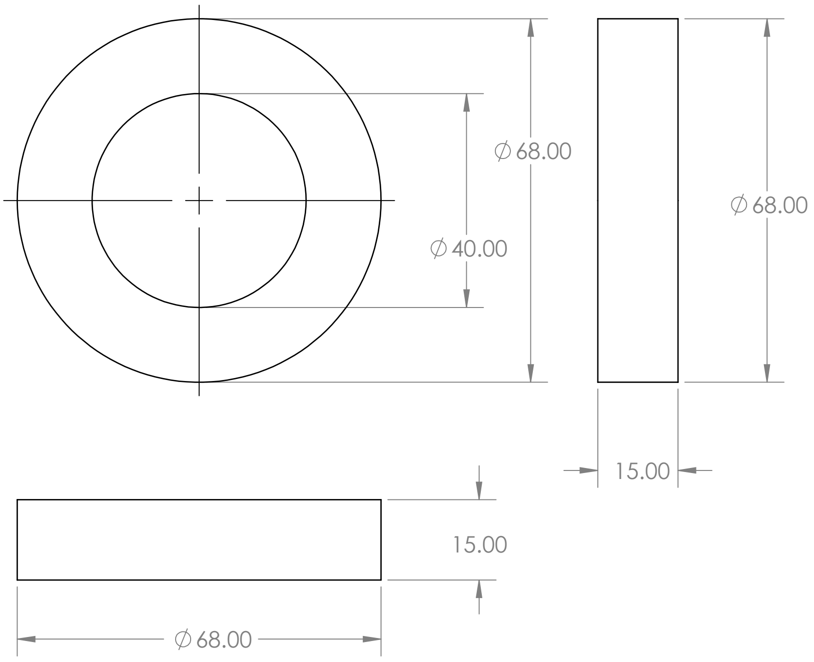
SCALE:1:1

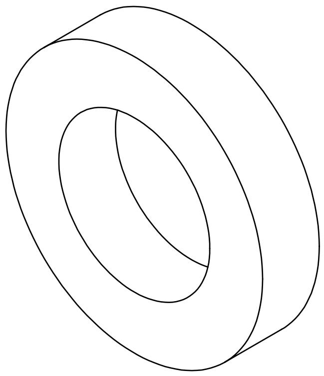
SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH: June 2020	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION		
	NAME	SIGNATURE	DATE			TITLE: Motor Fixer
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:		DWG NO. MotorFixer
						A4
				WEIGHT:	SCALE:1:1	SHEET 1 OF 1





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June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Bearing SKF

MATERIAL:

DWG NO.
BearingSKF

A4

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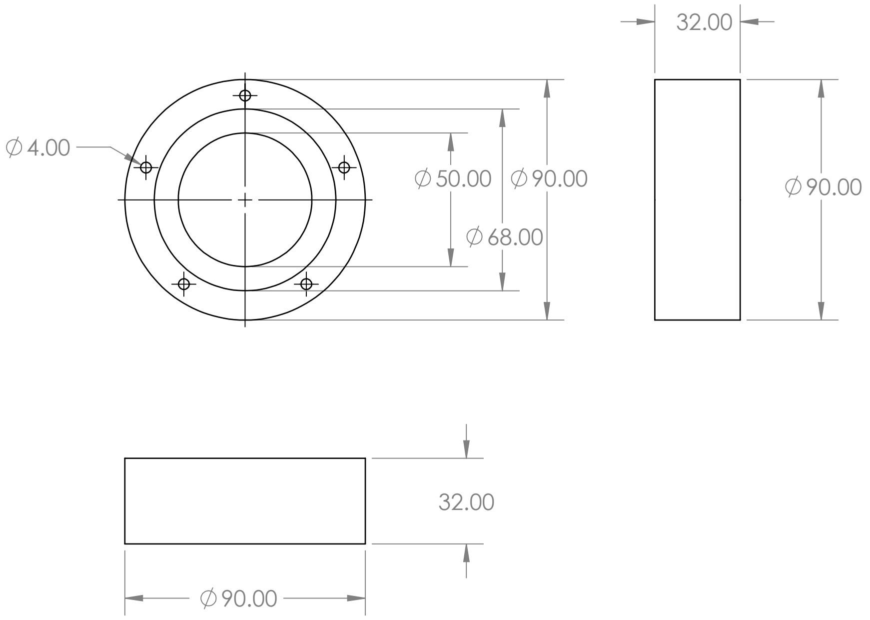
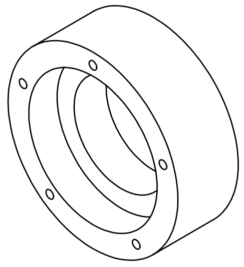
SHEET 1 OF 1





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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Bearin Box

MATERIAL:

DWG NO.

