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Powered Lower Limb Exoskeleton

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Abstract

Mobility is one of the most vital abilities that God gave to humans with which one can independently wonder the world and can do him/her daily activities. Exoskeletons are widely gaining interest since the last decade and a lot of cutting-edge research is going on related to lightweight design, the control algorithm design, adaptive trajectory planning, and execution with the robust control system, safety, affordability, efficient power source.

This project aims to develop a Powered Lower Limb exoskeleton for the assistance of any paraplegic patient. Exoskeleton designed with the Solidworks software, wearer's kinematics analysis executed with the use of Kinovea software and with that gait trajectories are plotted in kinovea software, and kinematics data fed into OpenSim for calculating torque that is needed to actuate particular joint. Proportional Integral Derivative (PID) control algorithm developed to control different joints.

Direct Current motor with the planetary gearbox motor is selected according to torque requirement and two-staged compound spur gears designed to increase output torque. Arduino mega controller selected and control algorithm tested under different conditions. Sensors data processing is done with the use of arduino serial monitor. Prototyping of the mechanical parts and simulation of the electronics parts was conducted with a 3D printer and fritzing software. The final model is made with the aluminum 6082 which is light weighted and high strength material & parts are cut with water jet cutting machine.

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Abbreviation

CAD	Computer aided design
CGA	Clinical gait analysis
CoG	Centre of gravity
CoM	Centre of mass
CoP	Centre of pressure
DoF	Degree of freedom
ECG	Electrocardiography
EEG	Electroencephalography
EMG	Electromyography
EOG	Electrooculography
FLC	Fuzzy logic control
MIMO	Multi input multi output
MISO	Multi input single output
PD	Proportional Deravitive
PID	Proportional Integral Deravitive
RMS	Root mean square
RoM	Range of motion
SCI	Spinal cord injury
SISO	Single input single output

Chapter 1: Introduction

1.1 Background and motivation

Mobility is one of the most vital abilities for human being that enables her/him to preserve his independence while performing physical activities. It is described as the ability to use and control body position in order to carry out daily life activities. Human locomotion process depends on collaboration between the neuromuscular and musculoskeletal systems to achieve natural mobility, and any condition of injury, illness or disease will affect the nature of human locomotion. Mobility disorder can result in reduced ability in performing daily life activities due to reduced functionality of muscles as in elderly people or due to medical or physical conditions in general.

According to the world health organization, worldwide 250,000 to 500,000 suffer from spinal cord injury (SCI) every year. SCI symptoms may include loss of full or partial body limb control and sensory functions. One of the essential measures to improve SCI medical care and rehabilitation services is to provide assistive devices to enable SCI patients to perform their daily life activities. However, only 5-15 % of people who live in low and middle income countries cannot afford assistive devices. Globally around 185 million people rely on wheelchair for their mobility and almost 20% of the aged populations are over 65 years, and this is expected to reach 35% by 2050, therefore the demand for assistive devices for injured and elderly people is growing so as to help them gain more independence with their daily life activities.

In order to provide better quality of life for people who experience gait disorder to perform their usual daily tasks, attempts have been made to develop various solutions to assist and support their locomotion. Assistive robotics such as exoskeletons could be an important key in addressing mobility issues.

Exoskeleton can be described as a user-oriented robotic system worn to replace or support limb function. Currently, exoskeletons are considered as significant addition to assistive technology, in which interest has been intensified in the last decade. Lower limb exoskeletons used in rehabilitation and enhancing quality of life have been the most successful applications, but exoskeletons are used in different fields such as industry, military and medical care. Recently several exoskeleton robotic devices have been launched to help paraplegic patients and wheelchair users to stand, walk and climb stairs. Among these Rewalk by Argo Medical Technologies (Rewalk, 2016), Ekso by Ekso Bionic (Chen et al., 2016) and HAL by Cyberdyne (Sankai, 2010) have proved efficiency in restoring gait disorder using sensing, actuation and control techniques. However, obstacles and challenges still exist in exoskeleton technology advancements such as energy efficiency, safe and lightweight mechanical design, actuation systems, control and sensing techniques and operation constraints

1.2 Types of Paralysis

The pathologies causing significant affects on neuromuscular and musculoskeletal system of human that causes different types of paralysis in human body such as quadriplegia, hemiplegia, paraplegia, monoplegia a name of few. In quadriplegia victim’s full body gets paralyzed, In hemiplagia victim’s half body gets paralyzed, In paraplegia and monoplagia victim’s lower limb fully and partial gets paralyzed respectively.

