WEARABLE EXOSKELETON ROBOT DESIGN

A Thesis Submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in Mechanical Engineering

by
Volkan GÜN

September 2007
İZMİR

We approve the thesis of **Volkan GÜN**

Date of Signature

.... **17 September 2007**

Asst. Prof. Dr. Emin Faruk KEÇECİ
Supervisor
Department of Mechanical Engineering
İzmir Institude of Technology

.... **17 September 2007**

Prof. Dr. Macit TOKSOY
Department of Mechanical Engineering
İzmir Institude of Technology

.... **17 September 2007**

Assoc. Prof. Dr. M. Salih DİNLEYİCİ
Department of Electrical & Electronics Engineering
İzmir Institude of Technology

.... **17 September 2007**

Assoc. Prof. Dr. Metin TANOĞLU
Head of Department
İzmir Institude of Technology

....

Prof. Dr. M. Barış ÖZDEREM
Head of the Graduate School

ACKNOWLEDGMENTS

In this thesis study, I had an opportunity to learn many things about designing of mechatronic systems and their stages of manufacturing processes. During this study I dealt with the robotic design, which I have been fascinated while following the robotic science and design news all around the world. I would like to thank Dr. Emin Faruk KEÇECİ to give me a chance to work with him and for supervising my project. From the beginning to the end of this study his motivation gives me the highest energy to complete this thesis.

In addition, I want to thank to my family for their belief and to my friends, Seyhun GEMİLİ, Salih AĞRIDAĞ and Deniz İNCEL for their support. Without any of these, this study could not be completed.

ABSTRACT

WEARABLE EXOSKELETON ROBOT DESIGN

In this thesis study it is intended to design a wearable exoskeleton robot which will replace paralytic or disable people's legs and provide to walk. The wearable exoskeleton robot will be an intelligent system that fulfill the gait necessities, climb the slopes up and down, and remove the disadvantages of the wheelchairs and mobility aid vehicles. Robot will be a wearable device like a trouser and it will work to carry out daily duties for users. Robot will increase user's maneuver capabilities and support users' legs and aid walking action for users thanks to 3-one degree of freedom (DOF) joints which are designed for each leg and are powered by DC electric actuators.

Design of the wearable exoskeleton robot includes, modeling and designing of the robot using a parametric solid modeling computer program (Solidworks®), selection of the most suitable material for the design characters and robot manufacturing processes, strength analysis of the critical part of the robot, mathematical modeling of the system, design and manufacturing of the test machine and finding the most suitable walking combination by investigating degree of freedoms of each joints on the legs.

In addition to mechanical design of the wearable exoskeleton robot, an electronic circuit is designed and manufactured in order to control each joint movement order and time in walking action. Moreover, in order to control the robot by the users, a keypad unit is manufactured on the robot and necessity functions are described in the program.

As a result of this thesis; a wearable exoskeleton robot is manufactured to be used as a walking assistant.

ÖZET

GİYİLEBİLİR İSKELET ROBOT DİZAYNI

Bu tez çalışmasının amacı belden aşağısını kullanamayan engelli yada felçli insanlar için kendi bacakları gibi kullanabilecekleri giyilebilir bir iskelet robot tasarlamaktır. Tasarlanacak olan robot, yürüme fonksiyonunu sorunsuz bir şekilde gerçekleştirecek, rampa yukarı yada aşağı hareket edebilecek, günümüzde kullanılan tekerlekli sandalyelerin dezavantajlarını büyük ölçüde ortadan kaldıracak, akıllı bir sistem olacaktır. Robot felçli yada engelli kullanıcı tarafından pantolon gibi giyilecek ve kullanıcının günlük işlerini problemsiz bir biçimde, doğallığa en yakın yerine getirmesine yönelik, çalışacaktır. Robot, yürüme işlemini, her bacak için tasarlanan ve D.C. elektrik motorundan tahrik alan, 3 adet 1 serbestlik dereceli yapay bacaklar sayesinde gerçekleştirecektir.

İskelet robotunun tasarlanması, robotun parametrik bir katı modelleme programı (Solidworks®) ile modellenmesi, imalat için en uygun malzemenin seçilmesi, dayanım hesaplarının yapılması, matematik modelinin oluşturulması, test cihazının tasarlanması ve imalatı ve eklemlerin serbestlik derecelerinin incelerenerek en uygun yürüme kombinasyonun oluşturulması aşamalarını kapsamaktadır.

Bu robot mekanik tasarım çalışmasına ek olarak, eklemlerde her bir eklemin yürüyüş sistemindeki hareket sırası ve hareket süresini control edebilmek amacıyla bir eletronik kontrol ünitesi tasarlanmış ve üretilmiştir. Ayrıca robotun kullanıcı tarafından kolay bir şekilde kumanda edilebilmesi amacıyla robotun üzerinde control amaçlı bir tuştakımı kullanılmış ve gerekli fonksiyonlar tuş takımında tanımlanmıştır.

Sonuç olarak bu tez çalışmasında, kullanıcının yürüme hareketine yardımcı olacak bir iskelet robot üretilmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

This research intends to design wearable exoskeleton robot. Wearable exoskeleton robot serves paralytic and disable people to walk and fulfill their duties without any problem. Robot replaces users' legs and provides to walk. Robot increase user's maneuver capabilities and support user's legs for walking action.

This project consists of designing, manufacturing, electronic control circuit designing, computer software writing and testing. In the design chapter some possible solutions for the exoskeleton robot are studied according to predefined design considerations. A test machine is build to test each joint movement. The critical parts of the robot joints and test machine are analyzed. These calculations are performed both in theory and in simulation programs.

Additionally, in order to control each joint movement and direction, an electronic control circuit is manufactured and a computer software program is written in the microprocessor 16F877 on the electronic control circuit. Control circuit and computer software are explained in Chapter 6.

After the theoretical design stage, wearable exoskeleton robot and test machine are manufactured. The material selection procedure and the manufacturing of the robot and the test machine are explained in the Chapter 2 and Chapter 5.

In the last part, testing process is done with real robot in the test machine to find each joint rotation values. Additionally some other evaluating criteria's such as weight, speed, power consumption, number of components, walking action investigation are going to be considered to choose the best robot design.

Finally conclusion of the test results is interpreted and the best robot design is determined. The future works is given as an answer of what else is going to be done in addition to this project in order to increase the robot performance and usability.

1.1. Walking Robots

Walking robots are important alternative to driving robots, since the majority of the world's land area is unpaved. Although driving robots are more specialized and better adapted to flat surface, they can drive faster and navigate with higher precision. Walking robots can be employed in more general environments. Walking robots follow nature by being able to navigate rough terrain or even climb stairs or over obstacles in a standard household situation, which would rule out most driving robots (Braunl 1998).

There are two types of walking, using for walking robots;

- *Static balance*

The robot's center of mass is at all times within the support area of its foot on the ground or the combine support area of its two feet (convex hull), if both feet are on the ground.

- *Dynamic balance*

The robot center of mass may be outside the support area of its feed during a phase of its gait.

The exoskeleton robots are more difficult to balance related to biped robots because exoskeletons have to adjust system balance not only itself but also users. Static balance for exoskeleton robots can be achieved if the robot's feet are relatively large and the ground contact areas of both feet are overlapping. However, this is not case in human-like "android" robots, which require dynamic walking (Caux et al. 1998).

1.2. The Definition of Exoskeleton Robot

The human body is unsurpassed in the complexity of its design, performance and efficiency, but there are definite limitations to what can be achieved by humans with a frame that's around 6ft high. So much weight can only be carried, jumped so far or run so fast before reached our physical boundary. Machines that overcome these limitations have been with us for centuries, but the world is only beginning to explore the possibilities of augmentation, extending our existing capabilities through wearable robot exoskeletons to create superhuman strength, speed and stamina.

Exoskeleton Robot (framework around our body's skeleton) is a prime example of wearable robotics that helps people to walk or lift things**.**

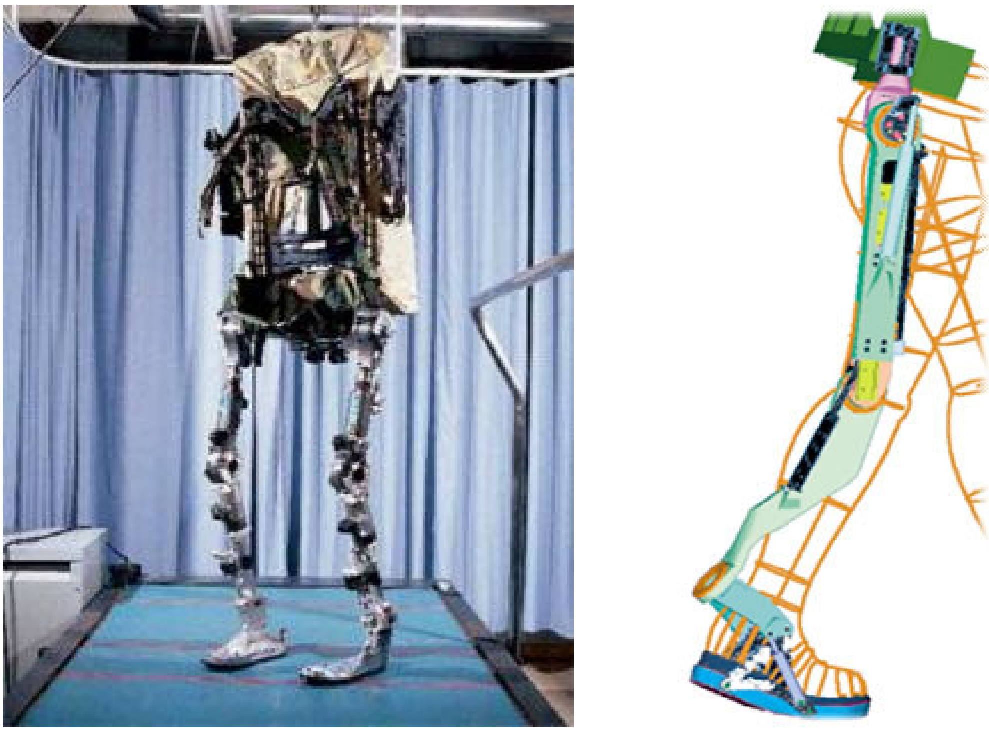


Figure 1.1. Exoskeleton robots.
(Source: WEB_1 2006)

An exoskeleton is one of such integrated mechanisms, which is also a wearable device attached to the human body. The physical contact between the operator and the exoskeleton allows direct transfer of mechanical power and information signals. Useful exoskeletons are controllable and wearable devices that can enhance the strength, speed, and endurance of the operator. The human provides control signals for the exoskeleton, whereas the exoskeleton actuators provide most of the power necessary to perform a task. The machine is anthropomorphic and is attached at several points along the operator's hands, legs and torso such that the geometry of the human and the machine approximately match one another.

1.3. The Need for Exoskeleton Robots

Up to now there are several vehicles used for disables or paralytic people to walk. One of them is wheelchair which has become a disabled people's best friend and showed the evaluation in time. Different types of wheelchairs have designed with development of robotic; manual wheelchairs, electricity wheelchairs, electricity trucked wheelchairs. They have become a part of the everyday activities of the disabled. At least, it reduces the burden and suffering that they feel whenever they're in their wheelchairs. At least, they're able to do the usual stuff that they do. But then, wheelchairs have several drawbacks which are listed below. Comparison of the current wheelchairs are shown in Table 1.1

- Manually operated
- Need physically force
- Only usable restricted area
- Cannot be control well
- Cannot climb the ladder

(a) (b) (c)

Figure 1.2. Evolution of the mobility aid. (a) Manual wheelchair (b) Electricity wheelchair (c) Our exoskeleton robot (Source: WEB_2 2007).

Table 1.1. Comparison of current wheelchairs.

	A-200	B-500	Rabbit	Belimo	WM120-D-46	Meyra Sprint GT	Meyra Optimus	Skippi	Supertrans
Dimentions	57x57x110	N/I	63x63x118	56x92x95	63x103x120	N/I	N/I	N/I	63x63x118
Weight	66kg	N/I	N/I	58kg	72kg	N/I	N/I	66kg	N/I
Operation Time	3.5h	5h	5h	3h	N/I	N/I	N/I	N/I	5h
Climbing Angle	12%	22%	22%	12%	N/I	N/I	N/I	N/I	22%
Max Speed	6km/h	6-10km/h	6-10km/h	6km/h	6km/h	6-10-12km/h	6-10-15km/h	6km/h	6-10km/h
Range Per Charge	20km	35km	35km	17km	N/I	40km	60km	N/I	35km
Load Capacity	100kg	120kg	100kg	115kg	110kg	120kg	100kg	50kg	150kg
Charging Time	12h	N/I	N/I	8h	N/I	N/I	N/I	N/I	N/I
N/I: No Information									

In order to overcome these drawbacks, Exoskeleton robots are designed as a new vehicle for handicap people of the new era.

1.4. Application Areas

With the help of the exoskeleton, the user can carry more loads and walk longer before feeling tired if compared to those without the exoskeleton system. The system might provide soldiers, fire fighters, disaster relief workers, and other emergency personnel the ability to carry major loads such as food, weaponry, rescue equipment, and communications gear with minimal effort over any type of terrain for extended periods of time.

1.5. Current Exoskeleton Robots

Since around the 1950s, several exoskeleton leg systems have been studied and developed, and can mainly be used for two conceptually different applications, according to which they can be categorized into two types:

1) Walking aid for gait disorder persons or aged people;

2) Walking power augmentation to travel long distances by feet with heavy loads.

1.5.1. HAL (Hybrid Assistive Limb)

The most successful example of exoskeleton used as a walking aid device for gait disorder persons is the Hybrid Assistive Leg (HAL) developed by Yoshiyuki Sankai. Sensors such as angle sensors, EMG (ElectroMyogram) sensors and floor reaction force sensors are adopted in order to obtain the conditions of the HAL and the operator. With all of the motor drivers, measurement system, computer, wireless LAN (Local Area Network), and power supply built in the backpack, HAL works as a completely wearable system. HAL has a hybrid control system that consists of autonomous posture controller and power assist controller based on biological feedback and predictive feed forward.

In the latter type, users are aided by the exoskeleton can carry more and walk longer before feeling tired if compared to those without the exoskeleton system. The initial intention of these powered structures was, in fact, to enable normal man to perform overloaded tasks, especially in military applications. (Kawamoto and Lee 2002)

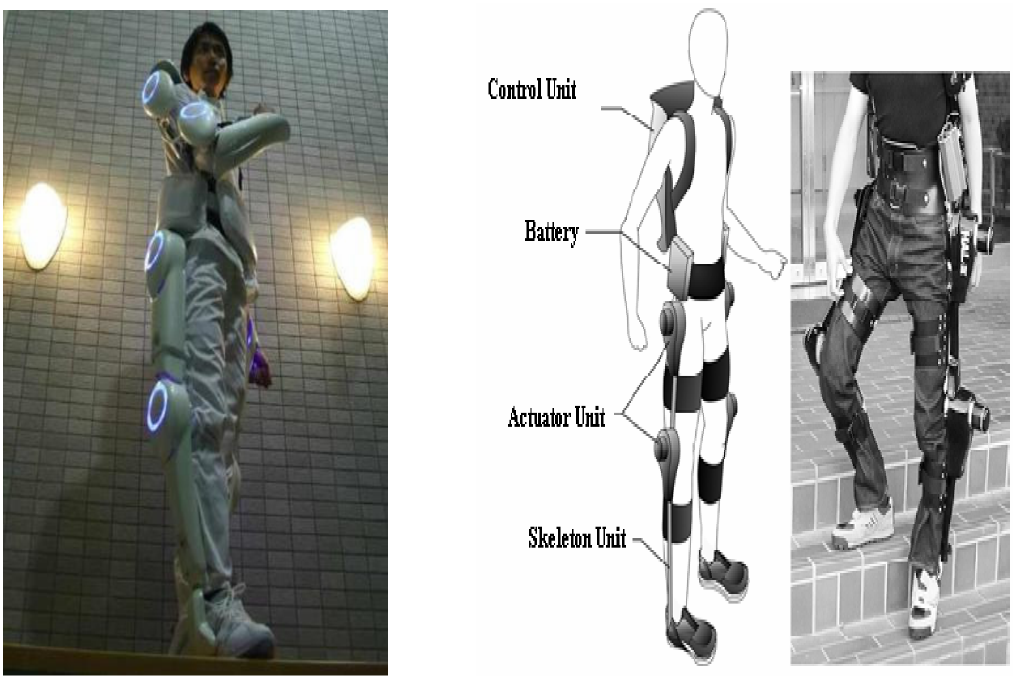


Figure 1.3. HAL (Hybrid Assistive Limb).
(Source: Kawamoto and Sankai 2002)

1.5.2. BLEEX (Berkeley Lover Extremity Exoskeleton Robot)

Some latest research results in this area come out of the BLEEX (Berkeley Lower Extremity Exoskeleton) project by Homayoon Kazerooni, who has been directing his research team in the Human Engineering Laboratory of UC. Berkeley to develop a DARPA (Defense Advanced Research Projects Agency) funded exoskeleton since the year 2000. The primary objective of the project is to create a self-powered exoskeleton for human strength and endurance enhancement that is ergonomic, highly maneuverable, mechanically robust, lightweight and durable. In November 2003, the first completely functional prototype experimental exoskeleton was demonstrated, which is comprised of two powered anthropomorphic legs, a power unit, and a backpack-like frame on which a variety of loads can be mounted. More than 40 sensors, including some that are embedded within the shoe pads, and hydraulic actuators form a LAN for the exoskeleton and function much like a human nervous system. The exoskeleton uses a state of the art small hybrid power source, which delivers hydraulic power for locomotion and electrical power for the exoskeleton computer. Wearing the exoskeleton, the operator can carry significant loads over considerable distances without reducing his/her agility, thus significantly increasing his/her physical effectiveness. As scheduled, a fully integrated prototype are powered by hydrogen peroxide is to be demonstrated in 2005. (Kazerooni 2005, Chu 2005, Zoss 2006)

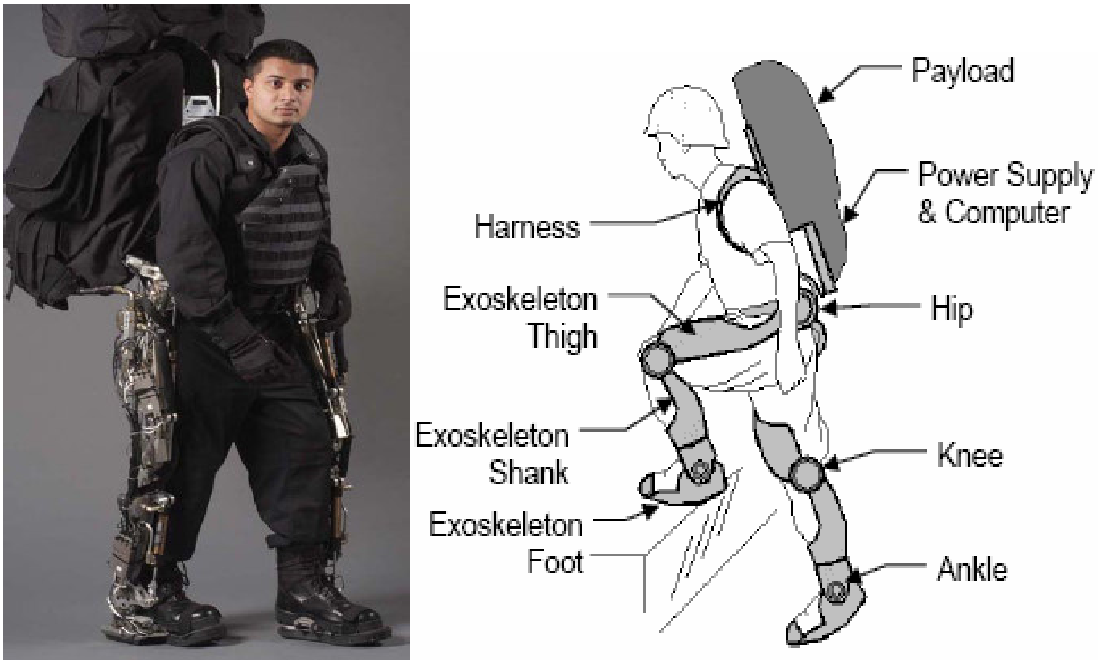


Figure 1.4. BLEEX (Berkeley Lower Extremity Exoskeleton).
(Source: WEB_3 2006)

1.5.3. DARPA's Works (Defense Advanced Research Projects Agency)

In a push to turn the science fiction of exoskeletons like the one used by Sigourney Weaver in Aliens into a military reality and deliver the advantages of such technology to soldiers in combat environments, the US Defense Advanced Research Projects Agency (DARPA) is funding a project known as "Exoskeletons for Human Performance Augmentation".

The scope of the program includes the development of actively controlled exoskeletons that not only increase strength and speed, but enable larger weapons to be carried, provide a higher level of protection from enemy fire or chemical attack, allow wearers to stay active longer and carry more food, ammunition and field supplies. Exoskeletons may eventually even be programmed to bring injured soldiers back to base by themselves.

Figure 1.5. Wearable solder exoskeletons.
(Source: WEB_4 2006)

Systems will range from un-powered mechanical devices that assist a particular aspect of human function to fully-mechanized exoskeletons relying on chemical or hydrocarbon fuels for totally independent operation by soldiers in the field. Several different projects under the DARPA umbrella are underway including SARCOS Research Corporation's Wearable Energetically Autonomous Robots (WEAR). Designed for on-foot combat, WEAR will include a base unit configured like legs, torso and arms that mimic human movement using complex kinematics systems and contain energy storage, power systems, actuators and everything needed for an autonomous wearable system.

ASP's (Application-Specific Packages) will provide additional protection against specific threats like radiation and biological agents or give expanded functionality for communications, surveillance or night operations. SARCOS is on track to have a legs only version of the exoskeleton ready for trial by 2003 and a working full-body prototype is expected around 2007.

The problems of actuation, power supply and energy storage are being tacked on several fronts with M-DOT Aerospace working on a META (Mesoscopic Turbo alternator) engine capable of acting as a viable electric power source for human exoskeletons and Quoin International developing a unique power supply and actuation system for anthropomorphic exoskeletons using hydrocarbon fuels and high-pressure pneumatic systems to mimic human movement. (WEB_4 2006)

1.6. The Scope of the Project

In the scope of this project, wearable exoskeleton robot that replace users' leg to walk are designed and manufactured, it is tested by the test machine which is also designed and manufactured. The best design is determined according to parameters in such criteria; dimension, strength, weight, volume, power consumption and walking speed. The stages of the whole project are listed below;

1.Designing of wearable exoskeleton robot: Three different wearable exoskeleton robots are designed in the 3D CAD software. All of them are compared according to design parameters which are determined above. Finally, the best wearable exoskeleton robot is decided to manufacture.

2. Designing of the testing machine: Test machine is designed for two main purposes by considering the working requirements of all robots designed. One of them is to be hung up wearable exoskeleton robot to help assemble section and by using encoder on each joint, test the joint movement and direction.

3. Manufacturing of the robot: All the parts of exoskeleton robot are produced with the material of Aluminum-T3 alloy by the conventional lathe, milling machine and laser cutting process.

4. Manufacturing of the test machine: The frame of test machine is manufactured by the conventional lathe, milling machine and laser cutting process.

5. Electronic Control Circuit and computer software: in order to control each joint movement and direction values a PWM based electronic control circuit is manufactured. Later a computer software program is written in microprocessor 16F877.

6. Testing of wearable exoskeleton robot: Wearable exoskeleton robot is tested with the test machine to each joint rotation values. Several test condition are determined such as; robot on the inclined surface, robot on the smooth surface, robot lifting the weight e.t.c. Finally, testing results are explained.

CHAPTER 2

MECHANICAL DESIGN OF WEARABLE EXOSKELETON ROBOT

In this chapter, the design limitations are determined and the wearable exoskeleton robot is designed according to these design constraints. Robot design is accomplished with SolidWorks® 2004. The parts of wearable exoskeleton robot designs are described; the working principles and the system elements are explained.

2.1. Design Limitations

In order to make wearable exoskeleton robot for paralytic and disable people walk, design constraints have to be defined.

These constraints are listed below;

1. The robot must have 1.8km/h speed and climb 7^0-slope which is the acceptable climb angle of paralytic and disable people, without any problem.

2. Robot must design to provide adjustability its balance using static walking character autonomously.

3. Robot must carry its and user weight and walk without any problem.

4. Robot must be wearable to carry out daily routine for its user intuitively.

5. The exoskeleton must use 1,5h with full battery.

6. The exoskeleton must be as quiet as possible maximum 100 decibel.

7. The actuation must apply torques at the joints of exoskeleton and human.

2.2. Human Gait Analysis

In this thesis, human walking data are used in order to specify the design requirements for the components at the exoskeleton joints. The power profiles for the hip, knee and ankle in the sagittal plane are plotted for a number of sets of gait data (WEB_5 2007). The biomechanical data present in this thesis come from studies where camera systems track markers place on a subject's legs while they walk on a set of force plates. The marker position data and the force plate data are then used to calculate the kinematics and kinetics of movement. Joint power is the dot-product of the moment at the joint and the angular velocity of the distal segment with respect to the proximal segment. Depending on the direction of the movement and the direction of the angular velocity, the power can be either positive or negative. In the biomechanics literature, positive power is called 'power generated', and negative power is called 'power absorbed'.

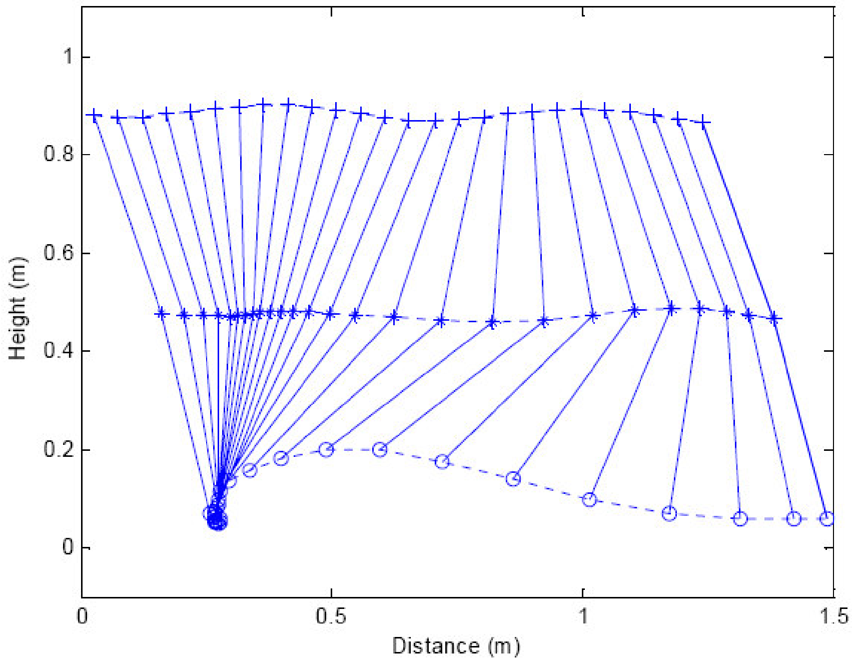


Figure 2.1. A plot of the gait data showing the trajectory of the hip, knee and ankle joints (Source: WEB_5 2007).