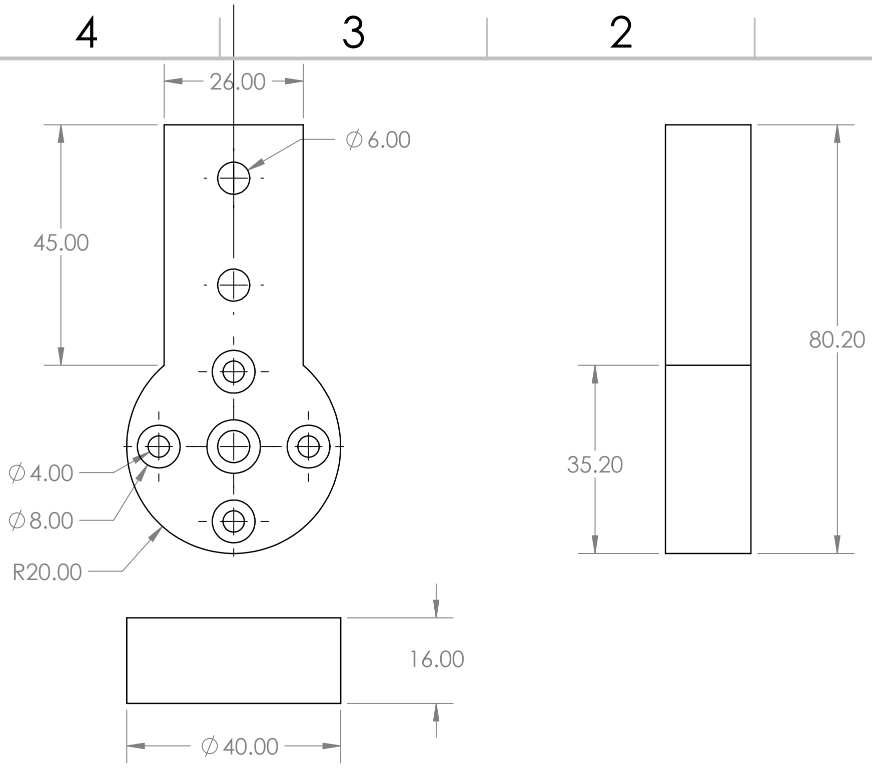
BearingBox

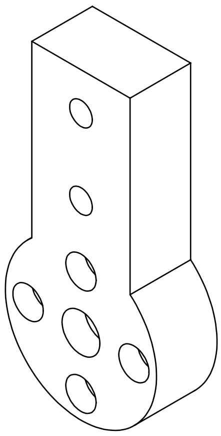
A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

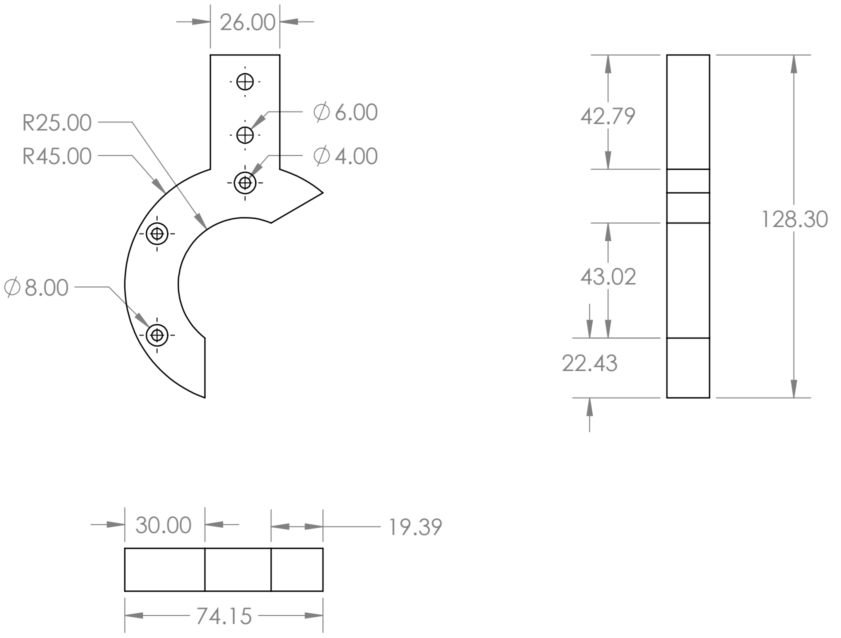
Inner Arm

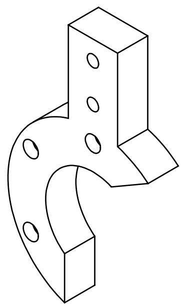
DWG NO.
InnerArm

A4

SCALE:1:1

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Outer Arm

MATERIAL:

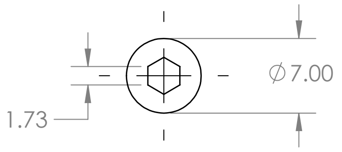
DWG NO.
OuterArm

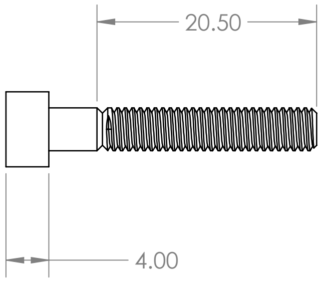
A4

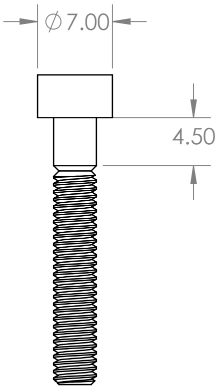
WEIGHT:

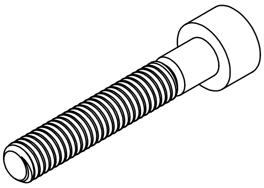
SCALE:1:1

SHEET 1 OF 1









UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Bolt Allen

MATERIAL:

DWG NO.

BoltAllen

A4

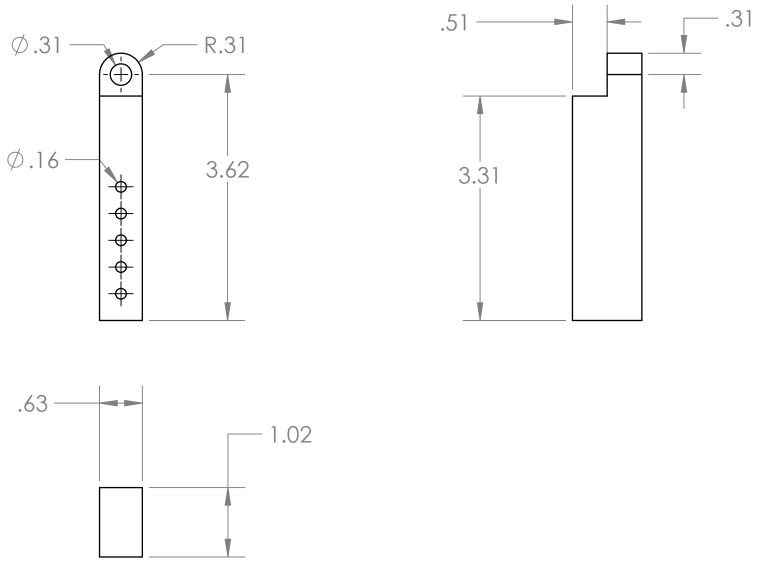
WEIGHT:

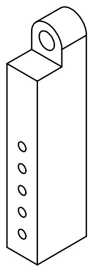
SCALE:2:1

SHEET 1 OF 1

IV. TECHNICAL DRAWINGS: BACK SUPPORT

D C B A





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH: June 2020	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Back 01

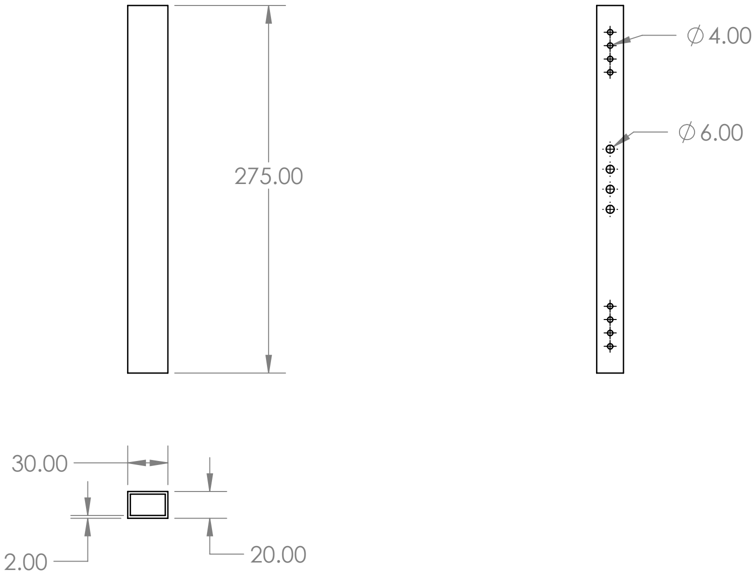
DWG NO.