A conservative estimate of the weight of the exoskeleton is chosen to be 30kg and the normative data are scaled to a 100kg person in order to estimate the torques and powers require at the joints of the exoskeleton. In estimating the torque and power requirements at the hip joint of the exoskeleton, the normative data are scaled to a 130kg person. This is due to the fact that the design goal is to have the actuator at the hip assist the exoskeleton (30kg) as well as the human (100kg). The human is assisted by means of a thigh cuff attachment between the human and exoskeleton thigh. The goal is to design an exoskeleton to assist slow walking speeds. As a result, the data use to extract specifications for actuations at the joints are that for a walking speed of 0.8m/s (WEB_5 2007).

A number of assumptions are made in the application of the human biomechanical data to the design of the exoskeleton. The first is that the exoskeleton carries its own weight and power supply. The second assumption is that joint torques and joint powers scaled linearly with mass. The third assumption is that the exoskeleton doesn't greatly affect the gait of the wearer.

2.2.1. Hip Joint Analysis

During normal walking, the human hip joint follows an approximate sinusoidal pattern as can be seen in Figure 2.2. The thigh is flexed forward on heel strike and then the hip moves through extension during stance as the body is pivoted over the stance leg in a pendulum-like motion. The range of motion of the hip joint can be seen to vary between (-20 to 45) degrees.

At heel strike there is a sharp increase in hip torque as the leg accepts the weight of body to begin the stance phase. A peak negative hip torque of approximately 130Nm is experienced as the leg accepts load and the body's center of mass is raised. A maximum positive torque of about 100Nm occurs during the swing phase as the hip muscles provide energy to swing the leg forward.

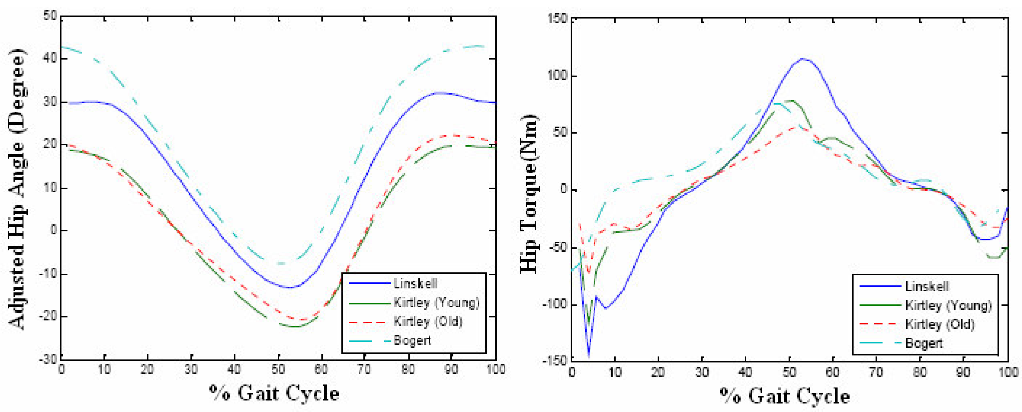


Figure 2.2. Hip angle and torque profiles scaled for a 100kg person.
(Source: WEB_5 2007)

A summary of the specifications for actuation at the hip joint of the exoskeleton are shown in Table 2.1. The approach taken in this thesis is to use DC electric motor as an actuator at the hip joint.

Table 2.1. Specifications for the hip joint of the exoskeleton that are extracted from the gait data (Source: WEB_5 2007).

Range of Motion	-20 deg to 45 deg
Max Joint Torque	130 Nm
Max Joint Velocity	4 rad/s

2.2.2. Knee Joint Analysis

Figure 2.3 shows plots of the angle and torque profile of the knee joint as a function of gait cycle. In early stance there is initial flexion-extension of the knee to help maintain a near horizontal trajectory of the body's center of mass. After the initial flexion-extension the knee remains locked for the remainder of the stance phase. The knee then undergoes flexion of approximately 60 degrees to allow for foot clearance during the swing phase. On heel strike, the knee bends slightly while exerting a maximum negative torque of 30Nm as the leg accepts the weight of the human. This is followed by a large positive extension torque of approximately 50Nm that keeps the knee from buckling during early stance and also assists in straightening the leg.

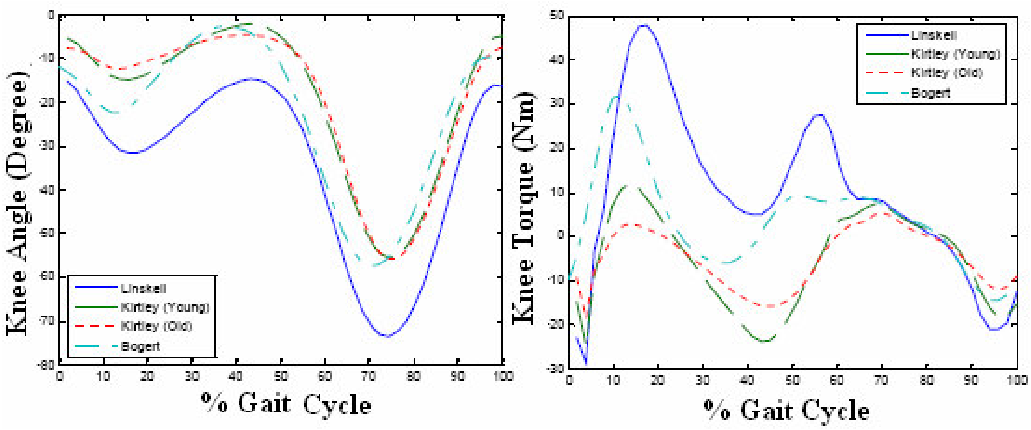


Figure 2.3. Knee angle and torque profiles scaled for a 100kg person. (Source: WEB_5 2007)

A summary of the specifications for actuation at the knee joint of the exoskeleton are shown in Table 2.2. From the gait data it appears that the ideal actuator for the knee of the exoskeleton is minimum 50Nm-actuator. Finally, according to gait data values DC electric motor is choused to use at the knee joint.

Table 2.2. Specifications for the knee joint of the exoskeleton that are extracted from the gait data (WEB_5 2007).

Range of Motion	0 deg to 90 deg
Max Joint Torque	50 Nm

2.2.3. Ankle Joint Analysis

The ankle joint experiences a range of motion of approximately 15 degrees in both directions during normal human walking. During the mid and late stance phases of walking the ankle eccentric plantar flexor activity creates negative joint torque as the ankle controls the forward movement of the center of mass. The peak torque experienced by the ankle is approximately 90Nm.

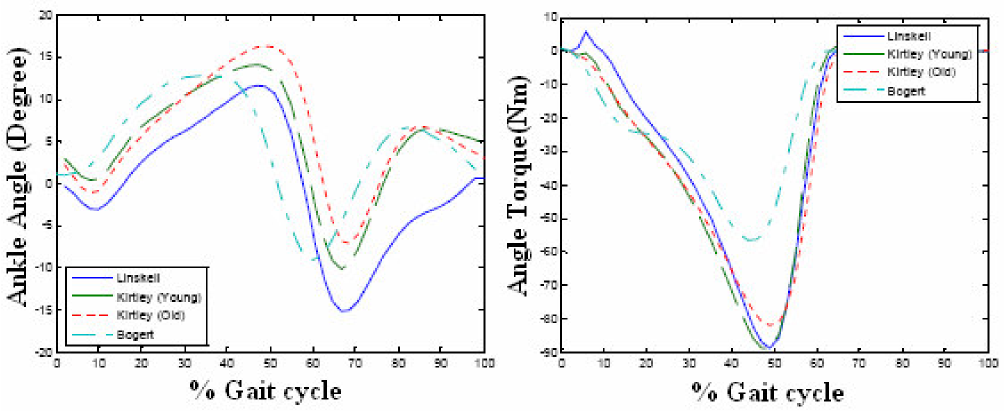


Figure 2.4. The ankle angle and torque profile scaled for a 100kg person are shown. (Source: WEB_5 2007)

A summary of the specifications for actuation at the ankle joint of the exoskeleton are shown in Table 2.3. From the gait data it appears that the ideal actuator for the knee of the exoskeleton is minimum 90Nm-actuator. Finally, according to gait data values DC electric motor is choused to use at the ankle joint.

Table 2.3. Specifications for the ankle joint of the exoskeleton that are extracted from the gait data (Source: WEB_5 2007).

Range of Motion	-15 deg to 15 deg
Max Joint Torque	90Nm

2.3. Earlier Designs

Before getting the final design, three preliminary designs are created. These are multiple motor and cable based exoskeleton robot, multiple motors and gear based exoskeleton robot and single motor and chain based exoskeleton robot. The working principle and system elements of each design are explained below.

2.3.1. Multiple Motors and Gear Based

This is the first design to consider for wearable exoskeleton robot. In this design multiple motors and small gear are used for each joint. The working principle of the system is; the motor surrounding on the joints rotate the metal bracelet which is on the joint so, the joint is open and close. However, later it is realized that multiple motor and gear based exoskeleton robot has several drawbacks. These are listed below.

- Extreme power consumption because of the using multiple motor.
- Extreme volume and weight values.
- Uncomfortable condition on the joints for users.
- So much friction between power transmission mechanism components.
- Need for complicated control system because of having so many motor.

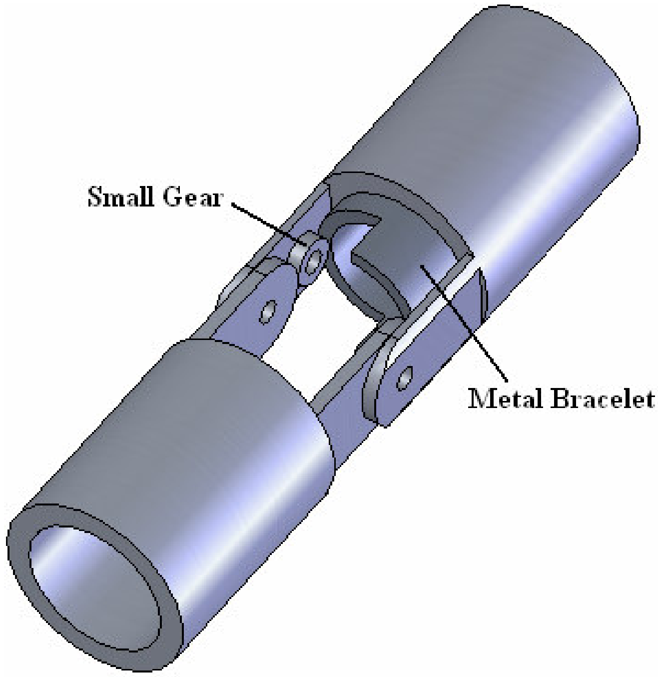


Figure 2.5. Multiple motors and gear based.

2.3.2. Multiple Motors and Cable Based

This is the second design to consider wearable exoskeleton robot. In this design, unlike the first design cables add the system to transmit the power to metal bracelet from motor outputs. The working principle of the multiple motor and cable based exoskeleton robot is, the motor surrounding on the joints rotate the metal bracelet which is on the joint. Two cables are tight on the metal bracelet and when the motor rotating, metal bracelet pull and push the cable so, the joint is open and close. Like first design, multiple motors and cable based exoskeleton robot has a lot of disadvantages. These are listed below.

- Extreme power consumption because of the using multiple motor.
- Extreme volume and weight values.
- Uncomfortable condition on the joints for users.
- So much friction between power transmission mechanism components.
- Need for complicated control system because of having so many motor.
- Because of the using cables, system creates backlash while working.

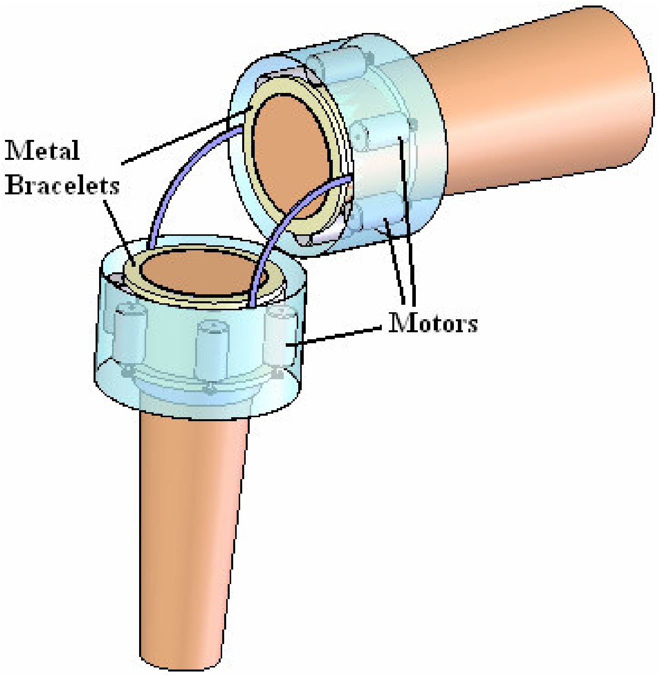


Figure 2.6. Multiple motors and cable based.

2.3.3. Single Motor and Chain Based

This is the third design of wearable exoskeleton robot. Unlike the others, this design has single motor and power transmission mechanism for each joint and it is completely different from the earlier design. Two sprocket gear and one chain are used for each joint so, necessary torque and speed are provided from these combination.

The working principle of the system is; power transmission mechanism are created for each joint and these are worked independently each other without any electronic control unit. Electronic control unit provide the synchronization of each joint. Control mechanism of wearable exoskeleton robot is described in chapter 6.

The system is designed in static balance principle in that the robot's center of mass is at all times with in the support area of its foot on the ground so; the robot adjusts its balance intuitively. Single motor and chain based Exoskeleton Robot are accepted as a final design and manufactured but after that system main material are changed and the robot manufactured using different material. Figure 2.7 shows Single motor and chain based Exoskeleton Robot

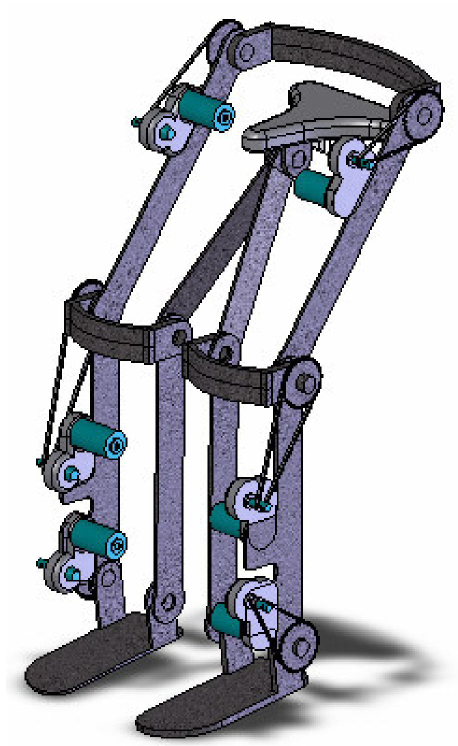


Figure 2.7. Single motor and chain based.

2.4. Final Design

The exoskeleton is designed to provide a parallel load path that support walking for paralytic and disable people. The exoskeleton had sufficient degrees of freedom to minimize kinematic constraints experienced by the wearer. Component design and selection for the hip, knee and ankle joints are based on the specifications outlined in section 2.2. The main components of the exoskeleton are shown in Figure 2.8. The main properties of final design are shown in Table 2.4.

Table 2.4. The main properties of final design.

PROPERTIES	
Weight	≈ 21kg
Chargeability	Yes, in maximum 7,5h
Cost	≈ 4000 YTL
Lifting Capacity	100kg (Average weight of subjects)
Actuator Type	Motor Based
Walking Speed	≈ 1,8 km/h
Battery Type	2 x 12V DC 17A Maintain-Free-Lead
Working Time	≈ 50min = 225m

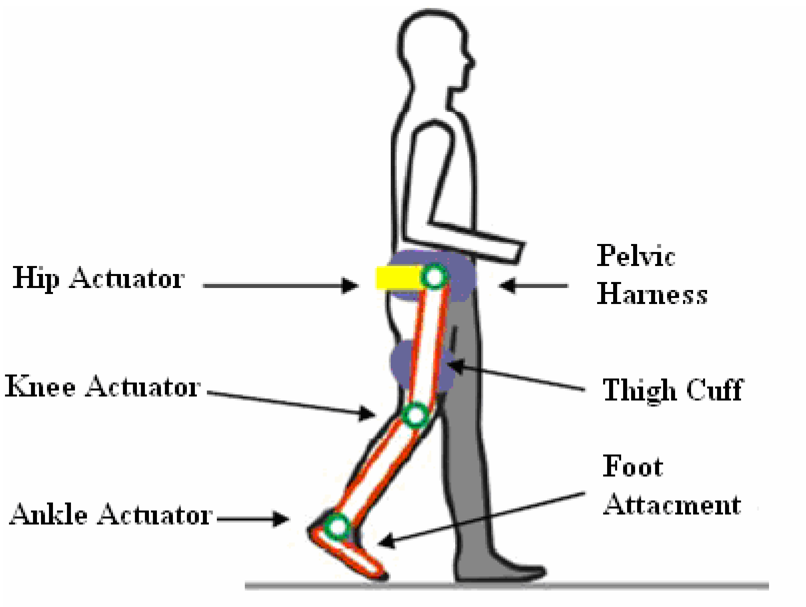


Figure 2.8. The main components of the exoskeleton.

2.4.1. System Components

The robot is comprised of six main sections which are actuators, power transmission mechanisms, inner exoskeleton and outer exoskeleton, power source, electronic control unit, (Figure 2.9). The reason for such a classification is that each of these sections is controlled independently walking operation.

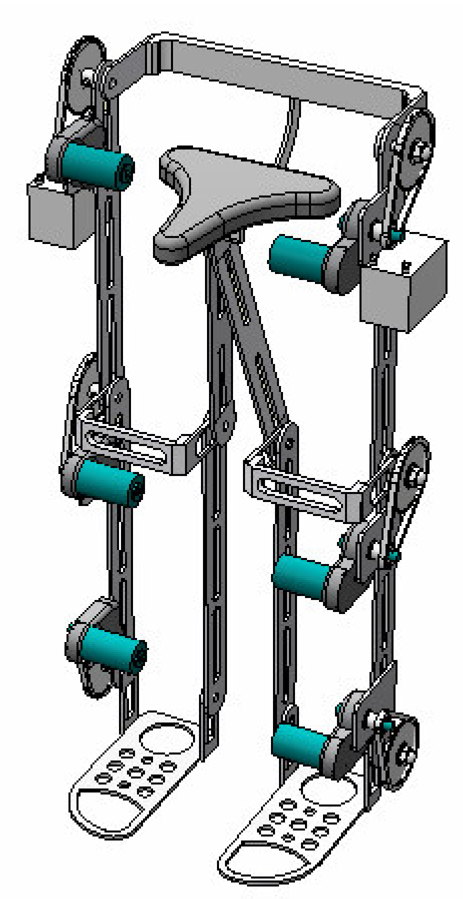


Figure 2.9. Wearable exoskeleton robot.

2.4.1.1. Actuators

Actuators with muscle-like properties could allow legged robots to achieve performance approaching that of their biological counterparts. Some of the beneficial properties of muscle include its low impedance, high force-fidelity, low friction, and good bandwidth. Dc electric motor and suitable gear combination share these beneficial properties with muscle and thus are well suited for legged robots. These high quality force-controllable actuators allow the control system to exploit the natural dynamics of the robot, to distribute forces among the legs, and to provide an active suspension that is robust to rough terrain.

In order to ability of easy control and meet the high power properties, DC electric motors are used as a main actuator in our project. Motors feed 24V DC electric and produce 2 rpm – 1, 7 Nm power.

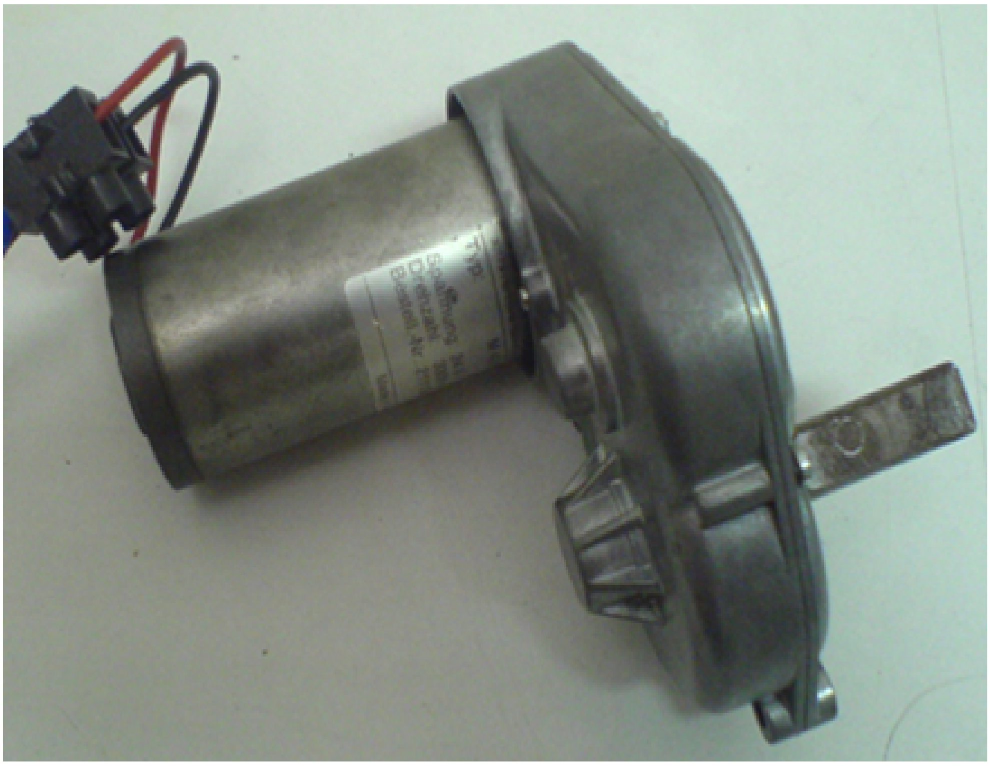


Figure 2.10. Actuator of the wearable exoskeleton robot (DC electric Motor).

Table 2.5. Comparison of major actuation technologies.

(Source: Pratt et al. 2004)

Actuation Type	**Max. Force**	**Max. Speed**	**Low Force Ability**	**Position Controllability**	**Back Drivability**
Pneumatic	M	M	F	P	F
Hydraulic	H	M	P	G	P
Direct Drive Electric	L	H	E	G	E
Electric gear motor	M/H	H	E	G	F
Electric Series Elastic Actuator	M/H	H	E	G	E
Hydraulic Series Elastic Actuator	H	M	E	G	E
P: Poor, L: Low, F: Fair, M: Medium, G: Good, H: High, E: Excellent					

2.4.1.2. Power Transmission Mechanism

Chains are a very robust means to transmit very large forces and torques. The power transmission mechanism of wearable exoskeleton system has 3 main parts. These are motor gearbox, sprocket gears and chain.

The gearbox connected the actuator directly and has a 1:147,5 ratios. Efficiency of the gearbox is 0,8.

In wearable exoskeleton system two sprocket gears are used. One of them connected the output of the actuator and has eleven teeth. The other sprocket gear connected with the output shaft of the outer exoskeleton shank and has thirteen teeth. The calculation of the sprocket gears ratio is shown equation 2.1.

$$ratio = \frac{i_1}{\dot{I}_2} = \frac{small\ gear\ teeth}{big\ gear\ teeth} \tag{2.1}$$

After the calculation of rotation and torque values of wearable exoskeleton robots joint, we need 17.7Nm power from get suitable motor, gearbox and power transmission mechanism.

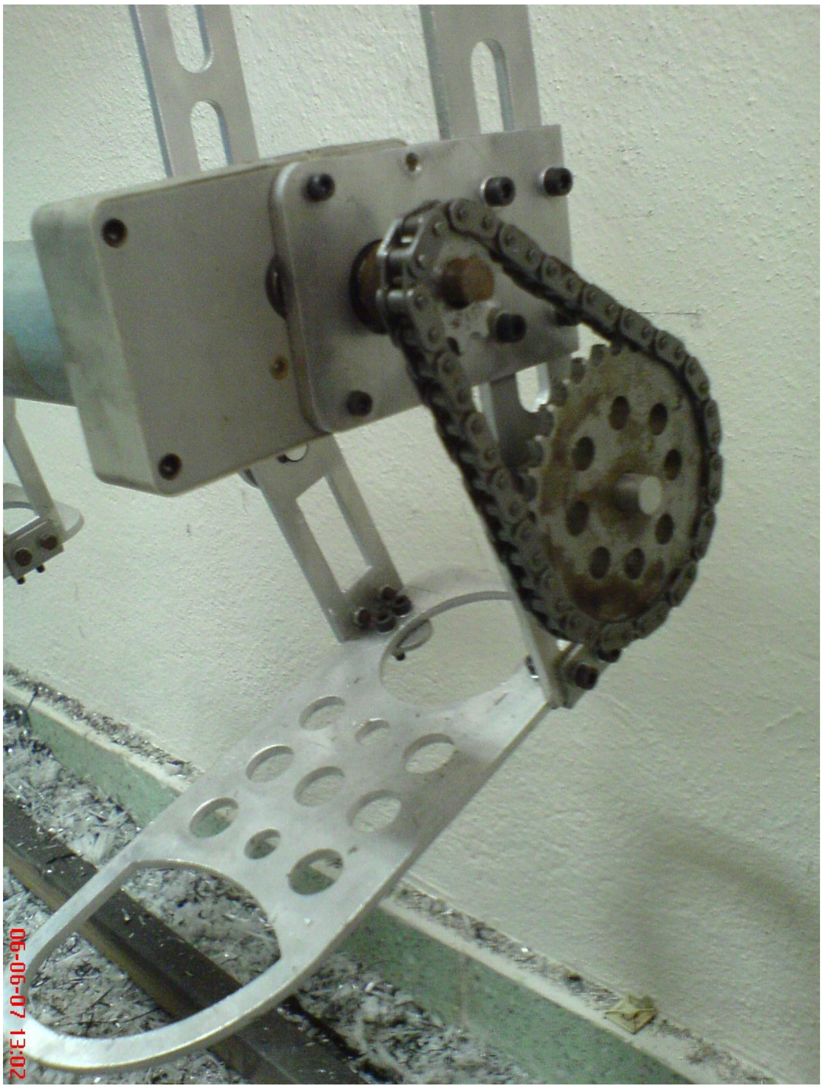


Figure 2.11. Actuator, gearbox and power transmission mechanisms.

2.4.1.3. Exoskeleton Structure

The design of the exoskeleton structure has to address the fact that the structure's primary function is to provide the mechanical interface to the operator. A parallel orthotic structure is the basic framework use to transfer the load from the backpack to the ground. The main structural elements consist of standard aluminum bar. This bar is used since it is lightweight, rated for human use, and interfaced with standard prosthetic connectors and components.

The criteria for sizing the structural elements have to take into consideration the stresses, and also the structural stiffness. Minimizing the size and weight of the structural elements are traded off against maintaining structural stiffness so that the user can be adequately supported. The strength to weight ratio of the exoskeleton components are maximized using finite element analysis.

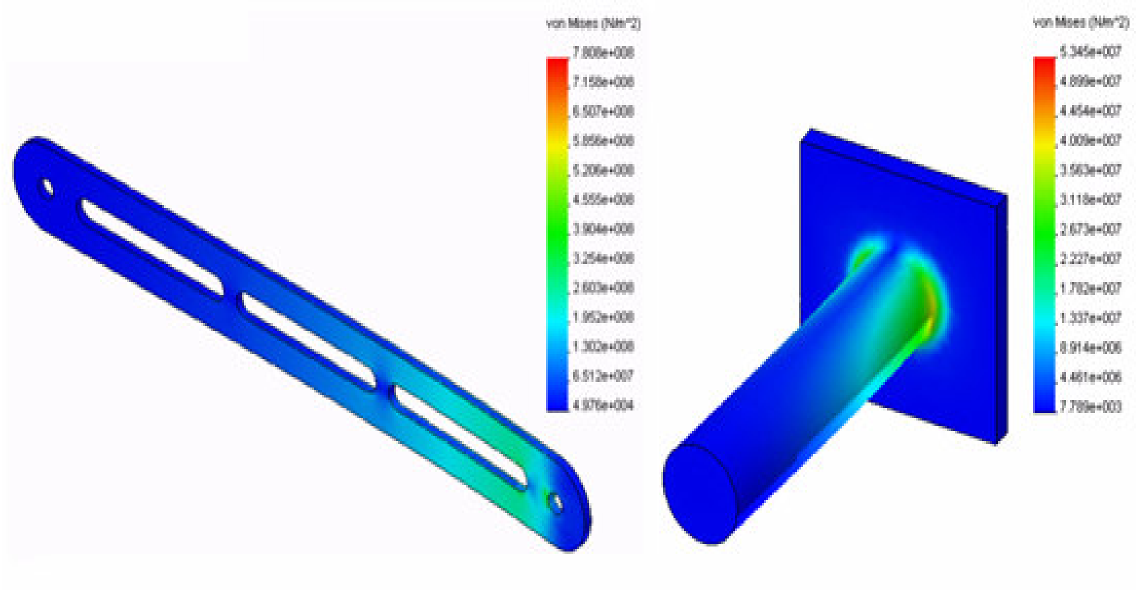


Figure 2.12. Finite element analysis results from testing maximum forced parts.

2.4.1.3.1. Inner Exoskeleton

Inner exoskeleton parts use on the robot to support legs without any problem and to meet the synchronization, during walking action.

Apart from the current exoskeleton robot, we use a seat on the inner exoskeleton. This provides easy to adjust balance for users and especially for paralytic people provide not to lose body posture during walking action. Therefore; the users drive the robot as if they are on the horse.

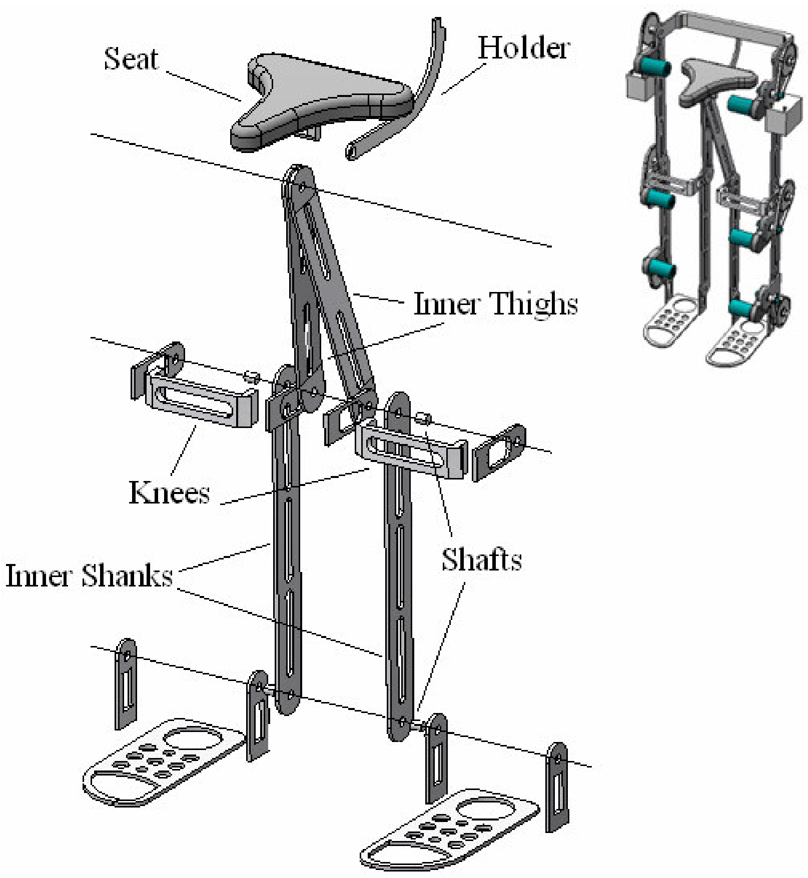


Figure 2.13. Inner exoskeleton.

2.4.1.3.2. Outer Exoskeleton

In order to achieve an ideal performance, the outer exoskeleton should satisfy the following criteria.

• High safety: The outer exoskeleton must be able to operate safely and not cause any injuries or pose any hazards to the user and the environment.

• Easy to wear: The user should be able to wear and subsequently disengage from the exoskeleton whenever needed in an easy, transparent and quick method.

• High aesthetic satisfaction: The exoskeleton must look sleek, compact and at the same time, must feel sturdy and reliable. Also, it is preferred that the exoskeleton will resemble the actual human lower limbs.

• Length adaptable: The length of shank and thigh of the exoskeleton can be adjusted in a broad range in order to accommodate average people with different physical figures to strap on.

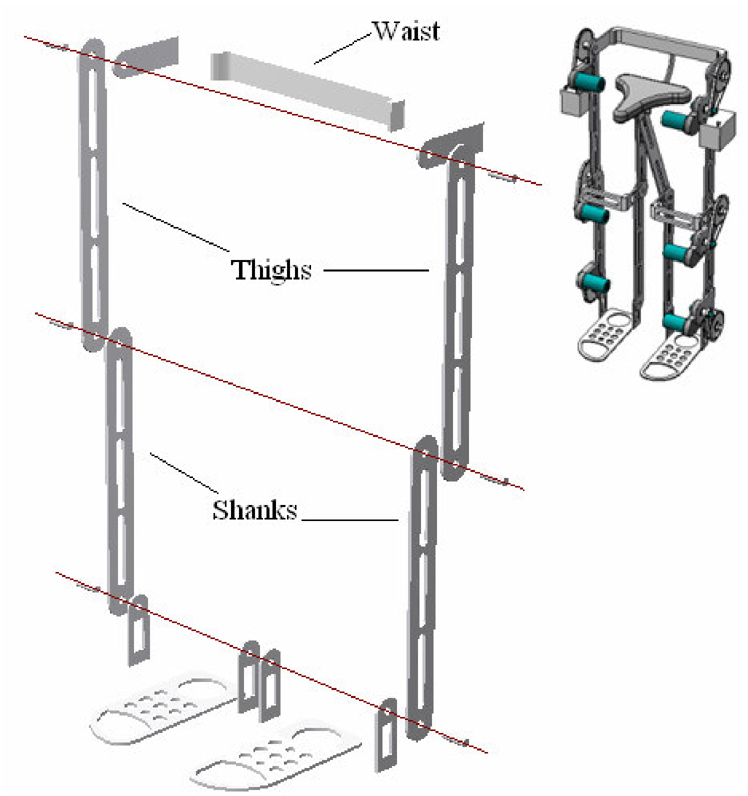


Figure 2.14. Outer exoskeleton.

2.4.1.4. Power Source

The power for the electric motors on both the wearable exoskeleton robot is supplied by two tractional type gel batteries. Considering an operation time and the unsteady working conditions, heavy-duty type batteries which are chosen similar to the ones commonly used in conventional electrical loaders. According to the power consumption ratings of the motors, the robot is equipped with two batteries each of which has the power supply rate of 10 Ah. The gel type batteries are very suitable for continuous power supply. The robot is included with a charging unit, which eliminates the necessity of removing the batteries for charging.

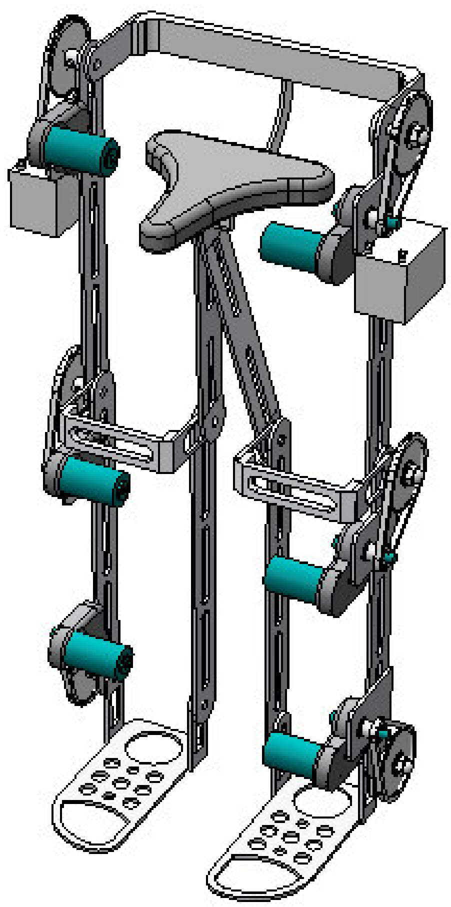


Figure 2.15. Wearable exoskeleton robot with batteries.

2.4.2 Material Selection

2.4.2.1 Commonly Used Engineering Materials

Some metals and their alloys can be considered as engineering materials to be used in this application. These are iron, aluminum and steel. Cast iron is a ductile and formable metal since it has enough yield strength for some certain applications. Shaping of this metal is much easier than the others.

Aluminum is the most preferable one because of its high machinability and low density. The weakest point of this metal is the mechanical strength which is less than cast iron. Therefore some high strength aluminum alloys are produced by the improving technology. One of these alloys is aluminum 2024-T3 which is used in many applications from car to aircraft industry where the high mechanical strength and the low weight are important.

Steel can be considerable when high mechanical strength is required while the weight is not important. In small machine elements such as gears and rocks steel is most preferred. (Black and Adams 1981)

2.4.2.2 Selection Procedure

In order to select the optimum material for wearable exoskeleton robot, mechanical and physical properties of materials are considered. These properties are especially tensile strength, yield strength, shear strength, density and magnetic property. Table 2.6 shows the properties of the common metals and alloys.

The point on the stress-strain curve where there is a sudden increase in strain, but no increase in stress is called yield strength. It is at this point that a metal is about to permanently deform. The metal with higher yield strength is more durable than the other materials. As it is seen in Table 2.6 steel has largest strength but aluminum-T3 has enough strength when the constraints are considered.

Ultimate tensile strength is a material's ability to resist forces that attempt to pull it apart or stretch it. This is another important factor desired for joint parts. The more ductile material has the less tensile strength. Thus, it is recommended for materials to have high tensile strength. Steel and aluminum-T3 have the greatest tensile strength values.

Table 2.6. Properties of the common metals and alloys.
(Source: Black and Adams 1981)

Metal / Alloy	Yield Strength (MPa)	Tensile Strength (MPa)	Density (kg/m^3)	Shear Strength (MPa)
Gray Cast Iron	135	170	7830	45
Aluminum 1100	105	110	2710	28
Alumin. 2024-T3	345	483	2768	30
Steel AISI 302	520	860	7850	186

Density is a measure of mass per unit of volume. The higher a material's density, the higher it's mass per volume. Steel has the largest density value while aluminum has the lowest density value. This means aluminum is much lighter than the steel since both lighter and stronger materials are most preferred in robotic applications. Aluminum 1100 alloy is light and weak but aluminum-T3 alloy is both lighter and stronger.

Shear stress, or just shear, is similar to stress, except that the force is applied such that the material is sheared or twisted. Aluminum alloys have the lowest shear strength according to the other metals in Table 2.6. Magnetic property is an ability of materials to attract or repulse each others. Most metals can be easily induced and behave like a magnet or attracted by a magnet. However; only aluminum has non-magnetic property.

Because of its unique properties of aluminum-T3 alloy; it will be used in manufacturing of wearable exoskeleton robot. Moreover the machining of aluminum-T3 is much easier than the other metals and alloys, and density is much lower than other metals, which means the weight of wearable exoskeleton robot will be as low as possible.

CHAPTER 3

KINEMATIC ANALYSIS

Kinematics is the relationship between the position, velocities, and accelerations of the links of a manipulator. In the kinematic analysis of manipulator position, there are two separate problems to solve. These are direct kinematics, and inverse kinematics.

Direct kinematics involves solving the forward transformation equation to find the location of the end point of the manipulator in terms of the angles and displacements between the links. The angles and displacement between the links are called joint coordinates and are described with link variables; while the location of the end point of manipulator in space is describe Cartesian coordinates.

Inverse kinematics involves solving the inverse transformation equation to find the relationships between the links of the manipulator from the location of the end point on the manipulator in space (McKerrow 1990).

3.1. Direct Kinematical Analysis

Direct kinematic analysis should be calculated in order to define the link and joint positions and motions which are needed to calculate dynamic analysis of the manipulator. Moreover, direct kinematic analysis is applied for obtaining the error between the real position and desired position of the gripper as feedback.

Two dimensional three-link manipulators Figure 3.1 can be analyzed using simple trigonometry, rather than homogeneous transformation equations. For complex manipulators the trigonometric relationships between links are difficult to visualize, and homogenous transforms are used. Both method procedures the same result. To demonstrate trigonometric methods, geometric model will be developed for three-link manipulator.

Table 3.1. Denavit-Hartenberg parameters of the manipulator.

Link	**Variable**	Q	α	l	d
1	Q_1	Q_1	0	l_1	0
2	Q_2	Q_2	0	l_2	0
3	Q_3	Q_3	0	l_3	0

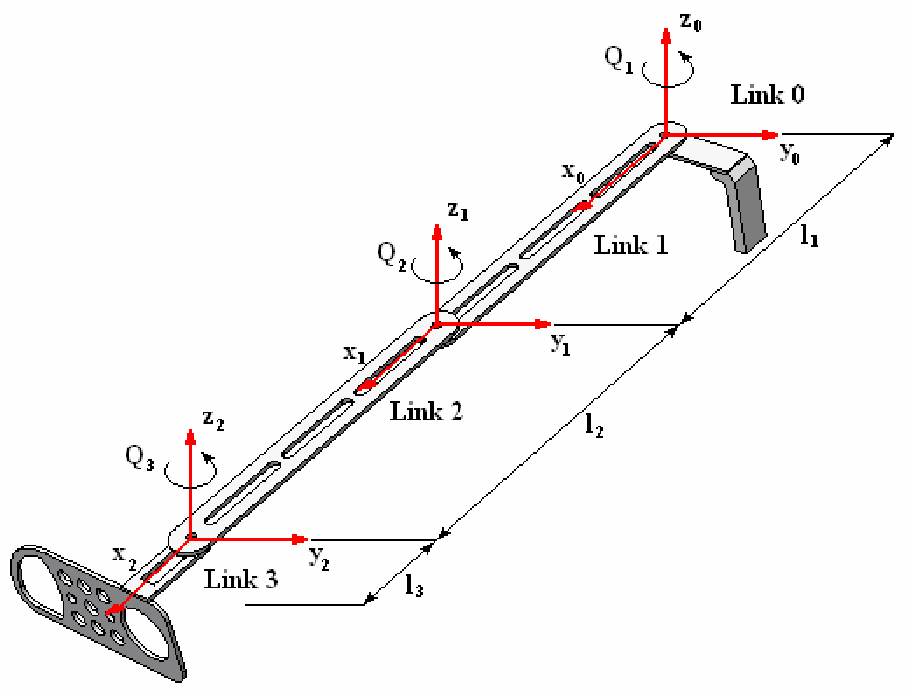


Figure 3.1. 3D representation of manipulator.

Exoskeleton robot can be described with a vector equation;

$$ {}^{0}\mathbf{P}_{0,3} = {}^{0}\mathbf{P}_{0,1} + {}^{0}\mathbf{P}_{1,2} + {}^{0}\mathbf{P}_{2,3} \quad (3.1) $$

where ${}^{0}\mathbf{P}_{0,3}$ is the vector from the origin of frame $\boldsymbol{i}$ to the origin frame $\boldsymbol{j}$ as seen from the reference frame.

With simple trigonometry, the x and y components of the vectors ${}^{0}\boldsymbol{P}_{0,1}$, ${}^{0}\boldsymbol{P}_{1,2}$ and ${}^{0}\boldsymbol{P}_{2,.3}$ can be found. When these values are substituted into Equation 3.1, geometric model of the exoskeleton robot is obtained (Equation 3.5).

$$^{0}\mathbf{P}_{0,1} = (l_1\cos (Q_1) , (l_1\sin(Q_1)) \quad (3.2)$$

$$^{0}\mathbf{P}_{1,2} = (l_2\cos (Q_1+Q_2) , (l_2\sin(Q_1+Q_2)) \quad (3.3)$$

$$^{0}\mathbf{P}_{2,3} = (l_3\cos (Q_2+Q_3) , (l_3\sin(Q_2+Q_3)) \quad (3.4)$$

$$^{0}\mathbf{P}_{0,3} = \begin{bmatrix} \mathrm{P}x \\ \mathrm{P}y \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} l_1\cos(Q_1) + l_2\cos(Q_1+Q_2) + l_3\cos(Q_2+Q_3) \\ l_1\sin(Q_1) + l_2\sin(Q_1+Q_2) + l_3\sin(Q_2+Q_3) \end{bmatrix} \quad (3.5)$$

The orientation of the third link is the sum of the joints angle. This geometric model relates the cartesian coordinates of the end effector to the joint angles. Thus, it can be used, to calculate cartesian coordinates of the manipulator. The work space of this robot is a flat disc is shown in Figure 3.2, where the maximum radius equals the difference between the lengths of the linkages.

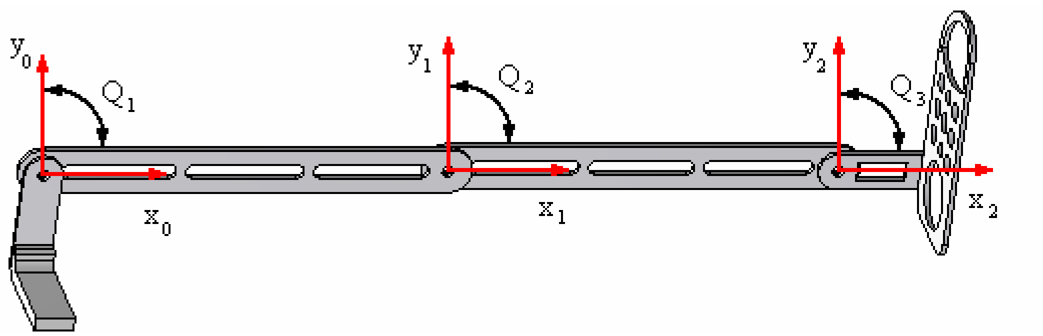


Figure 3.2. Manipulator in zero position.

3.2. Inverse Kinematical Analysis

Correct evaluation of inverse kinematic analysis has a vital importance in order to compute the correct joint parameters because the Exoskeleton robot is controlled in task space. However; this task becomes complicated as the number of links and joints increase.

The Exoskeleton leg consists of three revolute joints and each having one degree of freedom. The total degrees of freedom of the manipulator leg is 3 for the manipulator leg, the end effector and waist.

Consider the three-link planar manipulator shown in Figure 3.3.

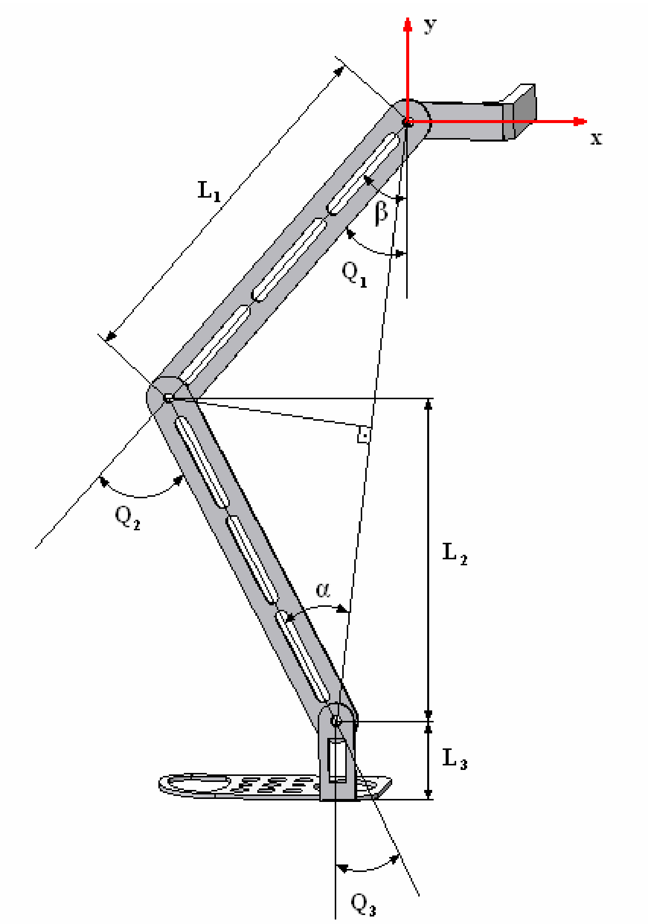


Figure 3.3. The assistant angles and distances used for kinematic analysis.

$$ {}^{0}_{3}T = {}^{0}_{1}T \; {}^{1}_{2}T \; {}^{2}_{3}T \tag{3.6} $$

where;

$$ {}^{0}_{1}T = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.7} $$

$$ {}^{1}_{2}T = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_1 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.8} $$

$$
{}^{2}_{3}T = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_2 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.9}
$$

$$
{}^{0}_{3}T = \begin{bmatrix} \cos(\theta_1+\theta_2+\theta_3) & -\sin(\theta_1+\theta_2+\theta_3) & 0 & \cos(\theta_1+\theta_2)L_2+\cos\theta_1 L_1 \\ \sin(\theta_1+\theta_2+\theta_3) & \cos(\theta_1+\theta_2+\theta_3) & 0 & \sin(\theta_1+\theta_2)L_2+\sin\theta_1 L_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.10}
$$

where

$$
\begin{aligned}
\cos(\theta_1+\theta_2+\theta_3) &= \cos(\theta_1+\theta_2)\cos\theta_3 - \sin(\theta_1+\theta_2)\sin\theta_3 \\
\sin(\theta_1+\theta_2+\theta_3) &= \cos(\theta_1+\theta_2)\sin\theta_3 + \sin(\theta_1+\theta_2)\cos\theta_3 \\
\cos(\theta_1+\theta_2) &= \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2 \\
\sin(\theta_1+\theta_2) &= \cos\theta_1\sin\theta_2 + \sin\theta_1\cos\theta_2
\end{aligned}
$$

In this case, only three parameters are required to specify the complete two-dimensional configuration of the end-effector of such a manipulator, as in the Figure 3.3, namely, the position vector [p_x, p_y] and ϕ, where ϕ is the orientation of link 3 in the plane. Hence, rather than giving a general ${}^{0}_{3}T$ as a goal specification, we will assume a transformation with the structure

$$
{}^{Base}_{Wrist}T = \begin{bmatrix} \cos\phi & -\sin\phi & 0 & x \\ \sin\phi & \cos\phi & 0 & y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.11}
$$

All attainable goals must lie in the subspace implied by the structure of equation (3.11). By equating (3.10) and (3.11) we arrive at a set of four nonlinear equations which must be solved for θ_1, θ_2, and θ_3:

$$\cos\phi = \cos(\theta_1 + \theta_2 + \theta_3) \tag{3.12}$$

$$\sin\phi = \sin(\theta_1 + \theta_2 + \theta_3) \tag{3.13}$$

$$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \tag{3.14}$$

$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) \tag{3.15}$$

We now begin our algebraic solution of equation (3.12) through (3.15). If we square both (3.14) and (3.15) and add them, we obtain:

$$x^2 + y^2 = L_1^2 + L_2^2 + 2L_1L_2\cos\theta_2 \tag{3.16}$$

Solving for $\cos\theta_2$ we obtain:

$$\cos\theta_2 = \frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2} \tag{3.17}$$

In order for a solution to exist, the right hand side of (3.17) must have a value between -1 and 1. In the solution algorithm, this constraint would be checked at this time to determine if a solution exist or not. Physically, if this constraint is not satisfied, then the goal point is too far away for the manipulator to reach.

Assuming the goal is in the workspace, we write an expression for $\sin\theta_2$ as

$$\sin\theta_2 = \pm\sqrt{1 - \cos\theta_2^2} \tag{3.18}$$

Finally, we compute θ_2 using the two-argument arctangent routine

$$\theta_2 = Arc\tan 2(\sin\theta_2 \cos\theta_2) \tag{3.19}$$

The sign of (3.9) corresponds to the multiple solution in which we can choose the ”foot-up” or the “foot-down” solution. By determine both the sine and cosine of the desired joint angle, and applying the two-argument arctangent function, we ensure that we have found all solutions, and that the solved angle is in the proper quadrant.

Having found θ_2 we may solve (3.14) and (3.15) for θ_1. We write (3.14) and (3.15) in the form

$$x = k_1 \cos\theta_1 - k_2 \sin\theta_1 \quad (3.20)$$

$$y = k_1 \sin\theta_1 - k_2 \cos\theta_1 \quad (3.21)$$

where

$$k_1 = L_1 + L_2 \cos\theta_2$$
$$k_2 = L_2 \sin\theta_2 \quad (3.22)$$

In order to solve an equation of this form, we perform a change of variables. Actually, we are changing the way in which we write the constants k_1 and k_2

if

$$r = +\sqrt{k_1^2 + k_2^2} \quad (3.23)$$

and

$$\gamma = Arc\tan 2(k_1, k_2)$$

then

$$k_1 = r\cos\gamma \quad (3.24)$$

$$k_2 = r\sin\gamma$$

Equation (3.11) and (3.12) can now be written;

$$\frac{x}{y} = \cos\gamma\cos\theta_1 - \sin\gamma\sin\theta_1 \quad (3.25)$$

$$\frac{y}{r} = \cos\gamma\sin\theta_1 - \sin\gamma\cos\theta_1 \quad (3.26)$$

or

$$\cos(\gamma + \theta_1) = \frac{x}{r} \quad (3.27)$$

$$\sin(\gamma + \theta_1) = \frac{y}{r} \quad (3.28)$$

Again, using the two-argument arctangent we get

$$\gamma + \theta_1 = Arc\tan 2(\frac{y}{r}, \frac{x}{r}) = Arc\tan(y, x) \quad (3.29)$$

and so,

$$\theta_1 = Arc\tan 2(y, x) - Arc\tan(k_2, k_1) \quad (3.30)$$

Finally, from (3.12) and (3.13) we can solve for the sum of θ_1 through θ_3:

$$\theta_1 + \theta_2 + \theta_3 = Arc\tan 2(\sin_\phi, \cos_\phi) = \phi \quad (3.31)$$

From which θ_3 can be solved since the first two angles are known (3.19), (3.30). It is typical with manipulators that have two or more links moving in a plane that in the course of solutions, expressions for sums of joint angles arise.