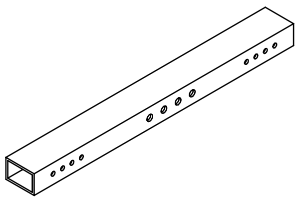
back_01

A4

SCALE:1:2

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

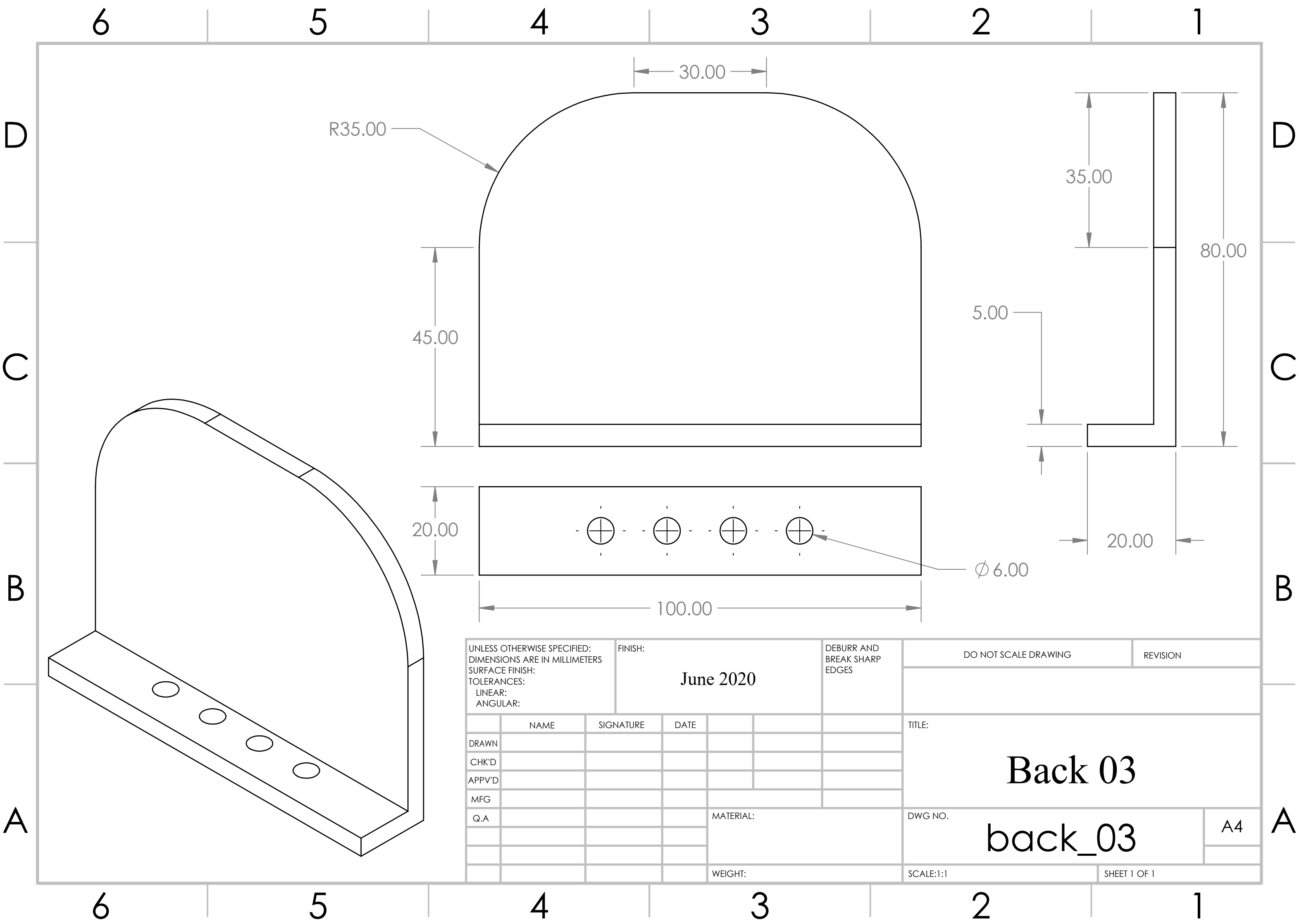
Back 02

DWG NO.
back_02

A4

SCALE:1:4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Back 03

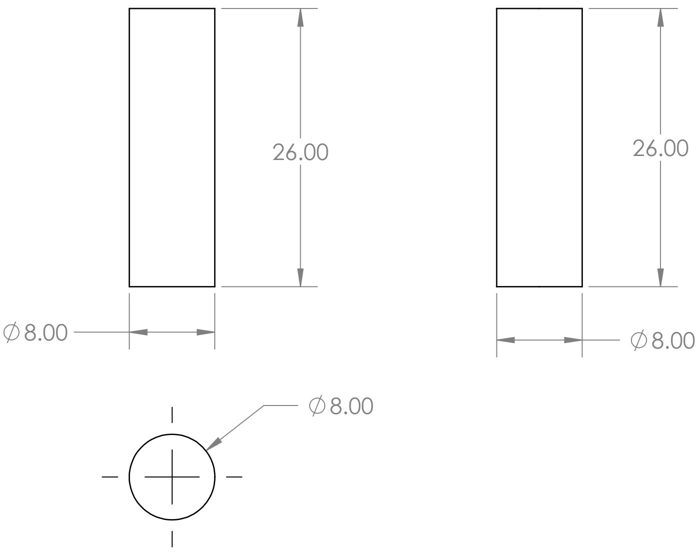
DWG NO.