CHAPTER 4

DYNAMIC ANALYSIS OF WEARABLE EXOSKELETON ROBOT

In order to control the leg of wearable exoskeleton robot in task space, the dynamic analysis of the leg should be calculated and the generalized force equations should be obtained according to the robot configuration. Dynamics deals with the manipulator in motion. It will be seen that the joint torques control the angular accelerations. The relationships are not direct however. First of all, the sensitivity of a given joint to torque varies with the arm configuration; secondly, forces appear that are functions of the products of the angular velocities; and thirdly there is considerable coupling between the motions of the links. The velocity product terms can be thought of as generalized centrifugal forces. The dynamic analysis in this study is accomplished by Lagrange formulation method.

The Lagrangian formulation describes the dynamic behavior of a robot in terms of the work done by, and energy stored in the system. The arm is treated as a black box that has an energy balance. The constraint forces are eliminated during the formulation of the equations. As with Lagrangian dynamics, the closed-form equations can be derived in any coordinate system.

The Lagrange formulation bases the differences between total kinematic energy of the manipulator and total potential energy of manipulator.

In this method, first the kinetic energy of each link is calculated depending on the center of gravity of the link, and later the difference between the sum of the kinetic energy and the sum of the potential energy of the links are calculated. This difference describes the Lagrangian of the system. By taking the derivative of the Lagrangian depending on the time change of the joint velocities and joint position and calculating the difference yields the generalized force needs to be applied to each joint (Angeles 1997).

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_n}\right) - \frac{\partial L}{\theta_n} = F_n \qquad (4.1)$$

where L is the Lagrangian of the system, define as;

$$L \equiv K - U \tag{4.2}$$

All vectors introduced below are two-dimensional, the scalar angular velocities of the links, w_i, for i = 1,2,3, being;

$$w_1 = \dot{\theta}_1 \tag{4.3}$$

$$w_2 = \dot{\theta}_1 + \dot{\theta}_2 \tag{4.4}$$

$$w_3 = \dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 \tag{4.5}$$

Moreover, the velocities of the mass center are;

$$\dot{c}_1 = \frac{1}{2}\dot{\theta}_1 E l_1 \tag{4.6}$$

$$\dot{c}_2 = \dot{\theta}_1 E l_1 + \frac{1}{2}\left(\dot{\theta}_1 + \dot{\theta}_2\right) E l_2 \tag{4.7}$$

$$\dot{c}_3 = \dot{\theta}_1 + E l_1 + \left(\dot{\theta}_1 + \dot{\theta}_2\right) E l_2 + \frac{1}{2}\left(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3\right) E l_3 \tag{4.8}$$

the kinetic energy then becoming;

$$K = \frac{1}{2}\sum_{1}^{3}\left(m_i \left\|\dot{c}_i\right\|^2 + I_i w_i^{\,2}\right) \tag{4.9}$$

The squared of the mass-center velocities are now computed using the expressions derived above. After simplifications, these yield,

$$\|\dot{c}_1\|^2 = \left[\frac{1}{4} l_1^{\,2} \dot{\theta}_1^{\,2} \right] \tag{4.10}$$

$$\|\dot{c}_2\|^2 = \left[l_1^{\,2}\dot{\theta}_1^{\,2} + \frac{1}{4} l_2^{\,2}\left(\dot{\theta}_1^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_2^{\,2}\right) + l_1 l_2 \cos\theta_2 \left(\dot{\theta}_1^{\,2} + \dot{\theta}_1\dot{\theta}_2\right) \right] \tag{4.11}$$

$$\|\dot{c}_3\|^2 = \begin{bmatrix} l_1^{\,2}\dot{\theta}_1^{\,2} + l_2^{\,2}\left(\dot{\theta}_1^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_2^{\,2}\right) \\ + \frac{1}{4} l_3^{\,2}\left(\dot{\theta}_1^{\,2} + \dot{\theta}_2^{\,2} + \dot{\theta}_3^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + 2\dot{\theta}_1\dot{\theta}_3 + 2\dot{\theta}_2\dot{\theta}_3\right) \\ + 2 l_1 l_2 \cos\theta_2 \left(\dot{\theta}_1^{\,2} + \dot{\theta}_1\dot{\theta}_2\right) + l_1 l_3 \cos(\theta_2 + \theta_3)\left(\dot{\theta}_1^{\,2} + \dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\dot{\theta}_3\right) \\ + l_1 l_2 \cos\theta_3 \left(\dot{\theta}_1^{\,2} + \dot{\theta}_2^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\dot{\theta}_3 + \dot{\theta}_2\dot{\theta}_3\right) \end{bmatrix} \tag{4.12}$$

so, kinetic energy for link 1,2,3 are equations; (4.13), (4.14), (4.15);

$$K_1 = \left[\frac{1}{8} m_1 l_1^{\,2} \dot{\theta}_1^{\,2} + \frac{1}{2} I_1 \dot{\theta}_1^{\,2} \right] \tag{4.13}$$

$$K_2 = \left[\frac{1}{2} m_2 l_1^{\,2}\dot{\theta}_1^{\,2} + \frac{1}{8} m_2 l_2^{\,2} + I_2\left(\dot{\theta}_1^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_2^{\,2}\right) + \frac{1}{2} m_2 l_1 l_2 \cos\theta_2 \left(\dot{\theta}_1^{\,2} + \dot{\theta}_1\dot{\theta}_2\right) \right] \tag{4.14}$$

$$K_3 = \begin{bmatrix} \frac{1}{2} m_3 l_1^{\,2}\dot{\theta}_1^{\,2} + \frac{1}{2} m_3 l_2^{\,2}\left(\dot{\theta}_1^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_2^{\,2}\right) \\ + \frac{1}{8} m_3 l_3^{\,2}\left(\dot{\theta}_1^{\,2} + \dot{\theta}_2^{\,2} + \dot{\theta}_3^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + 2\dot{\theta}_1\dot{\theta}_3 + 2\dot{\theta}_2\dot{\theta}_3\right) \\ + m_3 l_1 l_2 \cos\theta_2\left(\dot{\theta}_1^{\,2} + \dot{\theta}_1\dot{\theta}_2\right) + \frac{1}{2} m_3 l_1 l_3 \cos(\theta_2 + \theta_3)\left(\dot{\theta}_1^{\,2} + \dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\dot{\theta}_3\right) \\ + \frac{1}{2} m_3 l_2 l_3 \cos\theta_3\left(\dot{\theta}_1^{\,2} + \dot{\theta}_2^{\,2} + \dot{\theta}_3^{\,2} + 2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\dot{\theta}_3 + \dot{\theta}_2\dot{\theta}_3\right) \\ + \frac{1}{2} m_3 I_3\left(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3\right) \end{bmatrix}$$

(4.15)

and the potential energies of linkages are calculated as follows;

$$V_1 = \frac{1}{2} m_1 g l_1 \sin\theta_1 \tag{4.16}$$

$$V_2 = m_2 g\left(l_1 \sin\theta_1 + \frac{1}{2} l_2 \sin(\theta_1 + \theta_2)\right) \tag{4.17}$$

$$V_3 = m_3 g\left(l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) + \frac{1}{2} l_3 \sin(\theta_1 + \theta_2 + \theta_3)\right) \tag{4.18}$$

Then, the Lagrange equation is formed according to the kinetic and potential energy equations (4.19);

$$L = \frac{1}{8} m_1 l_1^2 \dot\theta_1^2 + \frac{1}{2} I_1 \dot\theta_1^2 + \frac{1}{2} m_2 l_1^2 \dot\theta_1^2 + \frac{1}{8} m_2 l_2^2 + I_2\left(\dot\theta_1^2 + 2\dot\theta_1\dot\theta_2 + \dot\theta_2^2\right)$$

$$+\frac{1}{2} m_2 l_1 l_2 \cos\theta_2\left(\dot\theta_1^2 + \dot\theta_1\dot\theta_2\right) + \frac{1}{2} m_3 l_1^2 \dot\theta_1^2 + \frac{1}{2} m_3 l_2^2\left(\dot\theta_1^2 + 2\dot\theta_1\dot\theta_2 + \dot\theta_2^2\right)$$

$$+\frac{1}{8} m_3 l_3^2\left(\dot\theta_1^2 + \dot\theta_2^2 + \dot\theta_3^2 + 2\dot\theta_1\dot\theta_2 + 2\dot\theta_1\dot\theta_3 + 2\dot\theta_2\dot\theta_3\right) + m_3 l_1 l_2 \cos\theta_2\left(\dot\theta_1^2 + \dot\theta_1\dot\theta_2\right)$$

$$+\frac{1}{2} m_3 l_1 l_3 \cos(\theta_2 + \theta_3)\left(\dot\theta_1^2 + \dot\theta_1\dot\theta_2 + \dot\theta_1\dot\theta_3\right)$$

$$+\frac{1}{2} m_3 l_2 l_3 \cos\theta_3\left(\dot\theta_1^2 + \dot\theta_2^2 + \dot\theta_3^2 + 2\dot\theta_1\dot\theta_2 + \dot\theta_1\dot\theta_3 + \dot\theta_2\dot\theta_3\right) + \frac{1}{2} m_3 I_3\left(\dot\theta_1 + \dot\theta_2 + \dot\theta_3\right)$$

$$-\frac{1}{2} m_1 g l_1 \sin\theta_1 - m_2 g\left(l_1 \sin\theta_1 + \frac{1}{2} l_2 \sin(\theta_1 + \theta_2)\right)$$

$$- m_3 g\left(l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) + \frac{1}{2} l_3 \sin(\theta_1 + \theta_2 + \theta_3)\right) \tag{4.19}$$

By using the Lagrangian calculated in equation below (4.20), (4.21), (4.22), the generalized forces for each joint are found as (4.23), (4.24), (4.25);

$$\tau_1 = \frac{\partial L}{\partial \theta_1} + \frac{\partial L}{\partial \dot{\theta}_1} \tag{4.20}$$

$$\tau_2 = \frac{\partial L}{\partial \theta_2} + \frac{\partial L}{\partial \dot{\theta}_2} \tag{4.21}$$

$$\tau_3 = \frac{\partial L}{\partial \theta_3} + \frac{\partial L}{\partial \dot{\theta}_3} \tag{4.22}$$

$$\tau_1 = \frac{1}{4} m_1 l_1{}^2 \left(\ddot{\theta}_1 + \dot{\theta}_1\right) + I_1\left(\ddot{\theta}_1 + \dot{\theta}_1\right) + m_2 l_1{}^2 \ddot{\theta}_1 + 2I_2\left(\ddot{\theta}_1 + \ddot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1 + \dot{\theta}_2\right)$$

$$+ \frac{1}{2} m_2 l_1 l_2 \cos\theta_2 \left(2\ddot{\theta}_1 + \ddot{\theta}_1\dot{\theta}_2 + 2\dot{\theta}_1 + \dot{\theta}_2\right) + m_3 l_1{}^2\left(\ddot{\theta}_1 + \dot{\theta}_1\right)$$

$$+ m_3 l_2{}^2\left(\ddot{\theta}_1 + \ddot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1 + \dot{\theta}_2\right) + \frac{1}{4} m_3 l_3{}^2\left(\ddot{\theta}_1 + \ddot{\theta}_1\dot{\theta}_2 + \ddot{\theta}_1\dot{\theta}_3 + \dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3\right)$$

$$+ m_3 l_1 l_2 \cos\theta_2\left(2\dot{\theta}_1 + \dot{\theta}_2 + 2\ddot{\theta}_1 + \ddot{\theta}_1\dot{\theta}_2\right)$$

$$+ \frac{1}{2} m_3 l_2 l_3 \cos\theta_3\left(2\ddot{\theta}_1 + 2\ddot{\theta}_1\dot{\theta}_2 + \ddot{\theta}_1\dot{\theta}_3 + 2\dot{\theta}_1 + 2\dot{\theta}_2 + \dot{\theta}_3\right)$$

$$+ \frac{1}{2} m_3 I_3\left(\ddot{\theta}_1 + 1\right) - \frac{1}{2} m g l_1 \cos\theta_1 - m_2 g\left(l_1\cos\theta_1 + \frac{1}{2} l_2 \cos(\theta_1 + \theta_2)\right)$$

$$- m_3 g\left(l_1 \cos\theta_1 + l_2\cos(\theta_1 + \theta_2) + \frac{1}{2} l_3 \cos(\theta_1 + \theta_2 + \theta_3)\right) \tag{4.23}$$

$$\tau_2 = 2I_2\left(\dot{\theta}_1\ddot{\theta}_2 + \ddot{\theta}_2 + \dot{\theta}_1 + \dot{\theta}_2\right) + \frac{1}{2}m_2 l_1 l_2\left(-\sin\theta_2\left(\dot{\theta}_1^2 + \dot{\theta}_1\dot{\theta}_2\right) + 2\dot{\theta}_1\cos\theta_2\right)$$

$$+ 2m_3 l_2^2 (2\dot{\theta}_1 + \ddot{\theta}_2 + \dot{\theta}_2) + \frac{1}{4}m_3 l_3^2\left(\ddot{\theta}_2 + 2\dot{\theta}_1 + 2\dot{\theta}_3 + \dot{\theta}_2\right)$$

$$+ m_3 l_1 l_2\left(-\sin\theta_2\left(\dot{\theta}_1^2 + \dot{\theta}_1\dot{\theta}_2\right) + 2\dot{\theta}_1\cos\theta_2\right)$$

$$+ \frac{1}{2}m_3 l_1 l_3\left(-\sin(\theta_2 + \theta_3)\left(\dot{\theta}_1^2 + \dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\dot{\theta}_3\right) + 2\dot{\theta}_1\cos(\theta_2 + \theta_3)\right)$$

$$+ \frac{1}{2}m_3 l_2 l_3\cos\theta_3\left(2\dot{\theta}_2 + 4\dot{\theta}_1 + 2\dot{\theta}_3 + 2\ddot{\theta}_2\right) + \frac{1}{2}m_3 I_3\left(1 + \ddot{\theta}_2\right)$$

$$- \frac{1}{2}m_2 l_2 g\cos(\theta_1 + \theta_2) - m_3 g\left(l_2\cos(\theta_1 + \theta_2) + \frac{1}{2}l_3\cos(\theta_1 + \theta_2 + \theta_3)\right) \qquad (4.24)$$

$$\tau_3 = \frac{1}{4}m_3 l_3^2\left(\ddot{\theta}_3 + \dot{\theta}_1\ddot{\theta}_3 + \dot{\theta}_2\ddot{\theta}_3 + \dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3\right)$$

$$+ \frac{1}{2}m_3 l_1 l_3\left(-\sin(\theta_2 + \theta_3)\left(\dot{\theta}_1^2 + \dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\dot{\theta}_3\right) + \cos(\theta_2 + \theta_3)\left(\dot{\theta}_1\ddot{\theta}_3 + \dot{\theta}_1\right)\right)$$

$$+ \frac{1}{2}m_3 l_2 l_3\begin{pmatrix} -\sin\theta_3\left(\dot{\theta}_1^2 + \dot{\theta}_2^2 + \dot{\theta}_3^2 + 2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\dot{\theta}_3 + \dot{\theta}_2\dot{\theta}_3\right) \\ + \cos_3\left(4\ddot{\theta}_3 + \dot{\theta}_1\ddot{\theta}_3 + \dot{\theta}_2\ddot{\theta}_3 + \dot{\theta}_1 + \dot{\theta}_2\right) \end{pmatrix}$$

$$+ \frac{1}{2}m_3 I_3\left(\ddot{\theta}_3 + 1\right) - \frac{1}{2}m_3 l_3 g\cos(\theta_1 + \theta_2 + \theta_3) \qquad (4.25)$$

According to these equations necessity torques for each joints to lift only frame are;

$$Toque\ Hib = 19{,}966\ Nm$$

$$Toque\ Knee = 12{,}707\ Nm$$

$$Toque\ Ankle = 6{,}270\ Nm$$

In order to lift 100 kg user, 4 motors which are 6 kg, 2 batteries which are 5 kg and frame are;

$$Toque\ Hib = 178{,}3\ Nm$$

$$Toque\ Hib = 115{,}8\ Nm$$

$$Toque\ Hib = 93{,}7\ Nm$$

CHAPTER 5

MANUFACTURING OF WEARABLE EXOSKELETON ROBOT

In this chapter, the manufacturing processes are investigated and manufacturing details are explained for wearable exoskeleton robot part by part.

After getting the final design of wearable exoskeleton robot, all parts of the robot are manufacturing. Generally lathe, milling and laser cutting machines are used in manufacturing process of the wearable exoskeleton robot parts. Mechanically wearable exoskeleton robot has three sections; inner exoskeleton, outer exoskeleton and power transmission mechanism parts.

5.1. Manufacturing of Outer Exoskeleton Components

Outer exoskeleton section includes two thighs, two shanks, two feet, four shafts and one waist. Since the main parts are in cylindrical shape, they are all shaped by a lathe. Rectangular shapes are produced by a milling machine, if the wide of the parts are not suitable for laser cutting process. The material of all joint parts is Aluminum T3 alloy which has high machinability and durability.

Thighs, shanks and arms have plate surfaces and their wide are suitable for the laser cutting processes so, they are manufacturing by laser cutting manufacturing process.

Shafts have the cylindrical surfaces so; all shafts are manufactured by using lathe machine process in robotic laboratory like other part which have cylindrical surface.

Waist part has the rectangular surfaces so; it is manufactured by using milling machine process in robotic laboratory like other part which have rectangular surface.

Figures 5.1 shows the components of the outer exoskeleton part and assemble type.

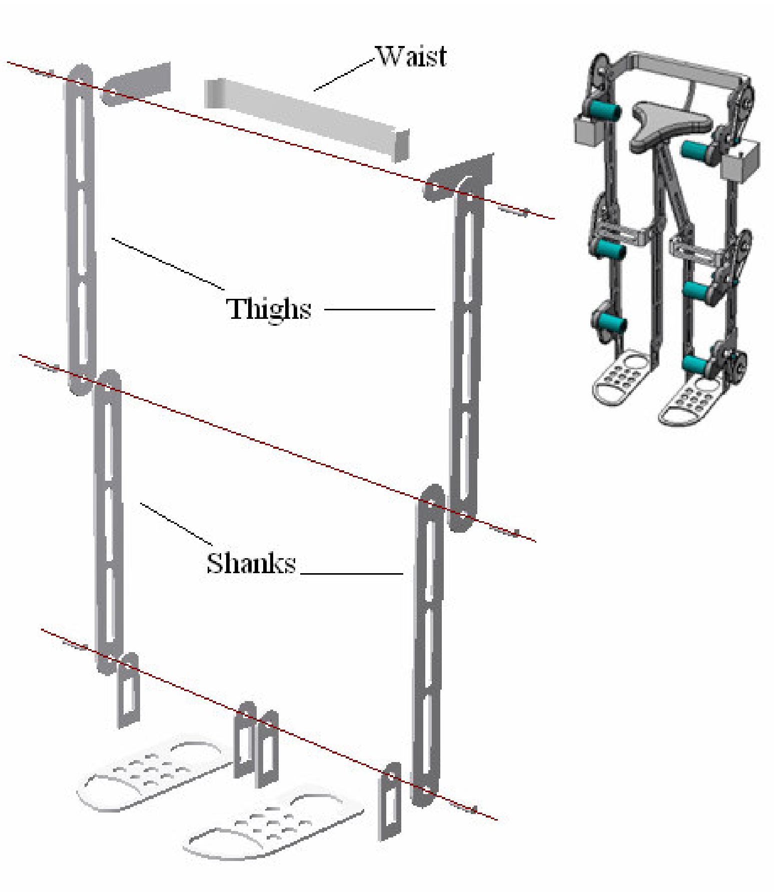


Figure 5.1. Components of outer exoskeleton section.

5.2. Manufacturing of Inner Exoskeleton Components

Inner exoskeleton section includes two inner thighs, two inner shanks, two knees, five shafts, one seat and one holder. The thighs, shanks and holder are manufactured by using laser cutting process, moreover in manufacturing of inner shanks CNC bending machine are used. The material of the thighs, shanks and holder parts is Aluminum T3 alloy which has high machinability and durability.

All shafts are manufactured by using lathe machine process in robotic laboratory like other part which have cylindrical surface.

Milling machine process is used in manufacturing of knee parts because of its rectangular shapes and polyimide plastic material is used in manufacturing of knee components.

Figures 5.2 shows the components of the inner exoskeleton part and assemble type.

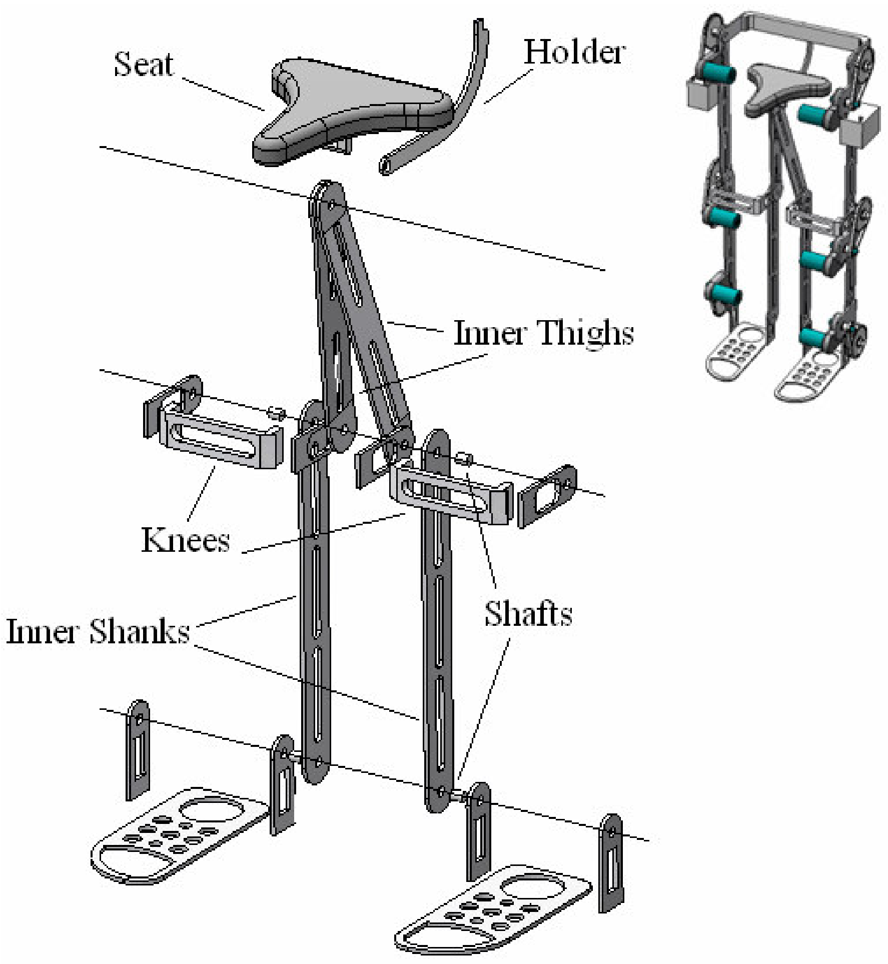


Figure 5.2. Components of inner exoskeleton section.

5.3. Manufacturing of Power Transmission Mechanism components

Power transmission mechanism includes actuator (DC Electric Motor), actuator holder, chain and sprocket gears. In this section the only thing to manufacture is actuator holder. Actuator holder has rectangular surfaces and its wide is suitable for the laser cutting manufacturing process so, actuator holder part is manufactured laser cutting process.

Figure 5.3 shows the components of the power transmission mechanism components and assemble type.

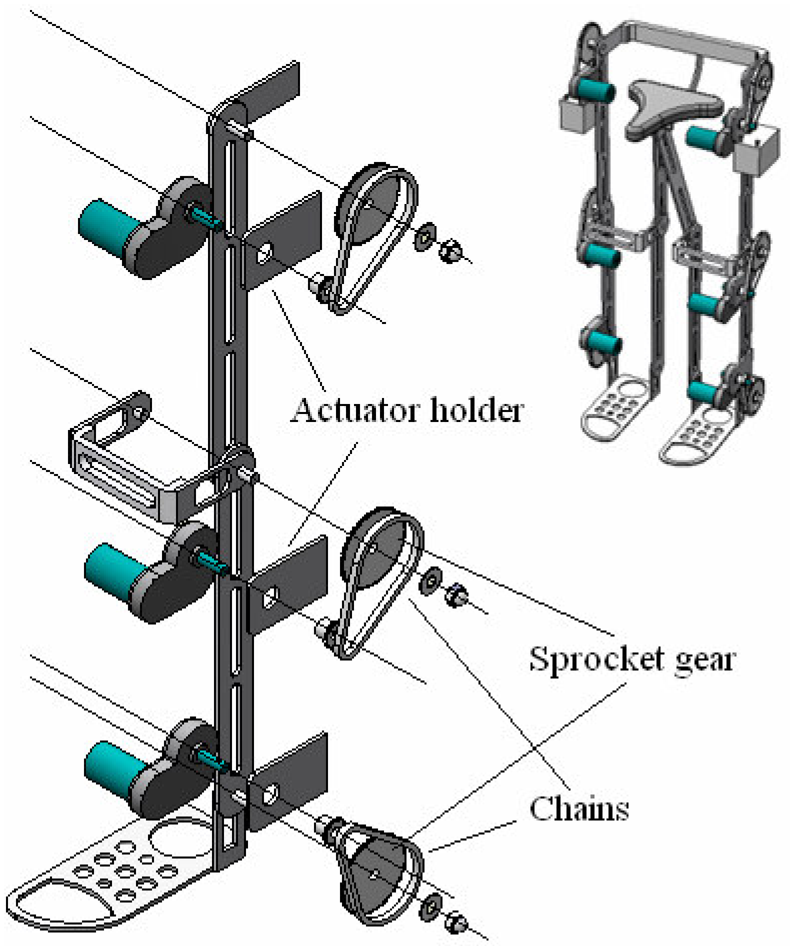


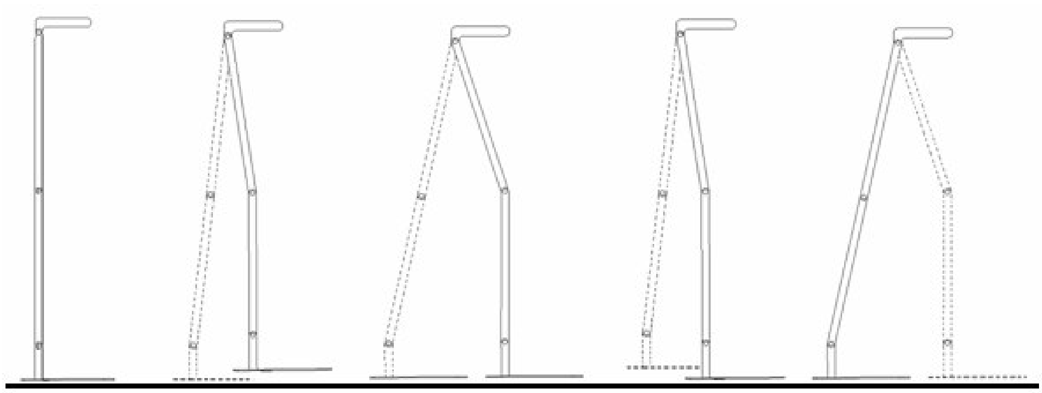
Figure 5.3. Components of power transmission mechanism.