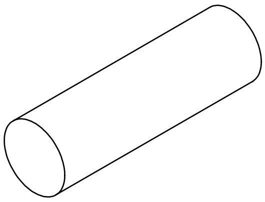
back_03

A4

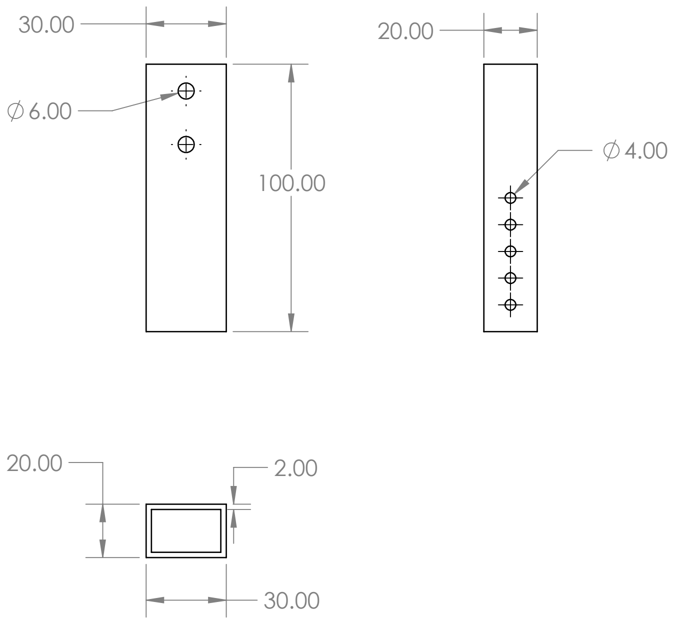
SCALE:1:1

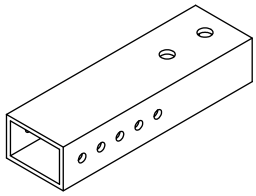
SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH: June 2020			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN					Back 04	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. back_04	A4
				WEIGHT:	SCALE:2:1	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Back 05

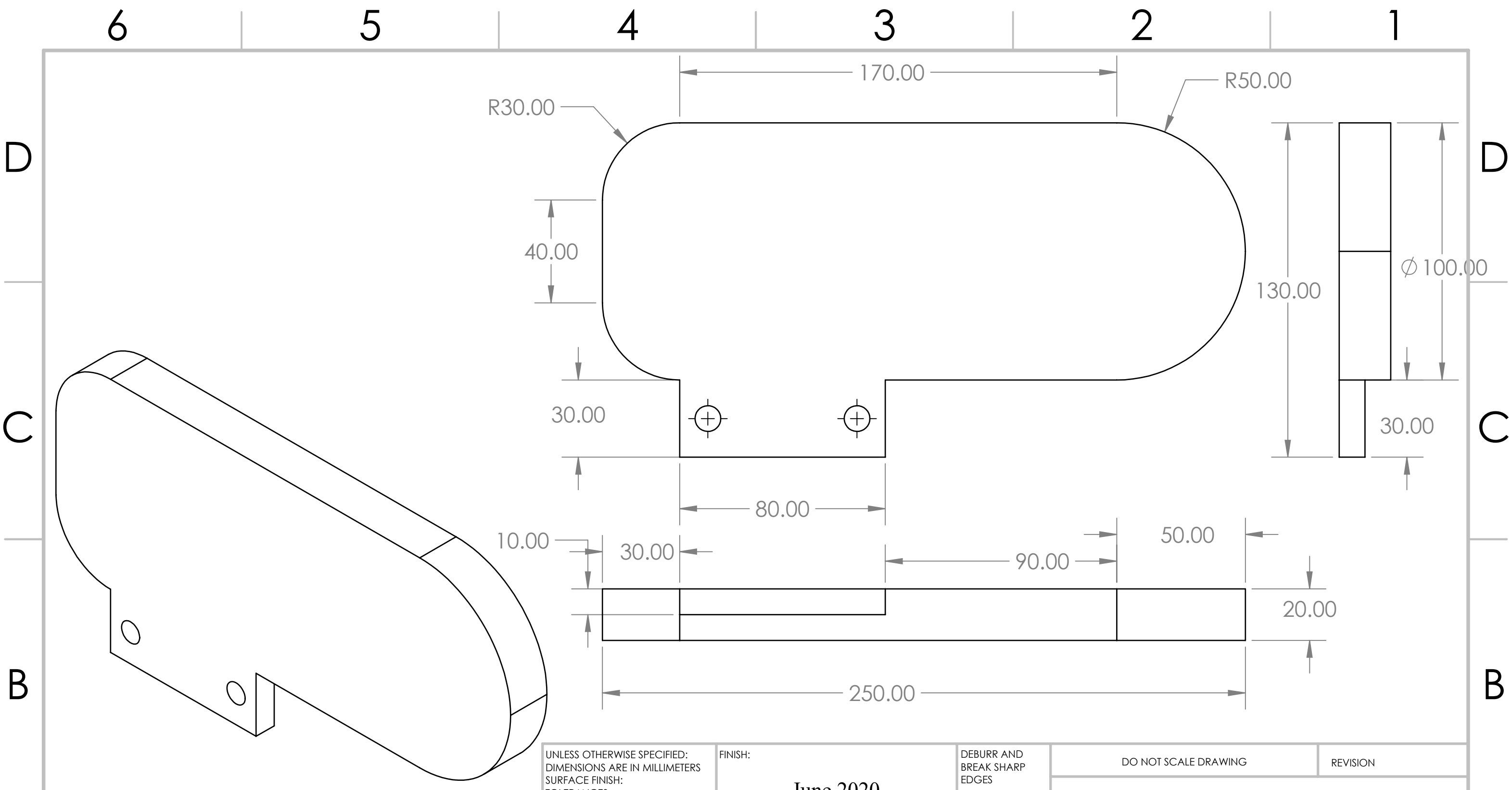
DWG NO.
back_05

A4

SCALE:1:2

SHEET 1 OF 1

V. TECHNICAL DRAWINGS: FOOT ARTICULATIONS



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH: June 2020	DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Sleeper

MATERIAL:

DWG NO.

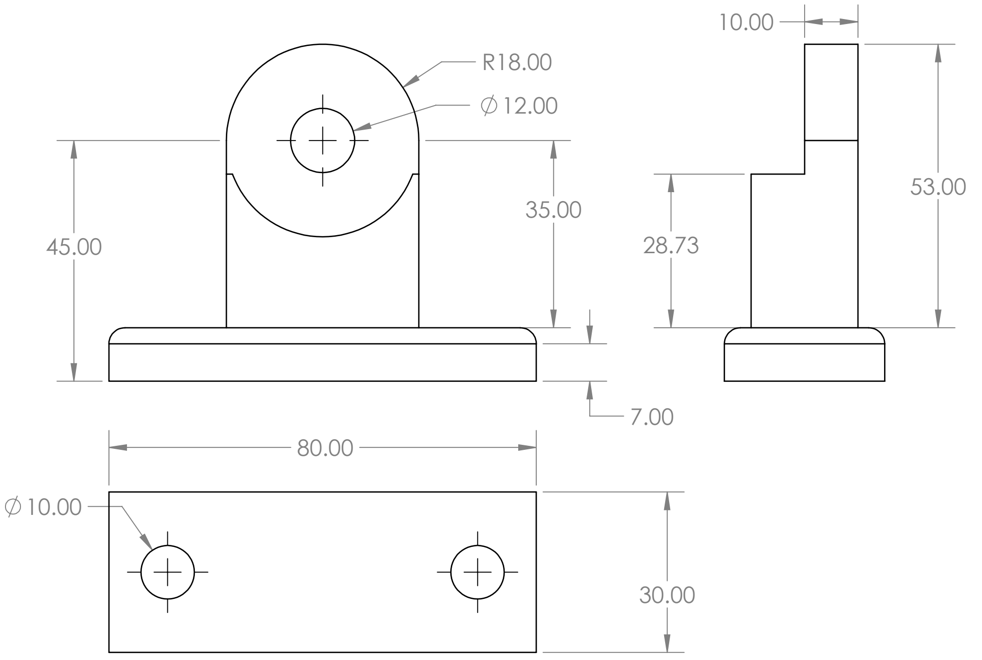
foot_right

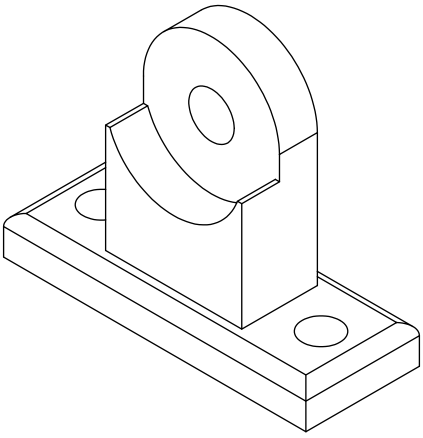
A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Comp1

MATERIAL:

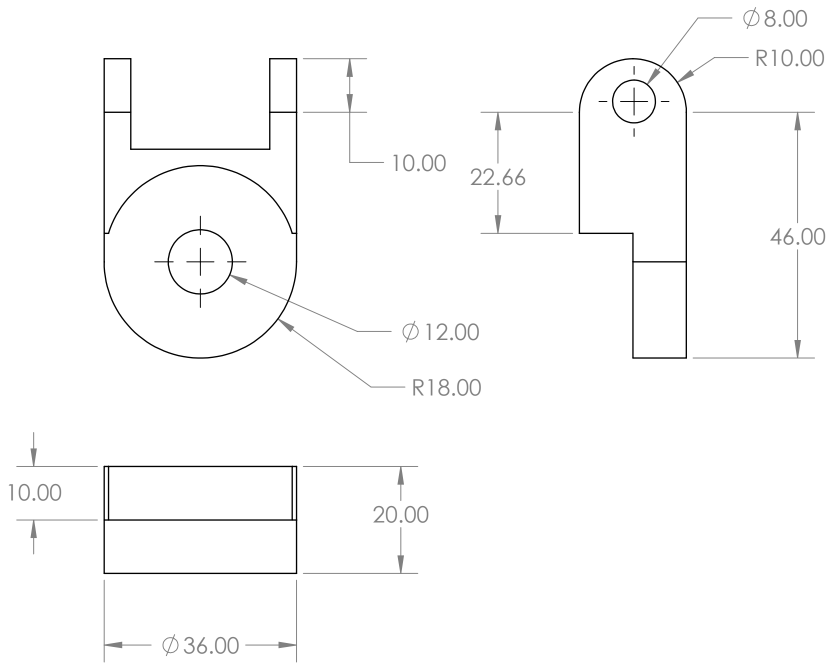
DWG NO.
foot_acop_01

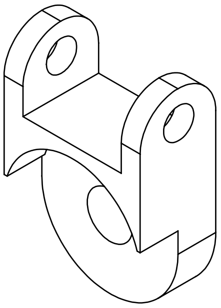
A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