CHAPTER 6

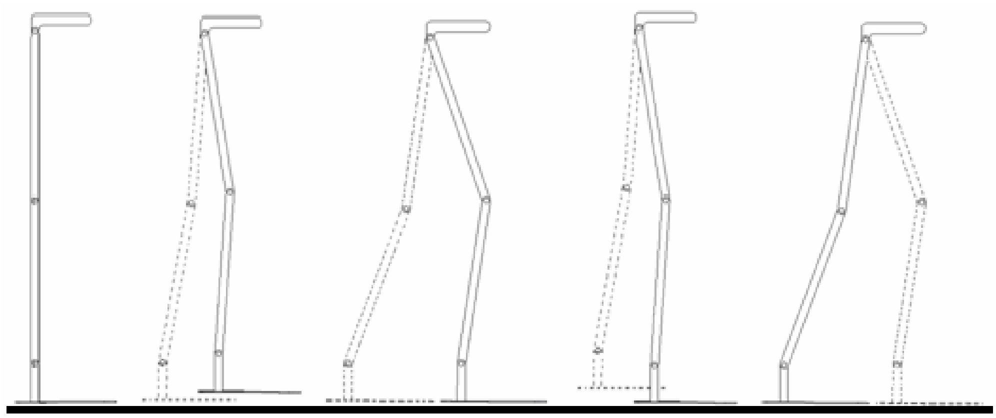
ELECTRONIC AND COMPUTER SOFTWARE

The controller for the wearable exoskeleton is required to perform actuation at the hip, knee and ankle based on knowledge of the current phase of the gait of the wearer. For this reason gait of the wearer are examined and hip, knee and ankle joint movement are determined.

Firstly, walking action is divided two main sections. These are start-stop walking and continue walking. And in order to calculate these section characters, semi step and full step are determined. For each section angles of joints are calculated by using manipulator kinematics and two different walking trajectories are calculated. Figure 6.1 shows the walking trajectories for user.



(a)



(b)

Figure 6.1. Walking trajectories (a) First walking mode, (b) Second walking mode.

6.1. Pulse Width Modulation (PWM)

Pulse width modulation (PWM), as it applies to motor control, is a way of delivering energy through a succession of pulses rather than a continuously varying (analog) signal. By increasing or decreasing pulse width, the controller regulates energy flow to the motor shaft. The motor's own inductance acts like a filter, storing energy during the "on" cycle while releasing it at a rate corresponding to the input or reference signal.

The advantage of controlling a motor with PWM instead of a real analog signal is that the full torque of the motor can be used. In DC motors, there is a linear relationship between the voltage supplied and the torque obtained from the motor: the higher the voltage, the higher the torque. Think of a small motor used for moving a loaded robot. If the analog voltage is too low, the motor will not move, because of the load and friction between the wheels and the floor. We have to start increasing the voltage until at some point the wheels move and the robot goes away at great speed (because dynamical friction is lower than static friction). A PWM signal, on the other side, gives always a full kick to the motor. For a short period of time the motor rotates with its full torque. Speed control is done by spacing the pulses as needed; this is, by adjusting the duty cycle of the signal. In this way, the speed of a robot can be controlled in a much smoother way. Figure 6.2 shows the duty cycle of a PWM signal.

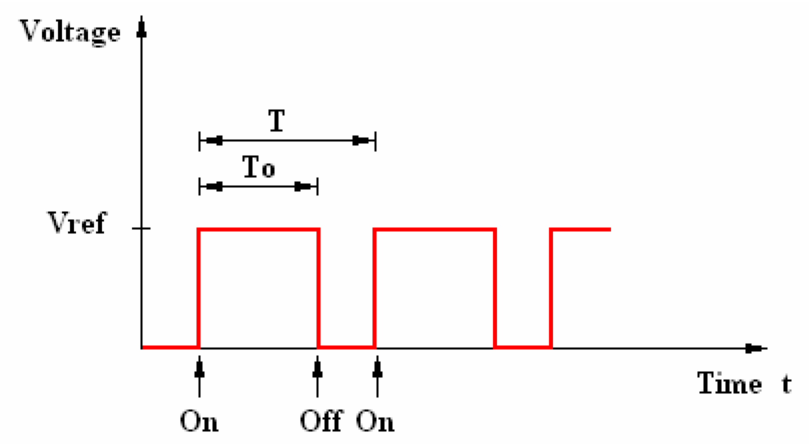


Figure 6.2. Duty cycle of a PWM signal.

(Source: Silva 2004.)

T = pulse period (interval between the successive on instant)

T_0 = on period (interval between on instant to the next off instant)

Then, the duty cycle is given by percentage;

$$d = \frac{T}{T_0} = \frac{average\,output}{peak\,output} \times 100\% \qquad (6.1)$$

The voltage level *Vref* and the pulse frequency *1/T* are kept fixed, and what is varied T_0. Pulse width modulation is achieved by chopping the reference voltage so that the average voltage is varied. It is easy the see that, with respect to an output pulse signal, the duty cycle is given by the ratio of average output to peak output; specifically. (Silva 2004.)

6.2. Electronic Control Circuit

In order to control each joint movement and direction of wearable exoskeleton robot, pulse width modulation based electronic control circuit is designed.

Because of its simplicity and reliability the PIC16F877 is used in the control circuit. This microcontroller runs at wide speed range up to 20 MHz. It has 33 I/O pins which are grouped under 4 main ports called Port A, B, C and D. These ports and pins can be able to configure as an input or output individually.

Electronic circuit system elements are mainly listed below;

- Six (24V-6rpm-13Nm) DC electric motor
- PIC16F877 microcontroller
- Six LMD18200T H bridge

6.3. Find the Suitable Frequency Value for Actuators Using on Joints

In order to find the suitable frequency value for actuators using on joints, several experiment are done and showed. During the experiment, PWM value is accepted 50%. Firstly, rotational speeds are investigated on the different frequency. Experimental data are shown in the table and rotational speed-frequency curves are shown in the figure.

Table 6.1. Experimental data about the finding suitable frequency in terms of rotational speed.

Frequency (Hz)	Rotational Speed (rpm)	Efficiency (%)
50	11,9	86,2
100	12,2	88,4
150	12,1	87,7
200	12,2	88,4
250	12,3	89,1
300	12,3	89,1
350	12,9	93,5
400	13	94,2
450	13,5	97,8
500	12,8	92,8
550	12,5	90,6
600	12,5	90,6
650	12,7	92,0
700	12,6	91,3

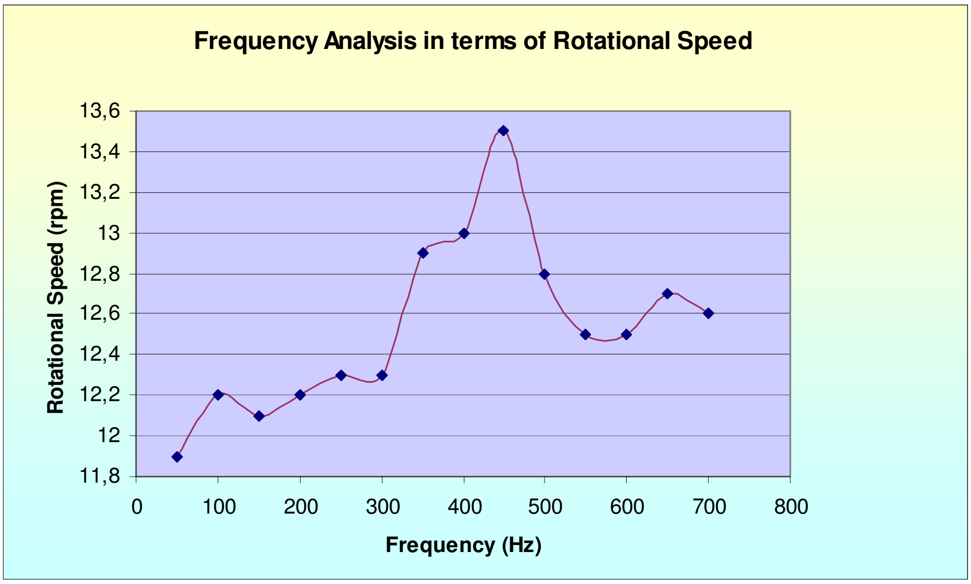


Figure 6.3. Speed-Frequency curves.

After that same experiment are done in terms of torque values.

Table 6.2. Experimental data about the finding suitable frequency in terms of torque.

Frequency (Hz)	Torque (Nm)	Efficiency (%)
50	13	74,0
100	11	62,6
150	12,69	72,2
200	14,44	82,2
250	12,27	69,8
300	13,6	77,4
400	13,9	79,1
450	15,48	88,1
500	14,3	81,4
550	13,82	78,7
600	12,7	72,3
650	13,5	76,8
700	14	79,7

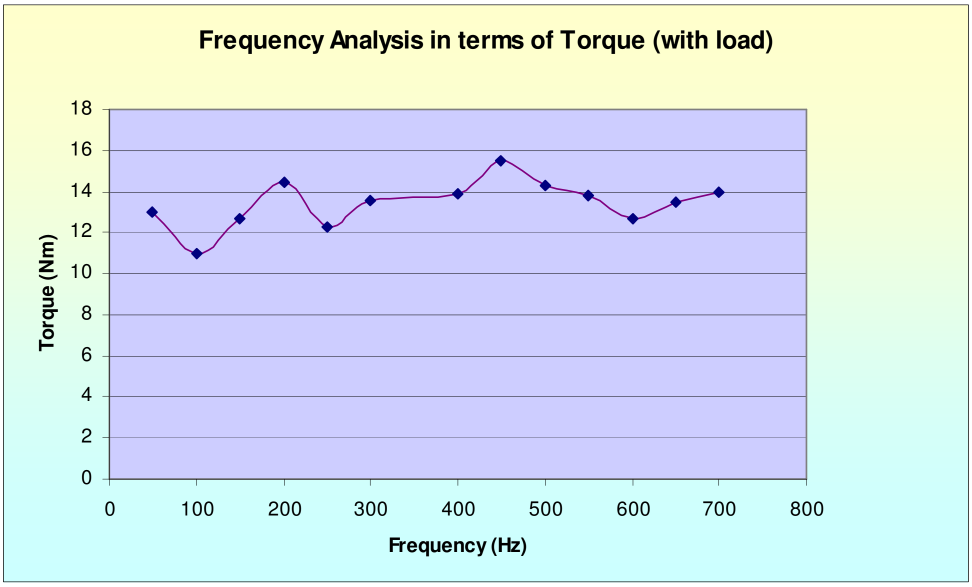


Figure 6.4. Torque-Frequency curves.

According to these graphics, 450Hz frequency value is the most suitable for the joints of wearable exoskeleton robot.

6.4. Motors' Torque and Rotational Speed Values on the 450Hz Frequency

After the find suitable frequency of the system motors, rotational speed and torque of the motors are investigated at different PWM values at 450Hz frequency.

Table 6.3. Motor reactions at different PWM values at 450Hz frequency.

		24 Volt		
pwm	Torque(Nm)	Speed (rpm)	Lifting capacity	eficiency (%)
10	3,6575	1,6	7,7	18,8
20	3,8	2,1	8	19,5
30	6,08	2,8	12,8	31,2
40	8,455	3,7	17,8	43,4
50	13,3	4,2	28	68,3
60	14,725	4,5	31	75,6
70	17,1	6,9	36	87,8
80	19	7,2	40	97,6
90	19,2375	8	40,5	98,8
100	19,475	9	41	100,0

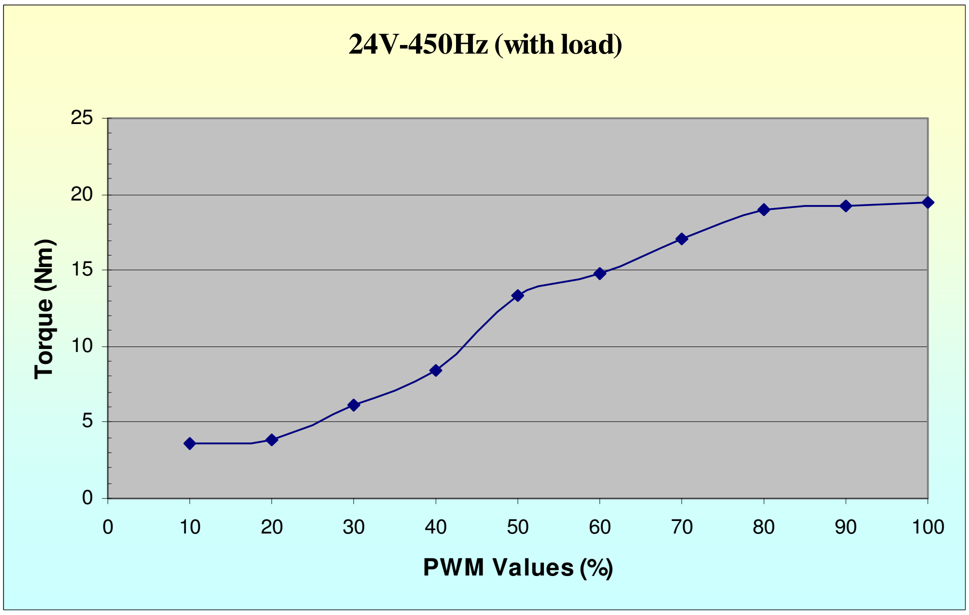


Figure 6.5. PWM values and torque curves.

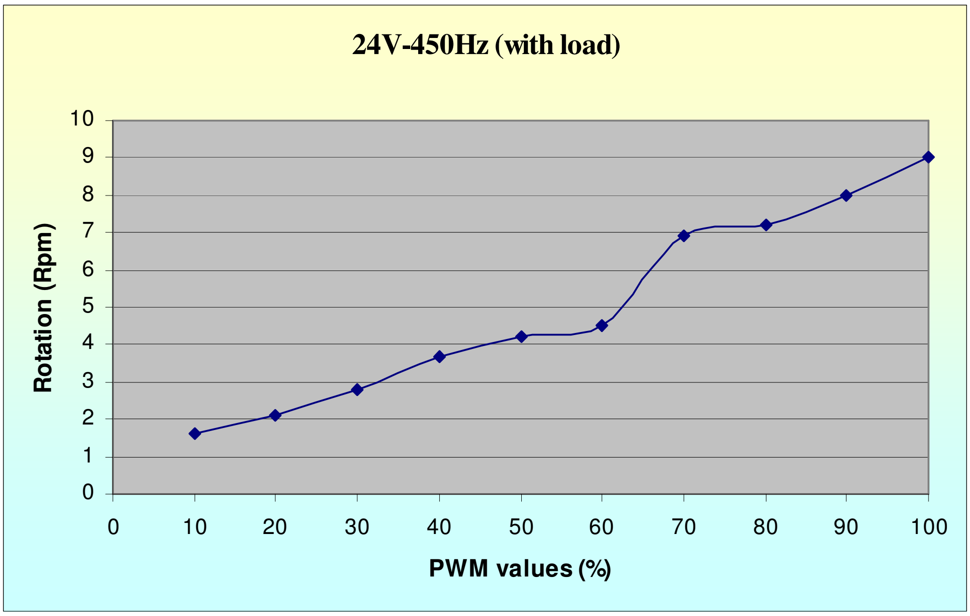
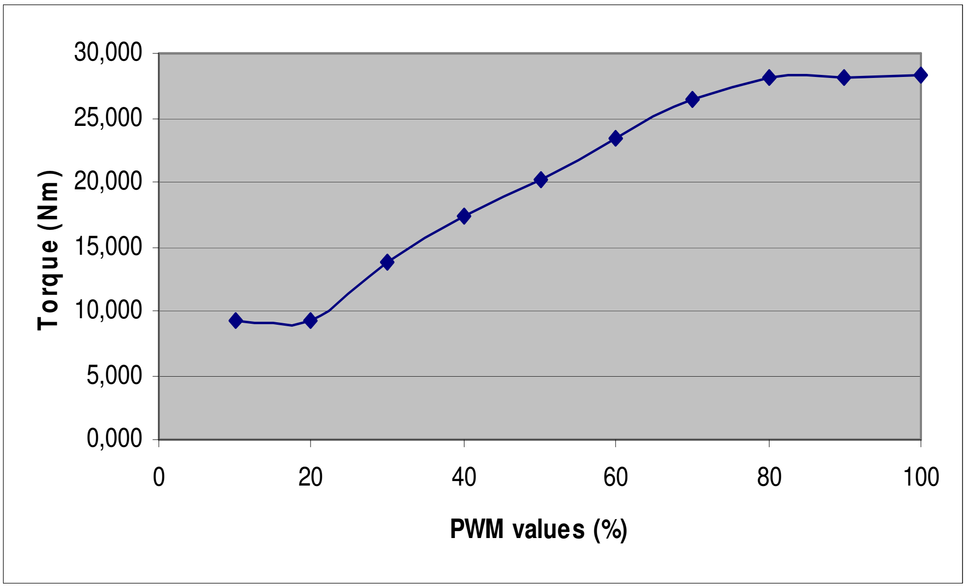


Figure 6.6. PWM values and rotational speed curves.

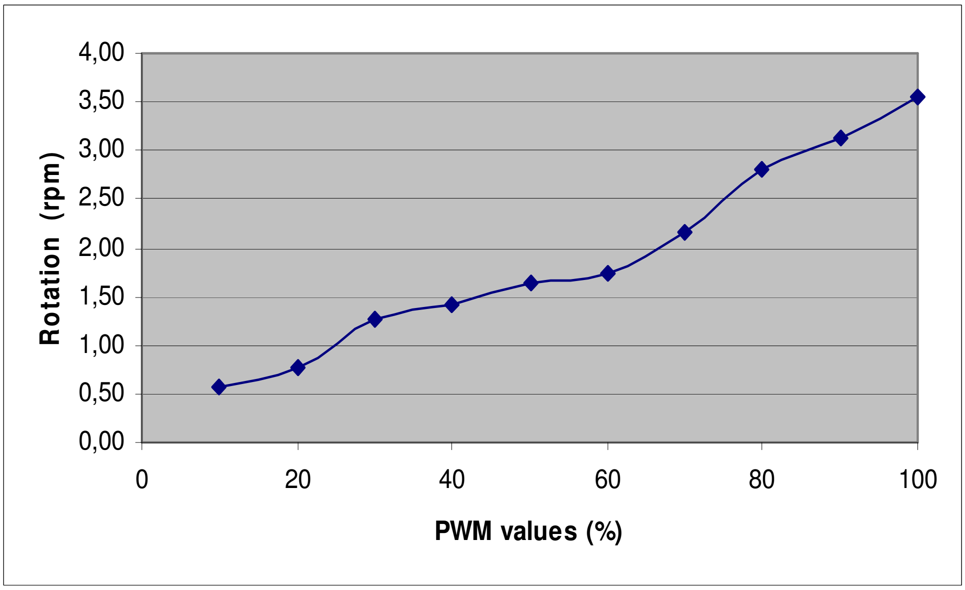
As it is explained in Chapter 5, 3/1 ratios gearbox for each joint are designed and manufactured. So, at 450 Hz frequency motor and 3/1 ratios gearbox combination is investigated.

Tablo 6.4. Motor reaction with 3/1 ratios gearbox at different PWM values at 450Hz frequency.

24 Volt	**with 3/1 ratio gearbox**	
PWM(%)	**Torque(Nm)**	**Speed (rpm)**
10	9,260	0,58
20	9,210	0,77
30	13,800	1,27
40	17,400	1,42
50	20,150	1,64
60	23,370	1,73
70	26,380	2,16
80	28,044	2,81
90	28,123	3,14
100	28,350	3,55



(a)



(b)

Figure 6.7. (a) PWM value and torque curves (with 3/1 ratios gearbox), (b) PWM value and rotational speed curves (with 3/1 ratios gearbox).

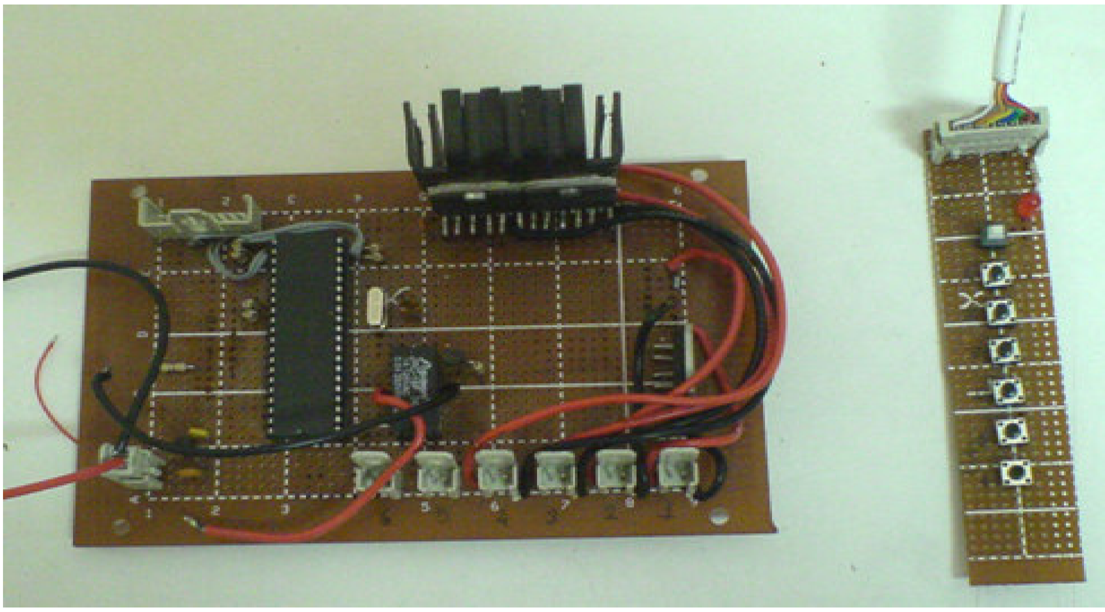


Figure 6.8. Electronic control circuit.

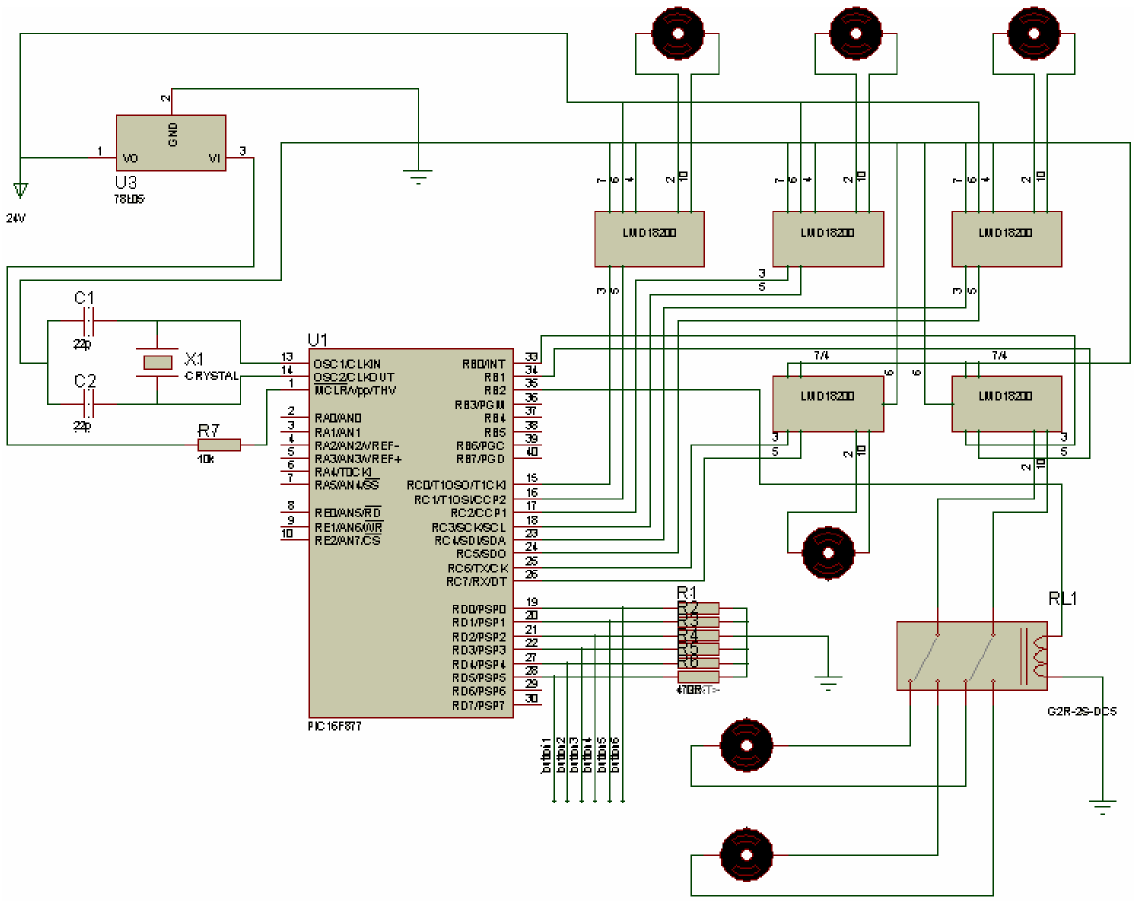


Figure 6.9. Circuit scheme of the electronic control unit.

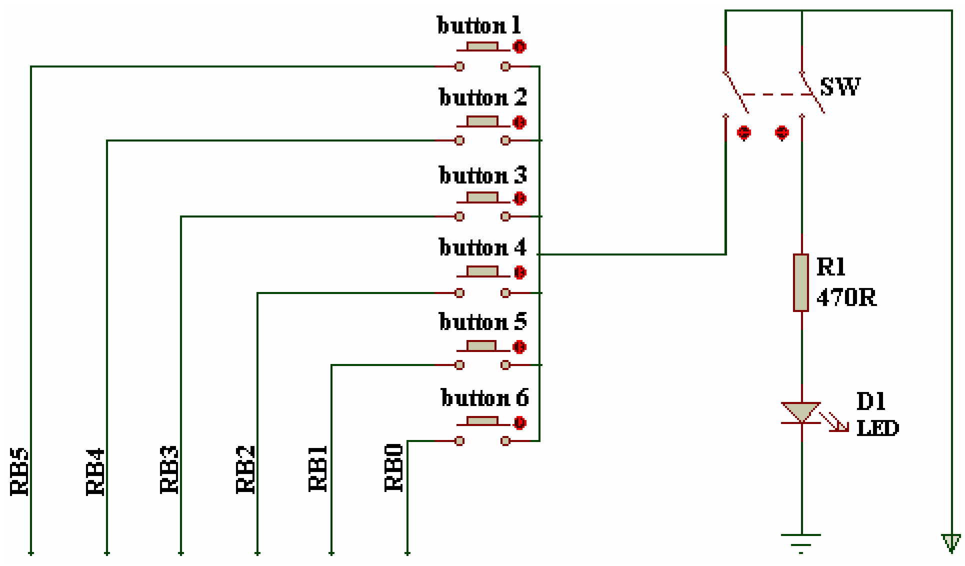


Figure 6.10. Circuit scheme of the keypad unit.

6.5. Computer Software

In addition to electronic components, electronic control circuit includes a computer software program. Computer software program is an example of the user interface. Using a specific program language, users install all expected tasks in microcontroller of the electronic circuit.

In this thesis, in order to control legs, each joint movements and direction values are calculated, and semi step and full step are determined in Chapter 6. According to these data, computer software program created and installed in PIC16F877 microcontroller. So, computer software program that are formed by the user, powers the actuators and adjusts each joint movements, directions and operation time.

Finally a computer software program for PIC 16F877 is written in PIC BASIC which is much easier to learn and use than the other programming languages such as PIC C, PIC Java or PIC Assembly. The whole computer software code is given in Appendix C.

CHAPTER 7

TESTING OF WEARABLE EXOSKELETON ROBOT

7.1 Testing Procedure

Manufactured wearable exoskeleton robot is tested according to different conditions which user can encounter in his/her daily life.

These are listed below;

1. Testing speed and performance on the smooth surface.

2. Testing speed and performance during climbing the slope which is maximum 7^0 that accepts climbing angle for paralytic people and disables.

3. Testing speed and maximum lifting capacity during carrying weight.

4. Testing performance at maximum speed.

5. Testing speed and performance on the inclined surface.

In this thesis wearable exoskeleton robots is designed for paralytic and disable people to walk. Handicap people generally spend their daily life at home or in their environment. And in that time, they should fulfill their daily duties. Because of this obligation, testing wearable exoskeleton robot on the smooth surface is accepted inevitable. In order to calculate each joint movement and analyzing of gait for a users a test machine is designed and manufactured. Figure 7.1 shows the manufactured test machine.

Especially outdoors for handicap people, they encounter several slopes to overcome. In order to help handicap people municipalities make almost all slope same degree that is 7^0. Overcome these slopes is one of the main disadvantages for mobility aid vehicles especially wheelchairs.

All things considered, wearable exoskeleton robot decided to test during climbing slope in terms of time, efficiency and speed. Figure 7.2 shows the Wearable Exoskeleton Robot on the inclined surface.

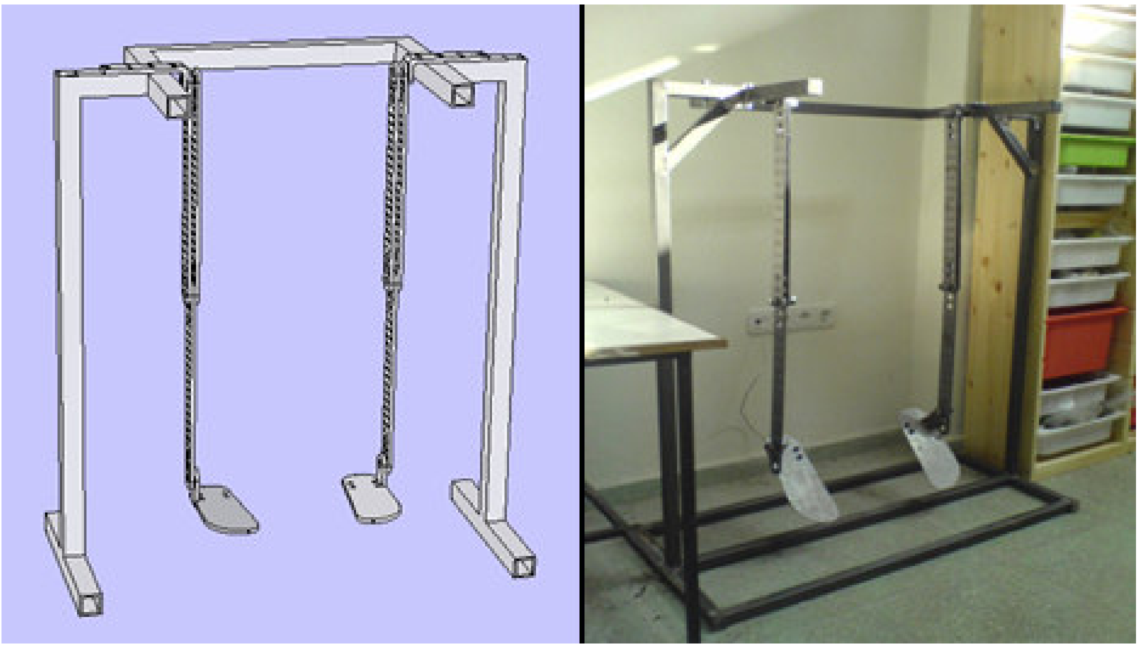


Figure 7.1. Test machine.

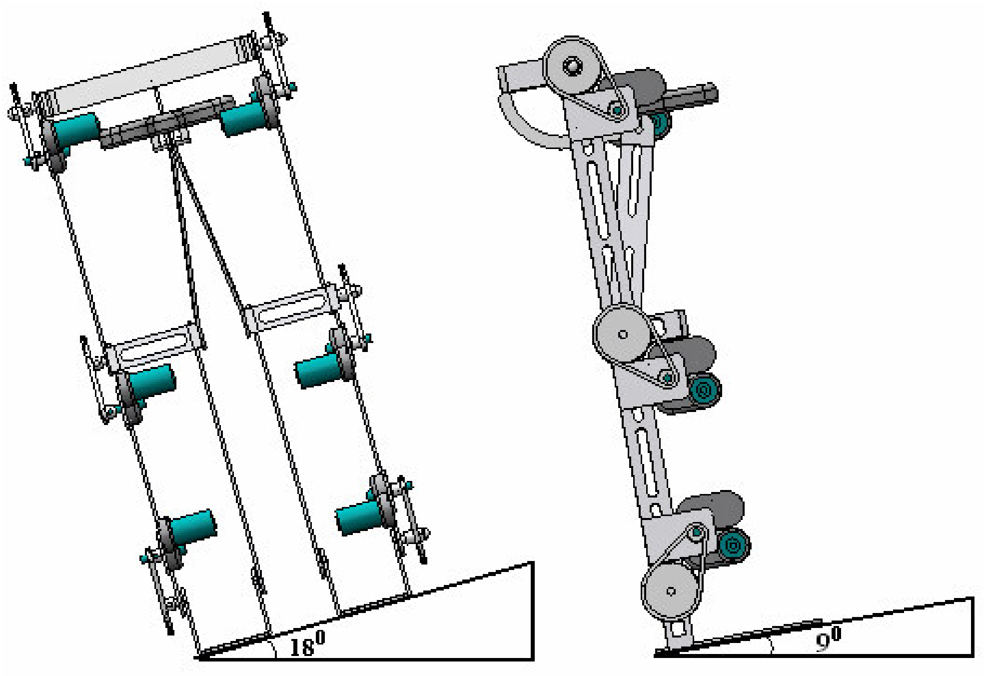


Figure 7.2. Wearable exoskeleton robot on the inclined surfaces.

7.2. Mechanical Changes

7.2.1. Inner Exoskeleton Redesign

During the test procedure, several problems are realized. One of them is not to provide synchronization of the robot while walking. After that all components of the robot are investigated and it is found that the main problems of the system are about the elastic deformations on the exoskeleton frame. First, inner thigh is investigated and motion planning that is shown in the figure 7.3 is described.

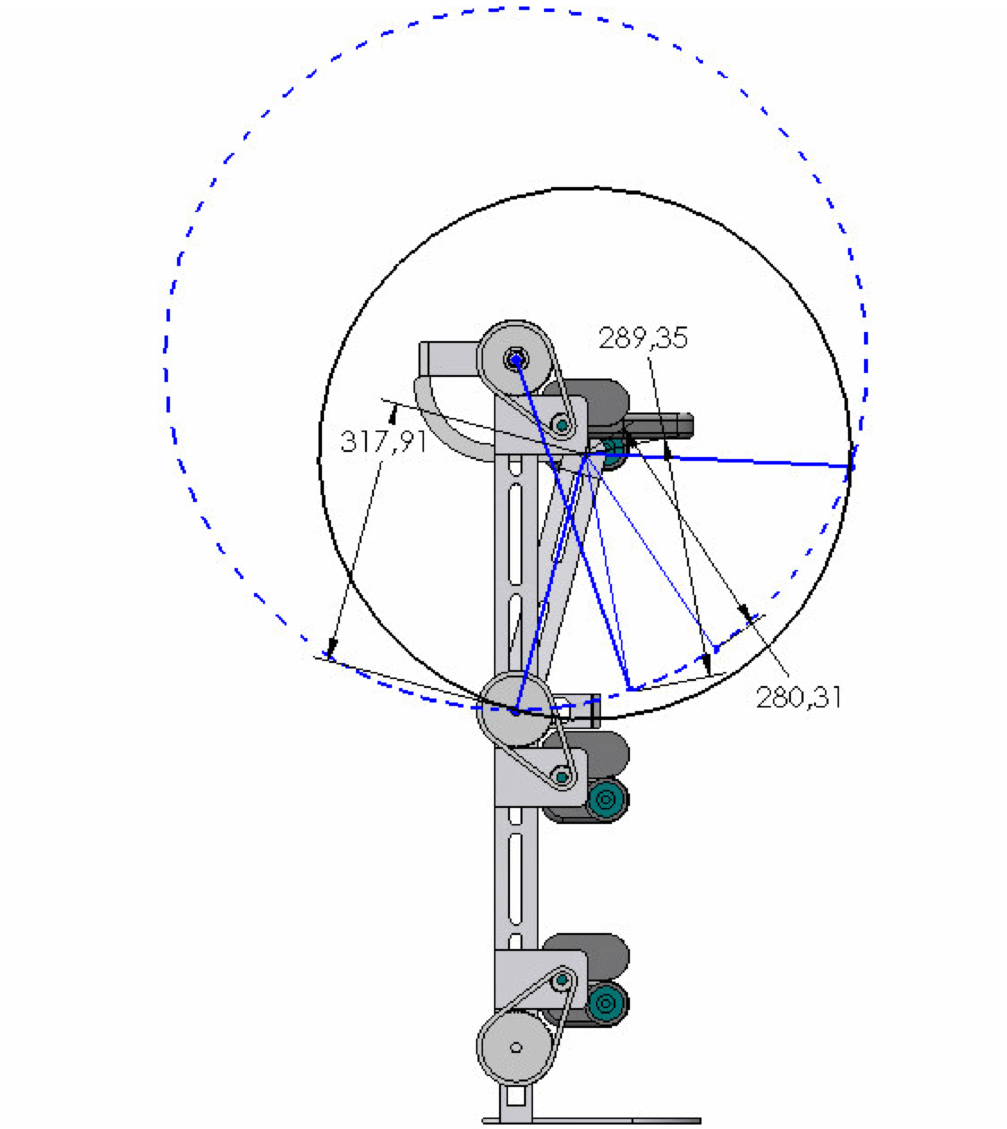
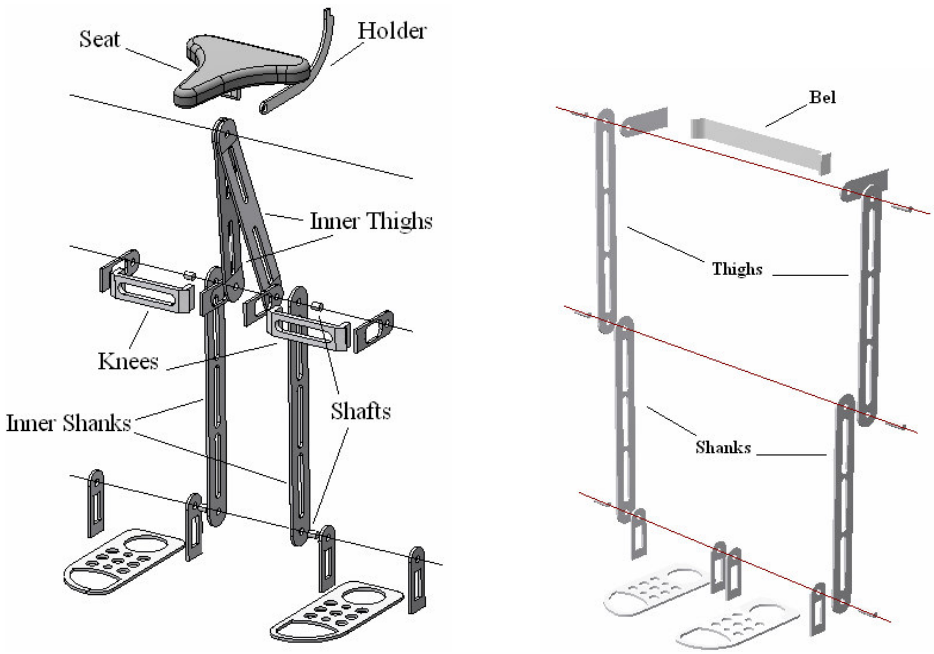


Figure 7.3. Inner tight motion planning.

As it is shown in the figure that at different point s in the inner thigh motion planning, the length of the inner thigh is changing because of this, inner thigh is redesigned and changed with a slider mechanism.

7.2.2. Waist, Knees, Outer Thigh and Outer Shank Redesign

Later, because of the continuous working during the test procedure, some parts of the robot are bended. At this point the main problem of these parts are mainly about material, so waist, knees, outer thigh and outer shank are redesign and changed.



(a) (b)

Figure 7.4. (a) Inner exoskeleton, (b) Outer exoskeleton.

7.3. Motor Characteristic at Higher Voltage

According to testing result and calculations, it is realized that motors on the robot are not suitable for the application at normal supply voltage. Later higher voltage are tried to use for motors. Testing result data are shown in the table. 3D graphics about the motor rotational speed and nominal torque are shown in the figure.

Table 7.1. Testing result data of 24V and 36V motor's characteristic.

Frequency	PWM	24V- rpm	24V-A	24V-Nm	36V-rpm	36V-A	36V-Nm
100	80	18,50	0,92	3,77	28,80	1,06	5,31
100	85	20,00	0,90	3,75	31,40	0,98	5,36
100	90	21,50	0,85	3,75	33,40	0,91	5,05
100	95	22,30	0,83	3,83	36,10	0,84	5,55
100	100	23,90	0,77	3,92	37,00	0,89	5,34
150	80	17,60	0,76	3,75	30,40	0,90	5,37
150	85	19,20	0,75	3,76	31,90	0,88	5,32
150	90	21,50	0,75	3,80	33,70	0,84	5,41
150	95	22,60	0,75	3,80	36,00	0,82	5,39
150	100	23,80	0,76	3,87	38,00	0,84	5,43
200	80	18,40	0,73	3,78	29,20	0,84	5,29
200	85	19,80	0,73	3,74	31,50	0,84	5,28
200	90	21,00	0,73	3,81	33,50	0,83	5,37
200	95	22,40	0,74	3,73	35,60	0,83	5,41
200	100	23,70	0,76	3,85	37,90	0,84	5,55
250	80	18,10	0,70	3,80	30,30	0,81	5,46
250	85	19,40	0,71	3,76	32,50	0,81	5,41
250	90	21,00	0,72	3,81	34,00	0,81	5,44
250	95	22,40	0,76	3,86	36,30	0,83	5,45
250	100	23,20	0,78	3,92	37,80	0,85	5,51
300	80	18,10	0,70	3,82	30,30	0,78	5,41
300	85	19,50	0,71	3,87	31,90	0,80	5,46
300	90	21,10	0,73	3,91	34,20	0,81	5,50
300	95	22,00	0,75	4,04	35,20	0,82	5,94
300	100	23,00	0,77	4,10	37,80	0,84	6,04
350	80	18,20	0,68	3,77	29,70	0,76	5,44
350	85	19,20	0,70	3,94	31,90	0,81	5,67
350	90	21,00	0,73	3,92	33,20	0,81	5,73
350	95	22,40	0,75	3,97	35,80	0,82	5,61
350	100	23,60	0,78	4,36	37,20	0,85	6,24
400	80	18,30	0,67	3,76	29,30	0,76	5,56
400	85	19,50	0,69	3,87	30,80	0,78	5,64
400	90	21,00	0,72	3,99	32,60	0,80	5,71
400	95	22,00	0,75	4,01	34,70	0,81	5,73
400	100	23,40	0,78	4,22	37,90	0,83	6,01
450	80	17,70	0,68	3,91	29,90	0,74	5,84
450	85	19,40	0,71	3,90	30,60	0,77	5,73
450	90	20,90	0,73	4,04	32,80	0,79	5,78
450	95	21,80	0,76	4,23	34,60	0,81	6,14
450	100	23,60	0,79	4,50	36,80	0,84	6,25
500	80	17,90	0,68	3,88	29,40	0,74	5,43
500	85	18,80	0,71	3,86	30,60	0,78	5,48
500	90	20,60	0,74	4,09	32,70	0,79	5,77
500	95	21,90	0,77	3,99	34,70	0,81	5,82
500	100	23,30	0,80	4,32	36,70	0,84	5,98
550	80	17,50	0,68	3,89	29,10	0,74	5,73
550	85	19,20	0,71	3,92	30,80	0,77	5,77
550	90	20,60	0,74	3,90	32,30	0,79	5,82
550	95	21,90	0,77	4,01	35,60	0,81	5,85
550	100	23,30	0,80	4,21	36,90	0,83	5,91

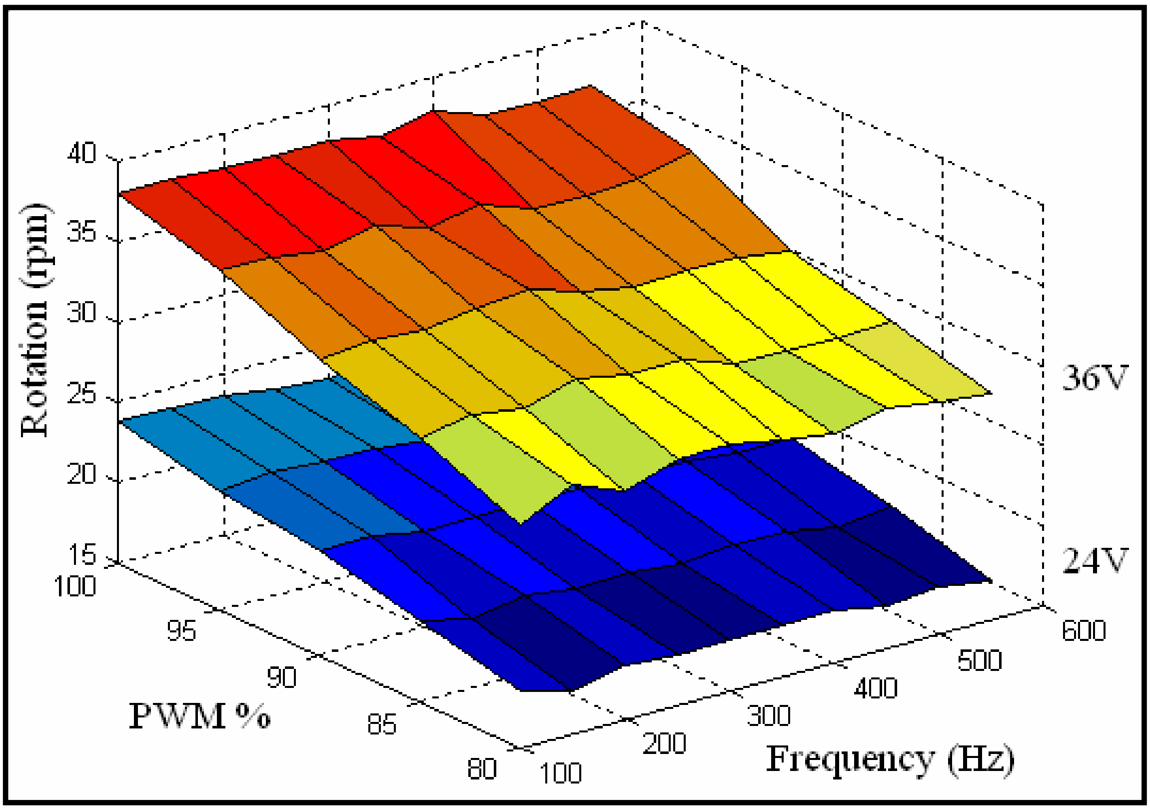


Figure 7.5. Rotational speed - Frequency and PWM values for 24V and 36V.

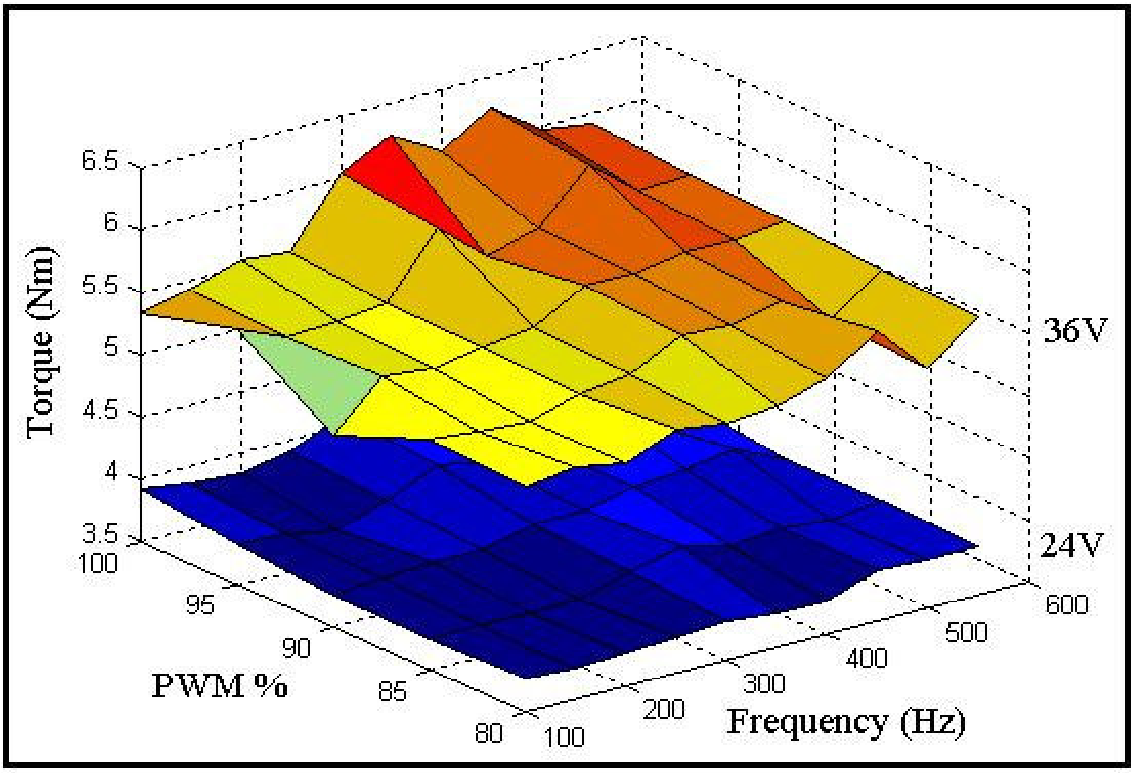


Figure 7.6. Nominal Torque - Frequency and PWM values for 24V and 36V.

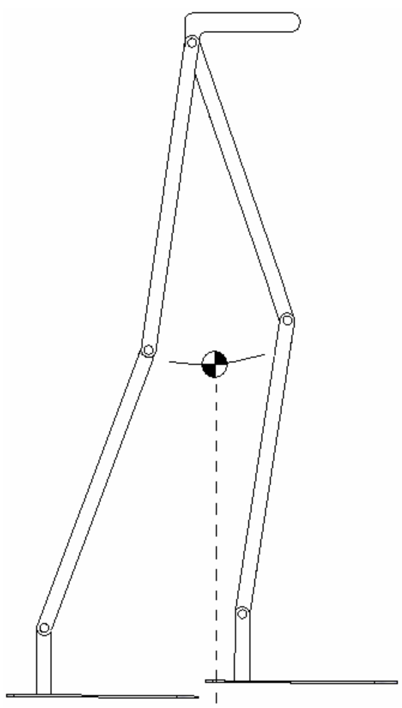
7.4. Leg Flying Distance Problem and Legs Broken Walking

At the normal walking mode whose timing diagrams are drawn, at the phase of stepping forward the stepping foot falls to its forepart before completing the specified motion as a consequence of the center of gravity's going out of the area belonging the foot on the ground before the specified working time.

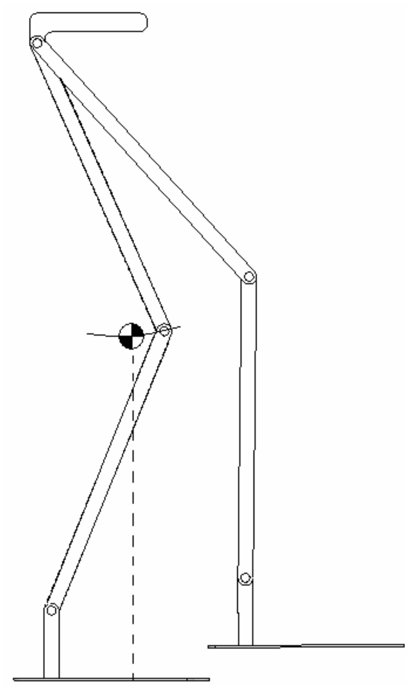
As a result of this, the synchronization in the walking operation, which works dependent on 3 joints of each leg separately, gets out of order and a reliable walking can not occur.

The walking mode is changed in order to keep the center of gravity of the system within the support foot zone which always stays fixed on the floor.

The difference of the new walking phase from the preceding is its breaking both two legs from the knee joints and placing the center of gravity behind the robot. Thus, in the all phases of the walking, the center of gravity remains within the support foot zone which is fixed.



(a)



(b)

Figure 7.7. Two different walking mode in terms of position of the center of the gravity (a) Normal walking mode, (b) Legs Broken Walking.

Table 7.2. Normal walking timing diagram.