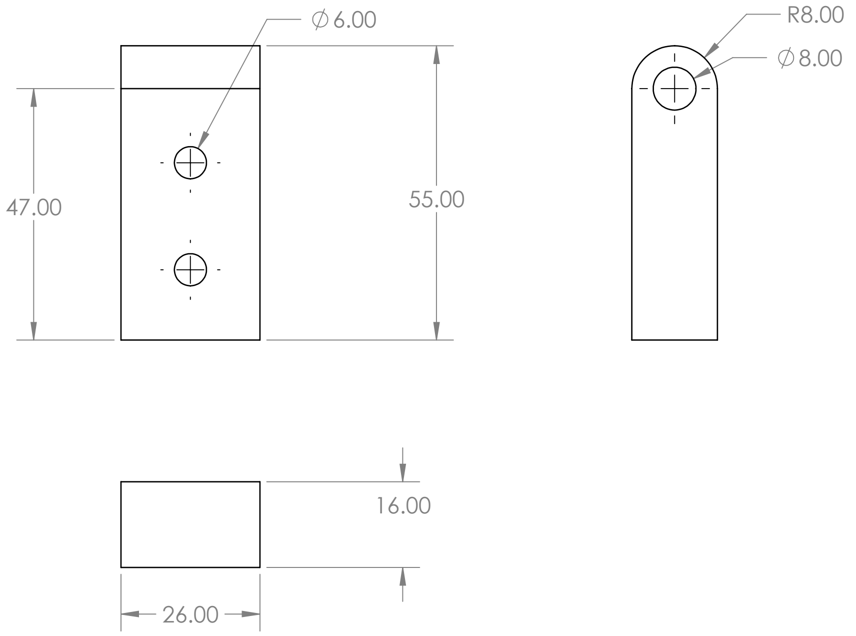
Comp2

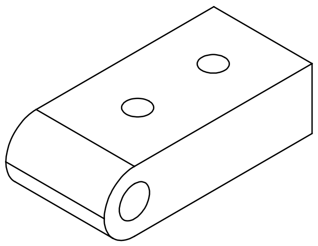
DWG NO.
foot_acop_02

A4

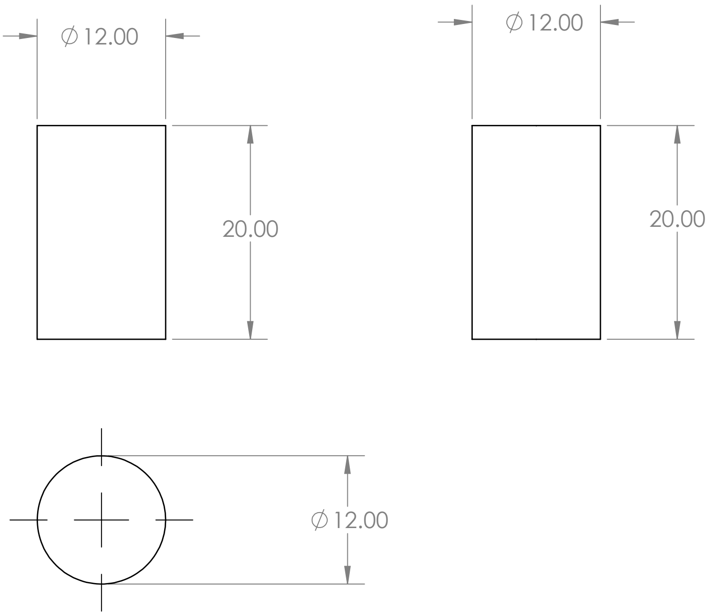
SCALE:1:1

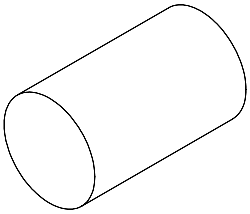
SHEET 1 OF 1



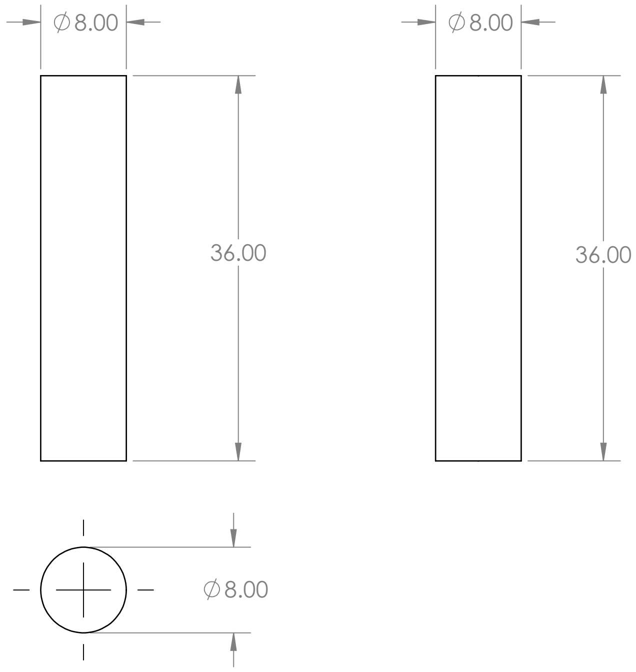


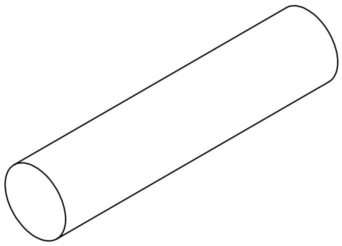
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH: June 2020		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN				Comp03	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO. foot_acop_03	A4
			WEIGHT:	SCALE:1:1	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH: June 2020	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE: Fist Joint	
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO. foot_acop_04	A4
			WEIGHT:	SCALE:2:1	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Secod Joint