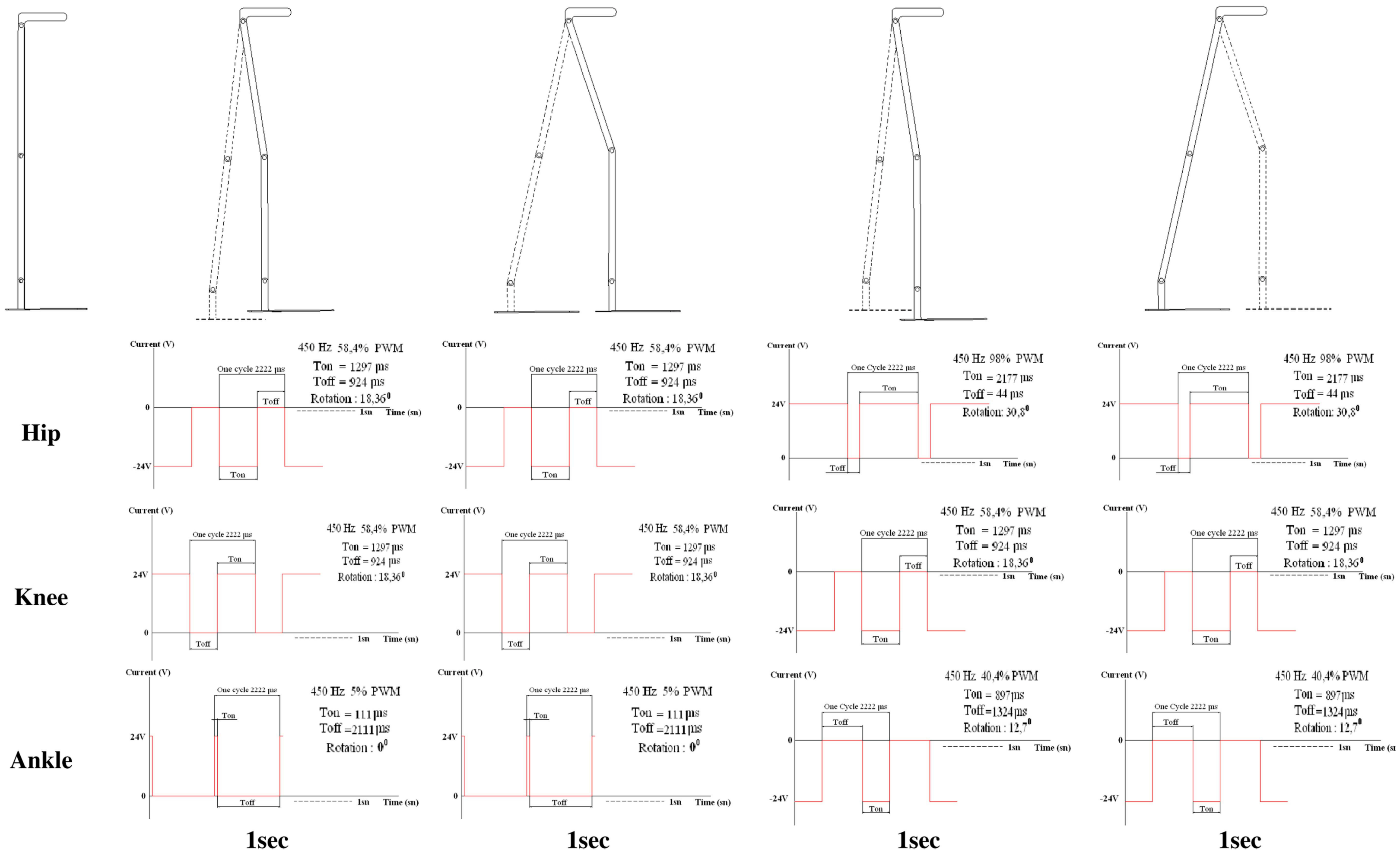
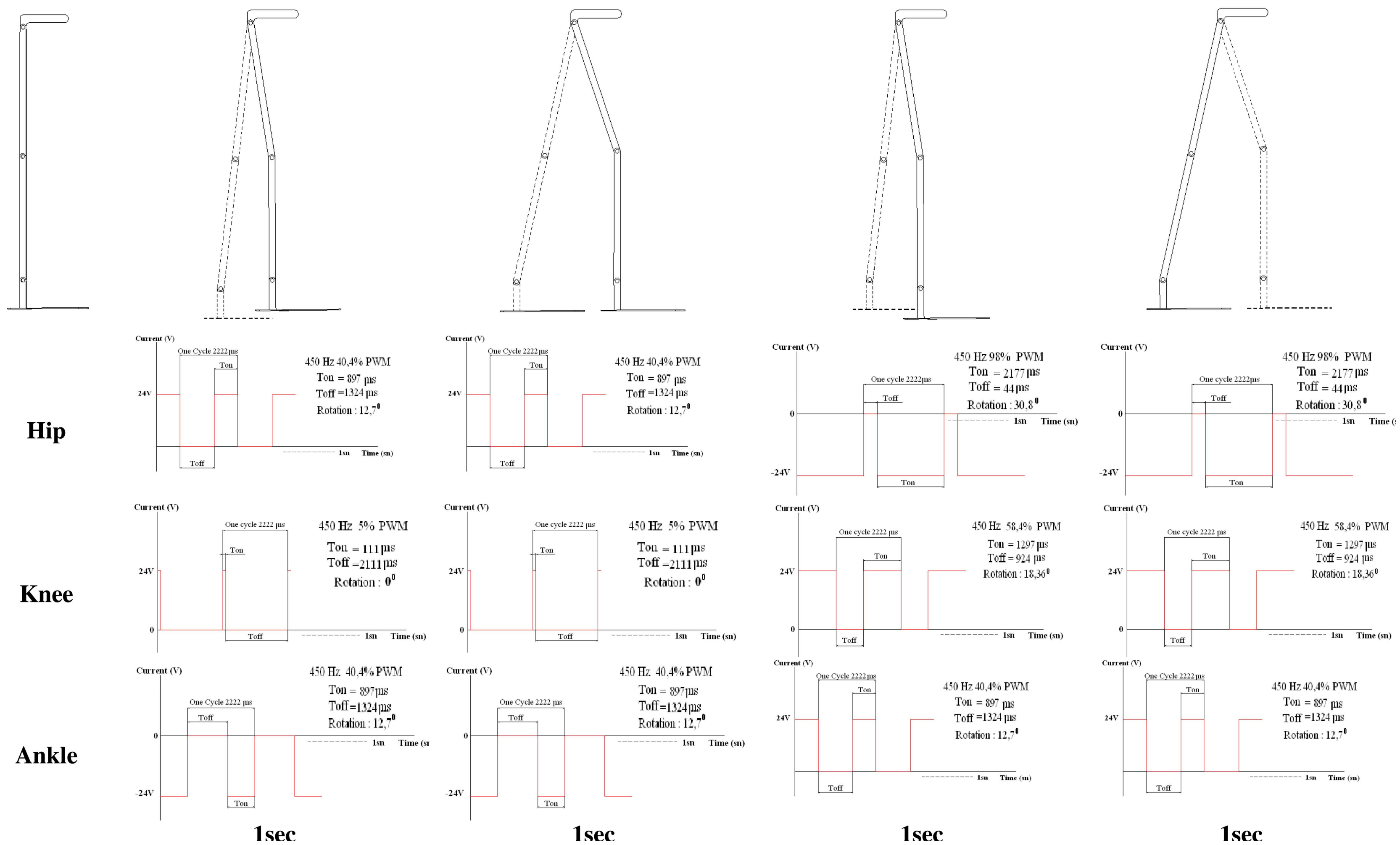
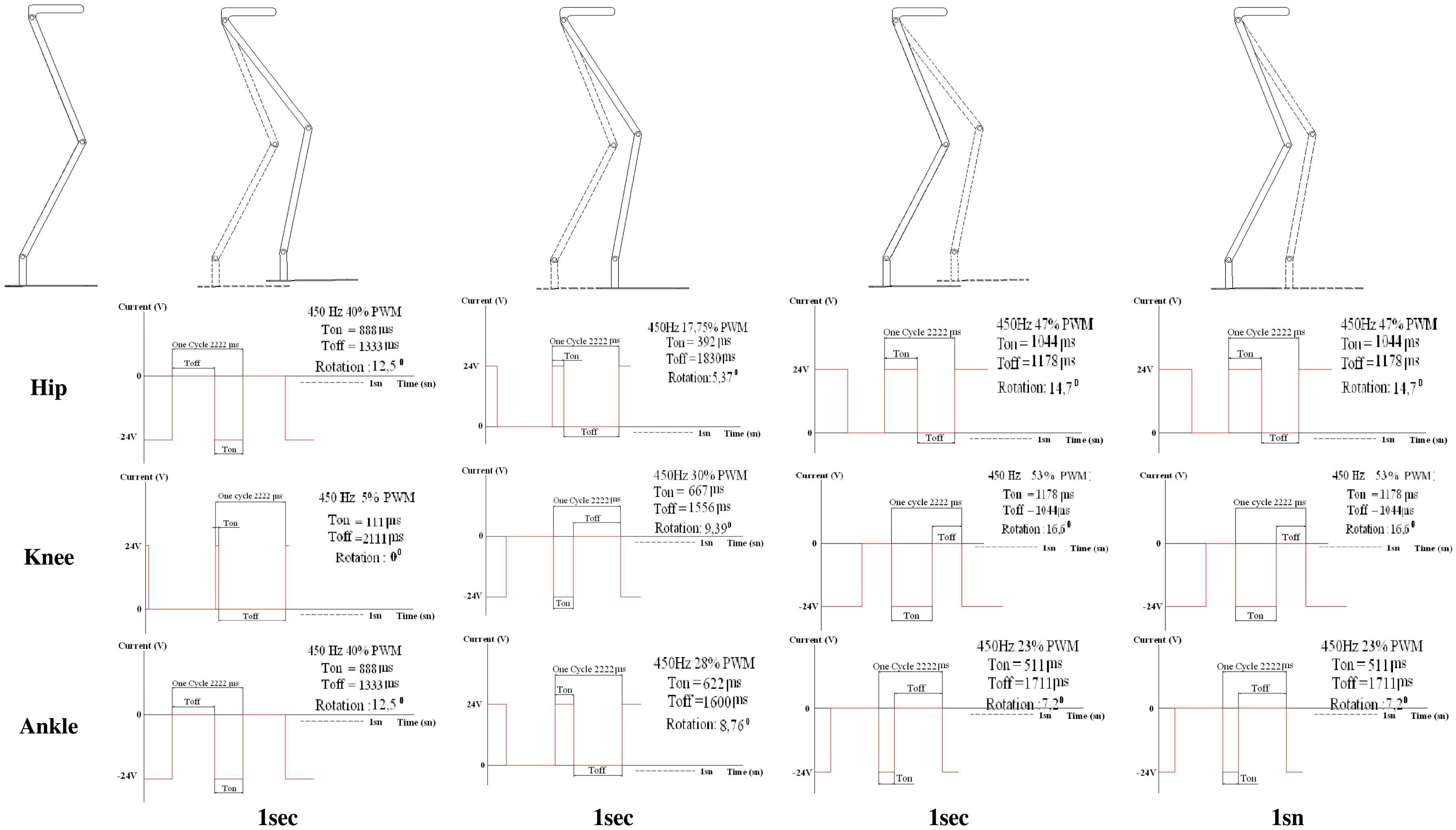


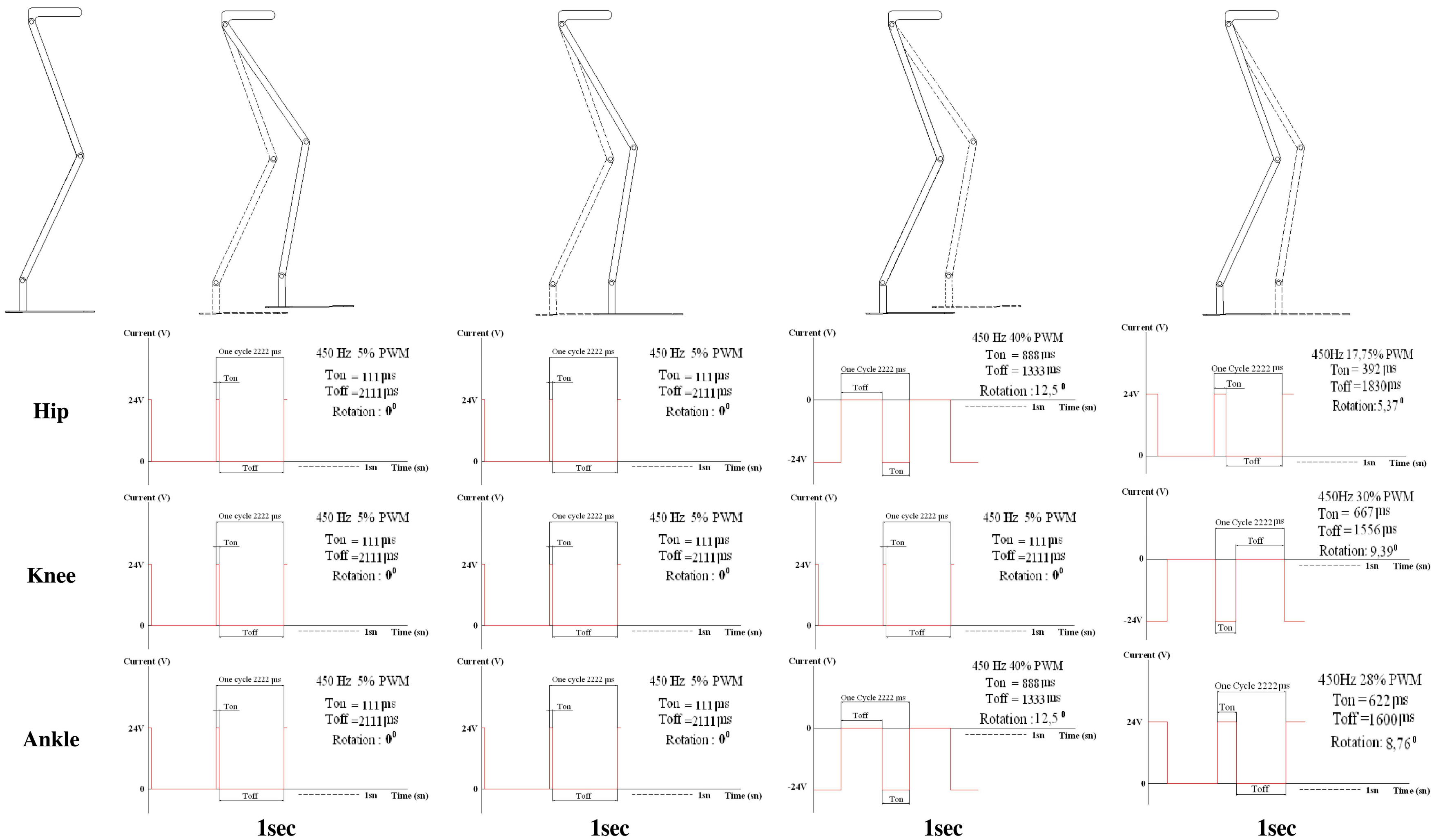
Table 7.2. Normal walking timing diagram (Continue).



Tablo 7.3. Leg-broken walking timing diagram.



Tablo 7.3. Leg-broken walking timing diagram (Continue).



7.5. Nominal Torque and Investigation of the Motors

If we examine the electricity motors generally two different output variables strike the eye. These are torque and speed. During the motor selection these two criteria are evaluated according to the application. At the step of motor selection 2 different torque values are met stall torque and nominal torque.

Stall torque is the torque value that is measured by loading the motor to its maximum capacity. To read this value the speed of the motor should be zero. That is motor should be loaded until its shaft stops. This torque value is the maximum value that can be obtained from a motor and does not change in a linear way.

Another torque value is nominal torque which stands for the maximum value of torque that can be obtained from the motor while the speed of the motor shaft is constant. Nominal torque is considered especially when position control is required.

The motor used at the designed exoskeleton robot has 5Ncm nominal torque value and 140/1 gearbox is mounted to the output of motors. Generally the efficiency factor is taken as 0,8 at thus cycle proportioned gearboxes. So the nominal torque which is to be obtained from this motor combination is;

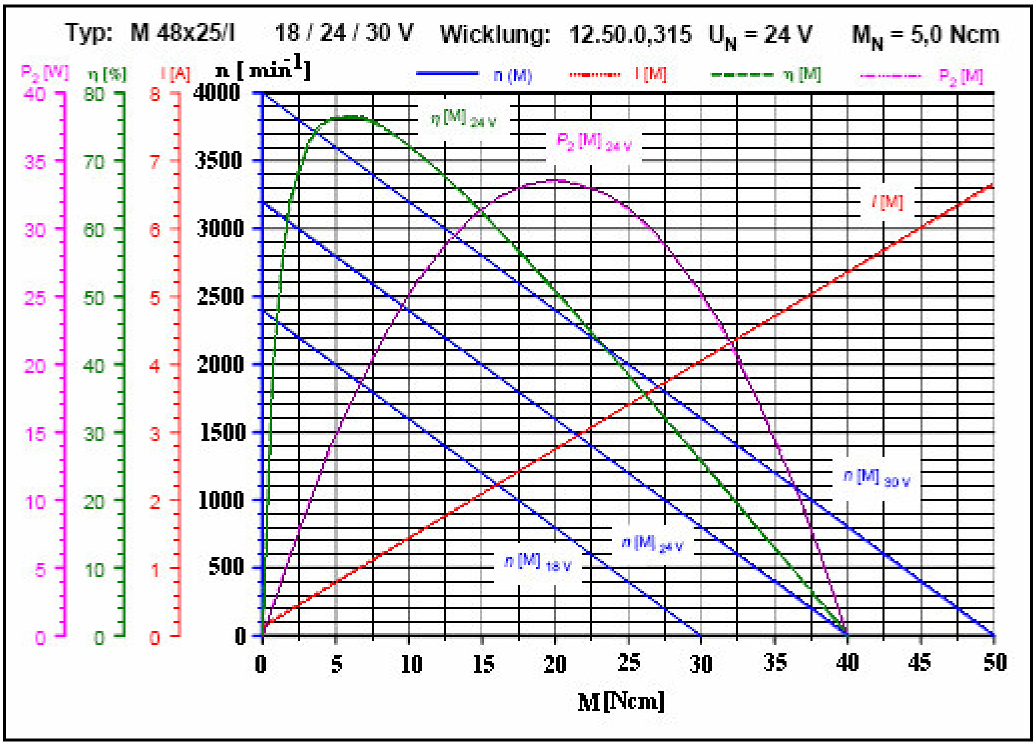
$$5\,Ncm \times 140 \times 0{,}8 = 560\,Ncm$$
$$= 5{,}6\,Nm$$

Nevertheless as it is seen at the experimentally measured values of Table 2.5 the nominal torque value that is obtained from the motor by a 24V battery at 450 Hz is 4,5Nm.This shows us that the efficiency of the gearbox reduces to 0,6328 when PWM is applied.

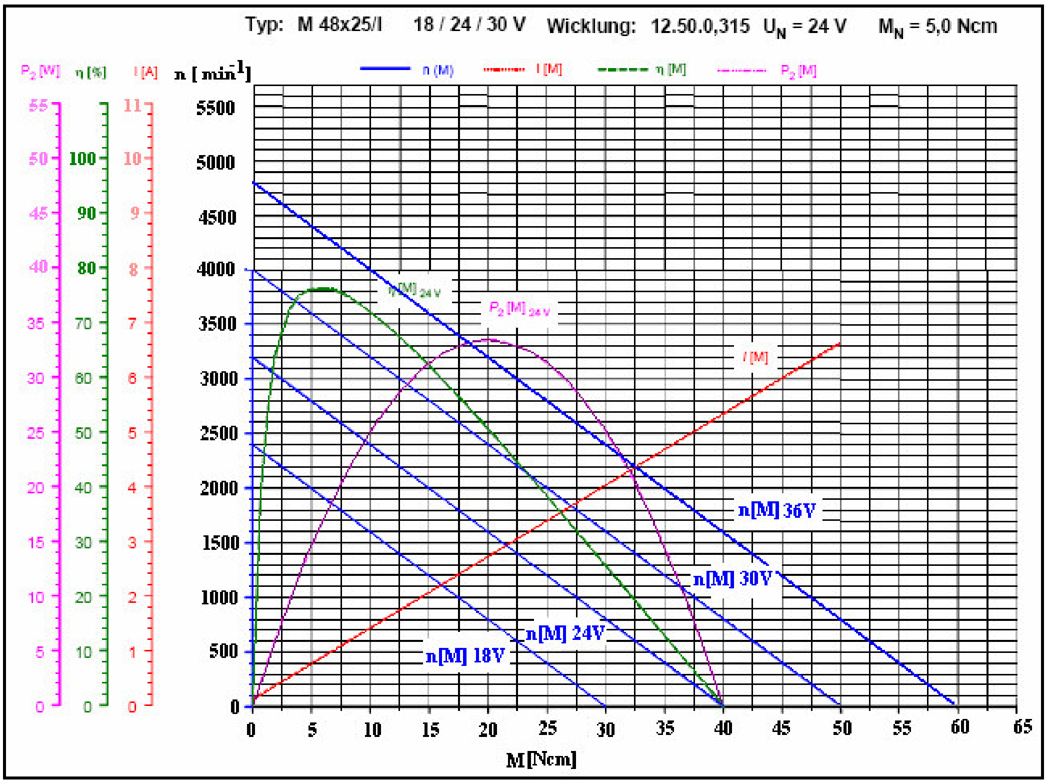
At the designed exoskeleton robot the required torque values for each joint is calculated with the help of formulas 1.1, 1.2 and 1.3 as torque 1 =19,916Nm, torque 2 = 12,707Nm and torque 3 = 6,27Nm.

At the designed exoskeleton robot even if it is assumed that 3/1 cycle ratio chain gear mechanism used for each joint worked with % 100 efficiency the maximum torque obtained from joints would be 13,5Nm.

At it can be seen here the motors used in the designed robot can not produce the required torque value for this application.



(a)



(b)

Figure 7.8. (a) Motor characteristic curves for 18V, 24V and 30V, (b) Motor characteristic curves for 18V, 24V, 30V and 36V.

If 36V is applied to the motors the nominal torque value obtained from the 1/140 gearbox motor combination with experimentally found efficiency is;

$$7{,}5\,Ncm \times 140 \times 0{,}6328 = 664\,Ncm$$
$$= 6{,}64\,Nm$$

This value is measured as 6,25Nm as a result of the experiment done.

Even if it is assumed that the chain gear mechanism worked with %100 efficiency. The obtained torque would be 19,92 Nm. This value is not enough for our exoskeleton robot to work without any problem.

If we assume that these torque value is enough and calculate the PWM values of joints according to the walking plan.

$$[rotation\ at\ 1\ \text{sec}] \times [movement\ \ duration\,(\text{sec})] \times [360] \times [PWM\ value] = [required\ angle] \tag{7.1.}$$

As it is clearly seen here if the movement angle required from the joint is constant rotation per unit time is inversely proportional with the movement time and PWM value. Despite the fact that we can get higher torque values at higher voltages because the motor's output speed will increase in this respect the movement time and PWM values will fairly decrease.

Motors' working for small time increments brings about another problem. In a motor that is working for small period the accelerating and decelerating times negatively effects position control and makes the system need the application of control.

Encoder will be needed for measuring the movement amount and accelerometer and gyroscope will be needed for measuring the angular acceleration.

7.6. Selection of the Suitable Motors

Torque values of the system which is designed to carry a 100 kg user are calculated according to equations 4.23, 4.24 and 4.25.

Here it is assumed that the exoskeleton is approximately 20 kg the user is 100 kg two batteries which are 24V weigh a total of 10 kg and the motors are 40 kg. According to these required torque values at the joints of the robot are calculated.

After that required motors are found at Bison Gear Company. Solid modeling of the motor is shown in the figure 7.9.

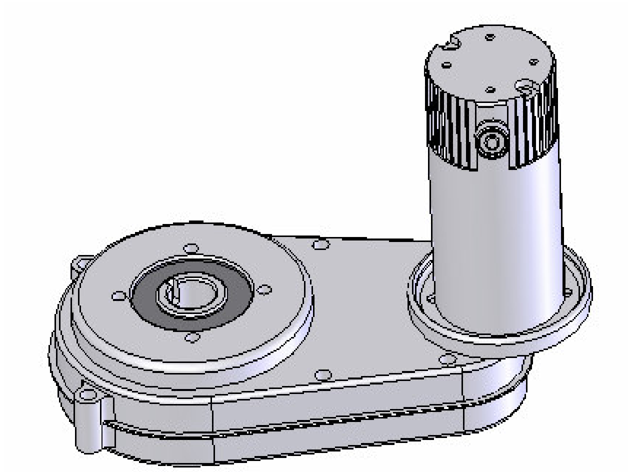


Figure 7.9. Solid modeling of selected 24V hollow shaft DC electric motor.

Table 7.4. Specifications of selected motor.

BISON 562 SERIES 24V DC 011-562-5261	
Specifications	
Stages	3
Nominal Torque (Nm)	127
Speed (Rpm)	6,9
Ratio	261.0
Approx. Weight (kg)	5,5
Amps	5,18

7.6.1. Power Consumption

In order to calculate power consumption of the wearable exoskeleton robot, current values of the each interval in the gait cycle are determined in the figure 7.10, 7.11. Later every interval current values are superposed and average current value of the each interval is found. Right leg average current is 0,361A per second and left leg average current is 0,147A per second. Finally total power consumption of the wearable exoskeleton robot is calculated by using equation 7.2.

$$P = I \times V \qquad (7.2)$$

Total power consumption of the wearable exoskeleton robot at 24V is 43,8 kW.

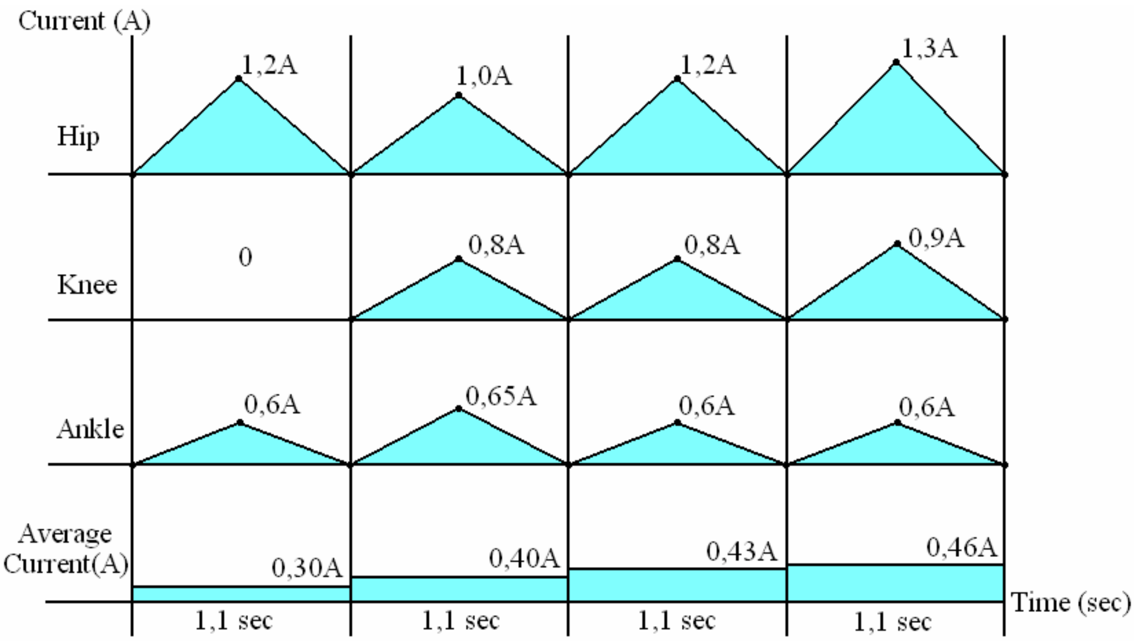


Figure 7.10. Current values of each interval in right leg for gait cycle.