MATERIAL:

DWG NO.
foot_acop_05

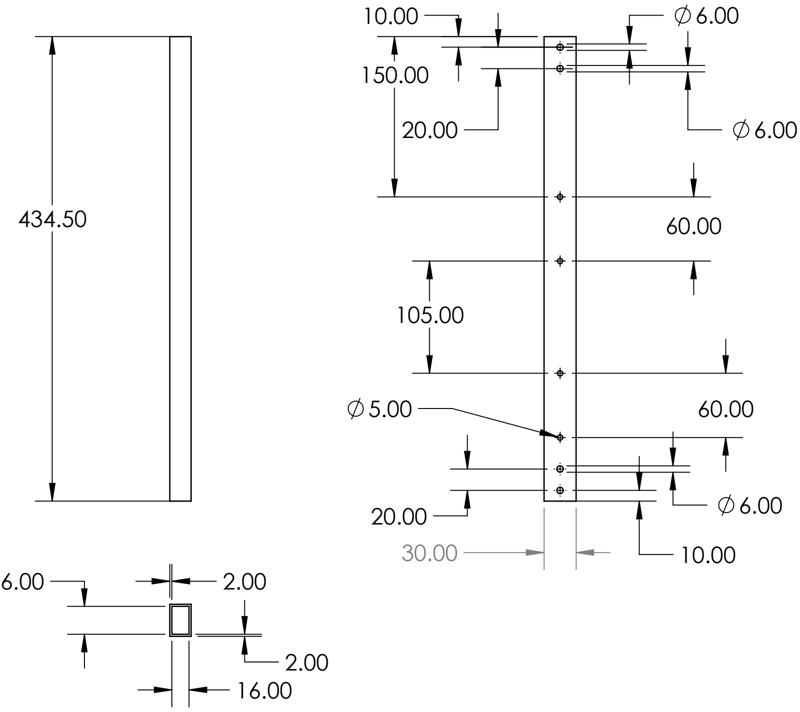
A4

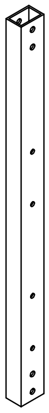
WEIGHT:

SCALE:2:1

SHEET 1 OF 1

VI. TECHNICAL DRAWINGS: LINKS





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:
June 2020

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

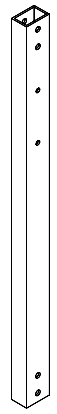
Upper Link

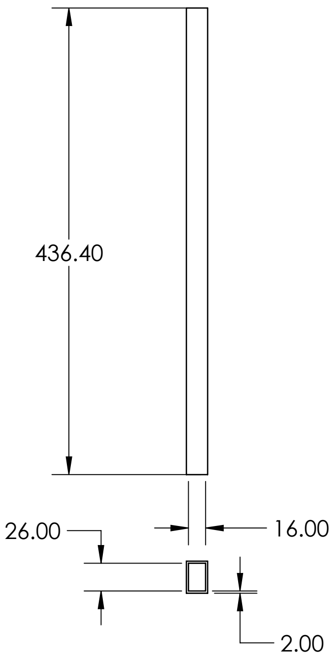
DWG NO.
Link_UpperLeg

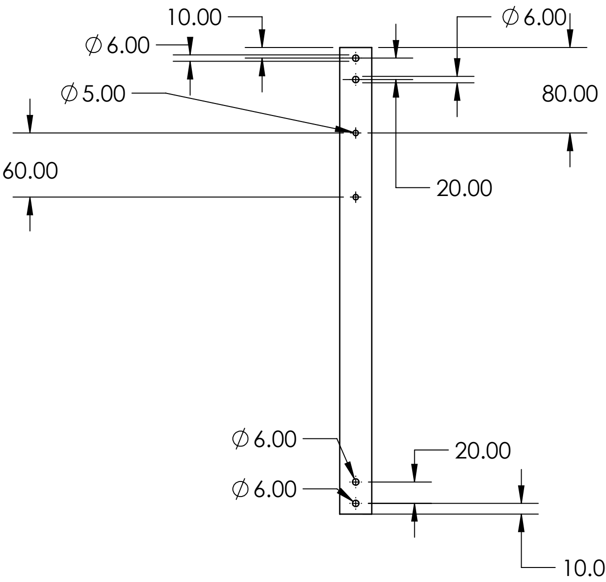
A4

SCALE:1:5

SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

Link_LowerLeg

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1