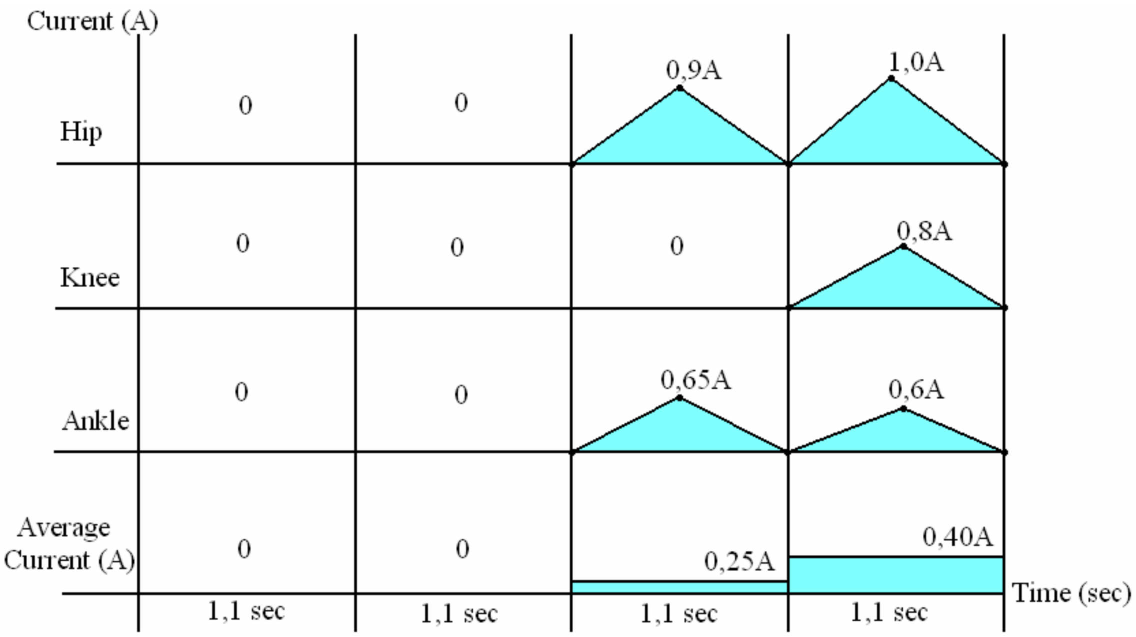


Figure 7.11. Current values of each interval in left leg for gait cycle.

7.6.1. Battery for Suitable Motors

Eight DC motors located at the designed robot consumes a current of 0.50 A per second and 43,8kW power per hour during walking.

In the light of these values two batteries which are 12V 17A are selected from Leader Company. The mostly considered criteria during this selection are batteries' having a high current capacity and their being lightweight.

Thanks to these batteries the robot can work during 50 minutes without any problem. Moreover the batteries can be recharged at 7,5 hours by applying a recharge voltage of 13,8V. Owing to these batteries the robot can walk 225 m if the batteries are fully charged.

CHAPTER 8

CONCLUSION AND FUTURE WORK

This thesis are presented a wearable lower exoskeleton system developed for augmentation of human walking ability, which incorporates human as the integral part of the control system and can relieve human's physical fatigue caused by excessive walking. The methodology of designing a wearable exoskeleton robot and adaptable exoskeleton system is discussed. Prototype of wearable exoskeleton robot is constructed and further experiments will be performed. Future work should focus on designing a more lightweight, compact, comfortable and flexible exoskeleton, and improving the control algorithm to be more robust and adaptable to various conditions. Future efforts should also include the development of lighter devices, speed controls, and more exoskeleton's degrees of freedom to better match the real human model. With respect to the controller system, a real-time learning method, by which the device adapts itself to the person wearing it, and a portable and independent embedded controller, should be built into the assist device to enable it for practical use. Future applications can be wearable exoskeleton system helping the user to climb over steep and rough slope/hill while carrying loads. An untethered, fieldable, and mountable power generation subsystem remains a more challenging issue for implementation. In fact, the research work of exoskeleton is still in its initial development stage. There is still a long way to go before one will see a reliable and useful exoskeleton that can effectively enhance human's strength and endurance.

A number of possible areas to focus on going forward are presented below

Actuators' Improvement and Redesign

In this thesis dc electric motor is used as an actuator. It is clear that so much torque the system requires to help 100kg-subject to walk. In this case actuator's type can be improved or redesigned. Hybrid actuation mechanism can be used as an example. One elastic actuator with a spring and dc electric motor combination can be more efficient.

Moreover, power transmission mechanism can be redesigned and more efficient system can be used, higher-ratio gear boxes can be used as an example for this solution.

Joint's Improvement and Redesign

In final wearable exoskeleton design, one degree of freedom (DOF) system is used for each joint; that forces the wearable exoskeleton robot walking with static balance. In this case adjustability of the total balance of wearable exoskeleton robot is so difficult during walking action. Especially for hip and ankle joint, two degree of freedom system can be used to provide wearable exoskeleton robot to move left and right side. It also removes the restriction to use static balance based exoskeleton. So, wearable exoskeleton robot can walk with dynamic balance and adjust their balance intuitively and efficiently.

Advance Manufacturing Processes and Advance Materials

For wearable exoskeleton robots, some of the most important properties are lightness and durability. In this thesis aluminum-T3 alloy is used as a material and milling, lathing and laser cutting processes are used. In order to increase lightness and durability properties, the system can be manufactured from advance materials and by using advance manufacturing processes.

Last decade there has been several studies on light and durable material production. For example composite material or advance material alloys, titanium for instant can be used the manufacturing of wearable exoskeleton robot.

Moreover, advance manufacturing process can be used. One of the well known advance manufacturing process is Computer Numerical Control (CNC). By manufacturing wearable exoskeleton robot in CNC, more suitable and natural design for user joints can be obtained. Also, high strength material can be used.

Using Sensors

The wearable exoskeleton robot is designed to create a base for new advance exoskeleton robots. The wearable exoskeleton robot on the rough terrain, it should be aware of the environmental obstacles. In order to realize these obstacles or any physical changes some specific sensors can be used for wearable exoskeleton robot.

Furthermore, it is not restricted just environmental changes, for joint movements and actuators; some special sensors can be used. These are encoder, accelometer, shock sensor e.t.c. So, not only the system can be aware of physical changes during walking action, but also adjust their physical posture, velocity, acceleration and position automatically.

Moreover, by using some specific sensors on the wearable exoskeleton robot, the system can be climb the ladder and slope easily.

Advance Applications

In this thesis, a wearable exoskeleton robot is designed for paralytic and disables to walk. In short the main purpose of the system is to aid gait for handicap people. But, it is clear that this system can be used for different applications. For example, lifting weight, supporting walking action for normal people e.t.c.

Moreover, the system can be thought a mobile platform for any robot. When the disadvantages of roller mobile platform such as wheeled, trucked, it can be quite efficient for rough terrain for robotic applications.

Furthermore, wearable exoskeleton robot has two legs to aid for handicap people to walk. But for different application, the number of joints and degree of freedom can be increase depend on applications. So, the system will be completely different, not only shape but also application.

REFERENCES

Angeles, J., 1997. *Fundamentals of Robotic Mechanical Systems Theory, Methods, and Algorithms* , (Springer-Verlag, New York), pp. 213-225.

Black, P.H. and Adams, O.E., 1981. *Machine Design Thirht Edition* (McGraw-Hill Book Company), pp. 122-143.

Braunl, T., 1998. *Embeded Robotics in Mobile Robot Design and Application with Embedded System*, (Springer-Verlag, New York), pp. 187-200.

Caux, S. And Mateo, E. 1998. *"Balance of biped robots: special double-inverted pendulum"*, IEEE International Conference on Systems, Man, and Cybernetics, p.3691-3696.

Chu, A. and Kazerooni, H. 2005. "*On the Biomimetic Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)*", IEEE International. Conferance on Robotics and Automation, Barcelona.

Kawamoto, H. and Sankai, Y. 2002. *"Power Assist System HAL-3 for Gait Disorder Person"*, (Proc. of ICCHP 2002 International Conference on Computers Helping People with Special Needs), pp.196-203.

Kawamoto, H. and Sankai, Y. 2002. *"Comfortable Power Assist Control Method for Walking Aid by HAL-3"*, Proc. of International Conference on Systems, Man and Cybernetics (SMC2002)

Kazerooni, H., Racine, J.L., Huang, L. and Steger R. 2005. *"On the Control of the Berkeley Lower Extremity Exoskeleton (BLEEX)"*, Proceedings of the 2005 IEEE International Conference on Robotics and Automation Barcelona, Spain, pp.4353-4360.

Lee, S. and Sankai, Y. 2002. *"Power Assist Control for Walking Aid with HAL-3. Based on EMG and Impedance Adjustment around Knee Joint"*. In Proc. Of IEEE/RSJ International Conf on Intelligent Robots and Systems (IROS 2002), EPFL, Switzerland, p.1499-1504

McKerrow, P.J. 1990. *Introduction to Robotics* (Addıson-Wesley Publishing Company, Sidney), p. 191-204.

Pratt, J., Krupp, B. and Morse, C. 2004. *"The RoboKnee: An Exoskeleton for Enhancing Strength and Endurance During Walking"*, Proceedings of the IEEE International Conference on Robotics and Automation.

Silva, C.W., 2004. *Mechatronics An Integrated Approach* (CRC Press), pp. 804-814.

WEB_1, 2006. Wearable R.'s web site, 25/11/2006. http://www.wearablerobotics.com

WEB_2, 2007. S.G.M.S.'s web site, 16/03/2007. htt://www.sgmsteresa.com

WEB_3, 2006. UC BERKELEY HUMAN ENGINEERING LAB0RATORY's web site, 22/04/2006. http://bleex.me.berkeley.edu/bleex.htm

WEB_4,2006. DARPA Defence Sciences Office's web site, 12/12/2006. http://www.darpa.mil

WEB_5, 1998. Kirtley (Old, Young) in CGA Normative Gait Database, 05/02/2007. http://guardian.curtin.edu.au:16080/cga/data/

Zoss, A.B., Kazerooni, H., and Chu, A. 2006. *"Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)"*, IEEE/ASME Transacton on Mechatronics, Vol.11, No. 2, pp.128-138.

APPENDIX A

SOLID MODELING OF WEARABLE EXOSKELETON ROBOT

The design of all mechanical parts of the Wearable Exoskeleton Robot is accomplished by the 3 dimensional modeling software SolidWorks®. The software applies parametric modeling principle; therefore the designed model is open for development.

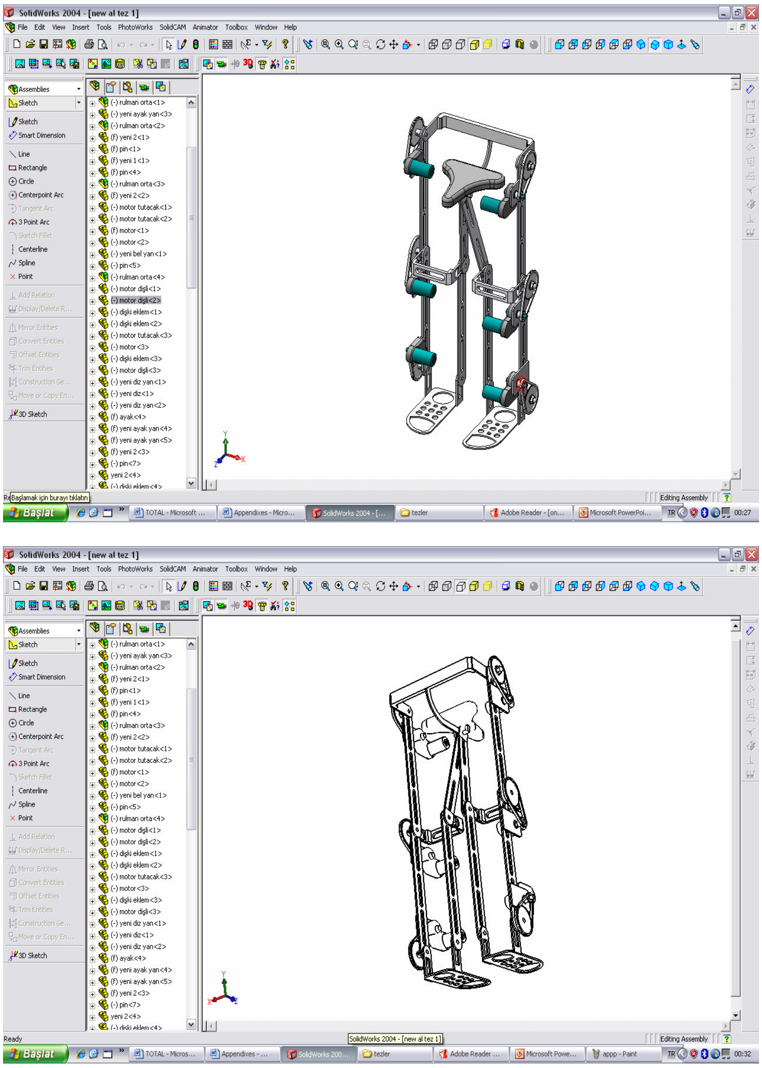


Figure A.1. Solid modeling of wearable exoskeleton robot.

APPENDIX B

STRENGTH ANALYSIS WITH SIMULATION SOFTWARE

The static analysis and strength calculations are computed by CosmoXpress plug-in tool of SolidWorks®. The components of EOD robot are analyzed and modified when required. The software also determines the weak points of the structure, shows the deformed shape under excessive load.

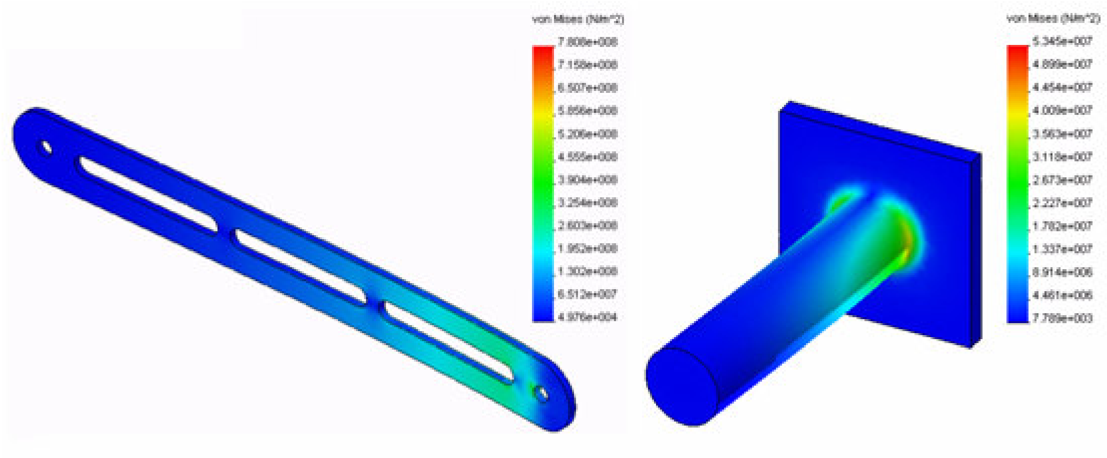


Figure B.1. Deformed shapes of the critical parts.

APPENDIX C

COMPUTER SOFTWARE PROGRAM CODES

The program code for PIC16F877 is written for the control of electronic circuit of the wearable exoskeleton robot. It is written in the language of PicBasic Proton.

```
program uygunmotoryuruyus

dim counter as word

sub procedure PWM1(dim y as byte) ' %45 duruş
    portc.y = 1
    delay_us(1000)
    portc.y = 0
    delay_us(1222)
end sub

sub procedure PWM2(dim y as byte) ' %99 duruş
    portc.y = 1
    delay_us(2200)
    portc.y = 0
    delay_us(22)
end sub

sub procedure PWM3(dim y as byte) ' %36 duruş
    portc.y = 1
    delay_us(800)
    portc.y = 0
    delay_us(1422)
end sub

sub procedure PWM2B(dim y as byte) ' %99 duruş portb
    portb.y = 1
```

```
        delay_us(2200)
        portb.y = 0
        delay_us(22)
end sub

sub procedure PWM3B(dim y as byte) ' %36 duruş portb
        portb.y = 1
        delay_us(800)
        portb.y = 0
        delay_us(1422)
end sub

sub procedure PWM4(dim y as byte) ' %40 sağ ayak ileri
        portc.y = 1
        delay_us(888)
        portc.y = 0
        delay_us(1334)
end sub

sub procedure PWM5(dim y as byte) ' %5 sağ ayak ileri
        portc.y = 1
        delay_us(111)
        portc.y = 0
        delay_us(2111)
end sub

sub procedure PWM4B(dim y as byte) ' %40 sağ ayak ileri portb
        portb.y = 1
        delay_us(888)
        portb.y = 0
        delay_us(1334)
end sub
sub procedure PWM5B(dim y as byte) ' %5 sağ ayak ileri portb
        portb.y = 1
```

```
        delay_us(111)
        portb.y = 0
        delay_us(2111)
end sub
sub procedure PWM6(dim y as byte) ' %17,75 sağ ayak yere basma
        portc.y = 1
        delay_us(394)
        portc.y = 0
        delay_us(1828)
end sub

sub procedure PWM7(dim y as byte)  '%30 sağ ayak yere basma
        portc.y = 1
        delay_us(666)
        portc.y = 0
        delay_us(1556)
end sub

sub procedure PWM8(dim y as byte)  '%28 sağ ayak yere basma
        portc.y = 1
        delay_us(622)
        portc.y = 0
        delay_us(1600)
end sub

sub procedure PWM7B(dim y as byte)  '%30 sağ ayak yere basma portb
        portb.y = 1
        delay_us(666)
        portb.y = 0
        delay_us(1556)
end sub

sub procedure PWM8B(dim y as byte)  '%28 sağ ayak yere basma portb
        portb.y = 1
```

```
        delay_us(222)
        portb.y = 0
        delay_us(1600)
end sub

sub procedure PWM9(dim y as byte)  '%47 sağ ayak geri çekme
        portc.y = 1
        delay_us(1044)
        portc.y = 0
        delay_us(1178)
end sub

sub procedure PWM11(dim y as byte)  '%60 sağ ayak geri çekme
        portc.y = 1
        delay_us(1333)
        portc.y = 0
        delay_us(888)
end sub

sub procedure PWM11B(dim y as byte)  '%60 sağ ayak geri çekme port b
        portc.y = 1
        delay_us(1333)
        portc.y = 0
        delay_us(888)
end sub

sub procedure PWM10(dim y as byte)  '%23 sağ ayak geri çekme
        portc.y = 1
        delay_us(511)
        portc.y = 0
        delay_us(1711)
end sub
sub procedure PWM10B(dim y as byte)  '%23 sağ ayak geri çekme portb
        portb.y = 1
```

```
        delay_us(511)
        portb.y = 0
        delay_us(1711)
end sub

sub procedure interrupt
   counter = counter + 1          ' increment value of cnt on every interrupt
   TMR0   = 1
   INTCON = $20                   ' set T0IE, claer T0IF
end sub

main:
  OPTION_REG = 199
  TRISB   = 0                ' portb as output
  TRISC   = 0                ' portc as output
  TRISD   = %11111111          ' portd as output
  PORTB   = %00000000          ' initialize portb
  PORTC   = %00000000          ' initialize portb
  PORTD   = %00000000          ' initialize portb
  counter = 0                ' initialize counter
  TMR0    = 1
  INTCON  = $A0              ' TMRO interrupt aktif edildi

 while true    ' program baslangıcı

      if counter <= 59 then ' 3 sn asimo durus pozisyonu

        PORTC.0=0    '1. motor direction secimi
        PORTC.2=1    '2. motor direction secimi
        PORTC.4=0    '3. motor direction secimi
        PORTC.6=0    '4. motor direction secimi
        PORTB.2=1    '5. motor direction secimi
        PORTB.0=0    '6. motor direction secimi
         PWM1(1)    '1. motor PWM secimi
```

```
 PWM2(3)    '2. motor PWM secimi
 PWM3(5)    '3. motor PWM secimi
 PWM1(7)    '4. motor PWM secimi
 PWM2B(4)   '5. motor PWM secimi
 PWM3B(1)   '6. motor PWM secimi

else if counter <= 81 then  ' 1.1 sn sag adımı ileri atma

 PORTC.0=0  '1. motor direction secimi
 PORTC.2=1  '2. motor direction secimi
 PORTC.4=0  '3. motor direction secimi
 PORTC.6=1  '4. motor direction secimi
 PORTB.2=1  '5. motor direction secimi
 PORTB.0=1  '6. motor direction secimi
 PWM4(1)  '1. motor PWM secimi
 PWM5(3)    '2. motor PWM secimi Duruyor
 PWM4(5)  '3. motor PWM secimi
 PWM5(7)    '4. motor PWM secimi Duruyor
 PWM5B(4)   '5. motor PWM secimi Duruyor
 PWM5B(1)   '6. motor PWM secimi Duruyor

else if counter <= 103 then ' 1.1sn sag tabanı yere basma

 PORTC.0=1   '1. motor direction secimi
 PORTC.2=0   '2. motor direction secimi
 PORTC.4=1   '3. motor direction secimi
 PORTC.6=1   '4. motor direction secimi
 PORTB.2=1   '5. motor direction secimi
 PORTB.0=1   '6. motor direction secimi
 PWM6(1)    '1. motor PWM secimi
 PWM7(3)    '2. motor PWM secimi
 PWM8(5)    '3. motor PWM secimi
 PWM5(7)     '4. motor PWM secimi
 PWM5B(4)    '5. motor PWM secimi
```

```
  PWM5B(1)    '6. motor PWM secimi

else if counter <= 125 then  'sag ayak geri cekme & sol ayak ileri
 PORTC.0=1   '1. motor direction secimi
 PORTC.2=1   '2. motor direction secimi
 PORTC.4=0   '3. motor direction secimi
 PORTC.6=0   '4. motor direction secimi
 PORTB.2=1   '5. motor direction secimi
 PORTB.0=0   '6. motor direction secimi
  PWM9(1)    '1. motor PWM secimi
  PWM7(3)    '2. motor PWM secimi
  PWM10(5)    '3. motor PWM secimi
  PWM4(7)   '4. motor PWM secimi
  PWM5B(4)    '5. motor PWM secimi
  PWM4B(1)   '6. motor PWM secimi

else if counter <= 147 then ' sag ayak geri cekme & sol ayak yere basma

 PORTC.0=1   '1. motor direction secimi
 PORTC.2=1   '2. motor direction secimi
 PORTC.4=0   '3. motor direction secimi
 PORTC.6=1   '4. motor direction secimi
 PORTB.2=0   '5. motor direction secimi
 PORTB.0=1   '6. motor direction secimi
  PWM9(1)     '1. motor PWM secimi
  PWM7(3)     '2. motor PWM secimi
  PWM10(5)     '3. motor PWM secimi
  PWM6(1)     '4. motor PWM secimi
  PWM7B(3)    '5. motor PWM secimi
  PWM8B(5)    '6. motor PWM secimi

  else if counter > 147 then
  counter=0
  PORTC=0
```

```
PORTB=0

while true  'burada sonsuz döngüye girecek
if counter <= 22 then ' sol ayaka geri cekme & sag ayak ileri

PORTC.0=0  '1. motor direction secimi
PORTC.2=1  '2. motor direction secimi
PORTC.4=0  '3. motor direction secimi
PORTC.6=1  '4. motor direction secimi
PORTB.2=1  '5. motor direction secimi
PORTB.0=0  '6. motor direction secimi
PWM4(1)  '1. motor PWM secimi
PWM5(3)    '2. motor PWM secimi
PWM4(5)  '3. motor PWM secimi
PWM9(7)   '4. motor PWM secimi
PWM7B(4)  '5. motor PWM secimi
PWM10B(1)  '6. motor PWM secimi

else if counter <= 44 then ' sol ayaka geri cekme & sag ayak yere basma

PORTC.0=1   '1. motor direction secimi
PORTC.2=0   '2. motor direction secimi
PORTC.4=1   '3. motor direction secimi
PORTC.6=1   '4. motor direction secimi
PORTB.2=1   '5. motor direction secimi
PORTB.0=0   '6. motor direction secimi
PWM6(1)     '1. motor PWM secimi
PWM7(3)     '2. motor PWM secimi
PWM8(5)     '3. motor PWM secimi
PWM9(7)    '4. motor PWM secimi
PWM7B(4)    '5. motor PWM secimi
PWM10B(1)    '6. motor PWM secimi
else if counter <= 66 then  'sag ayak geri cekme & sol ayak ileri
PORTC.0=1   '1. motor direction secimi
```

```
      PORTC.2=1   '2. motor direction secimi
      PORTC.4=0   '3. motor direction secimi
      PORTC.6=0   '4. motor direction secimi
      PORTB.2=1   '5. motor direction secimi
      PORTB.0=0   '6. motor direction secimi
       PWM9(1)    '1. motor PWM secimi
       PWM7(3)    '2. motor PWM secimi
       PWM10(5)    '3. motor PWM secimi
       PWM4(7)   '4. motor PWM secimi
       PWM5B(4)    '5. motor PWM secimi
       PWM4B(1)   '6. motor PWM secimi

else if counter <= 88 then ' sag ayak geri cekme & sol ayak yere basma

      PORTC.0=1   '1. motor direction secimi
      PORTC.2=1   '2. motor direction secimi
      PORTC.4=0   '3. motor direction secimi
      PORTC.6=1   '4. motor direction secimi
      PORTB.2=0   '5. motor direction secimi
      PORTB.0=1   '6. motor direction secimi
       PWM9(1)     '1. motor PWM secimi
       PWM7(3)     '2. motor PWM secimi
       PWM10(5)     '3. motor PWM secimi
       PWM6(1)     '4. motor PWM secimi
       PWM7B(3)    '5. motor PWM secimi
       PWM8B(5)    '6. motor PWM secimi

    else if counter > 88 then
       counter = 0
       PORTC=0
       PORTB=0

    end if
    end if
```

```
  end if
  end if
  end if
wend
  end if
  end if
  end if
  end if
  end if
  end if
wend
 end.
```