Lower limb exoskeleton can be used for treatment of hemiplegia and paraplegia’s patients. Below picture depicts different types of paralysis that can cause in human body.

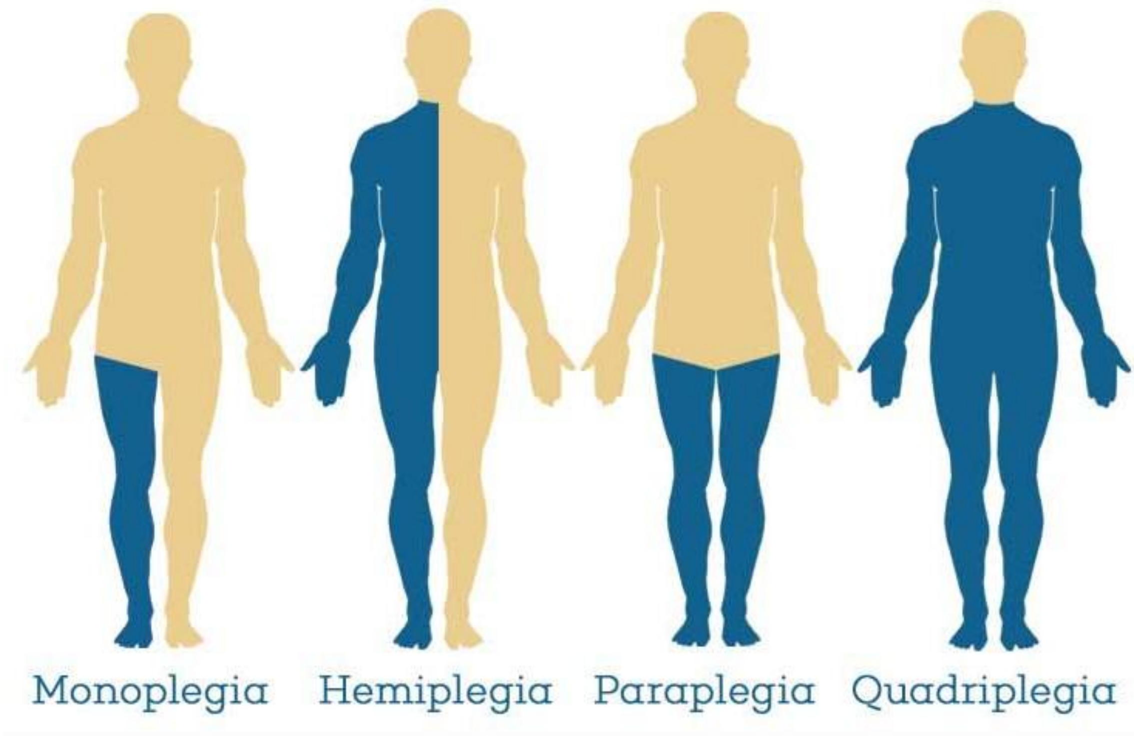


Figure 1 Types of Paralysis

1.3 Human lower limb

Human upper body is reinforced by the lower limbs carrying its weight while in locomotion. Lower limb consists of four main parts, they are foot, thigh, calf and pelvis linked to the trunk’s lower part (see Figure 2). Hip, knee and ankle are the main joints linking the lower limb segments together. Most of human body parts are engaged while in motion. However, it has been identified that lower limb joints are more relevant than other joints as they implement main motions and torques. Torque calculation gait analysis shown in later chapters.

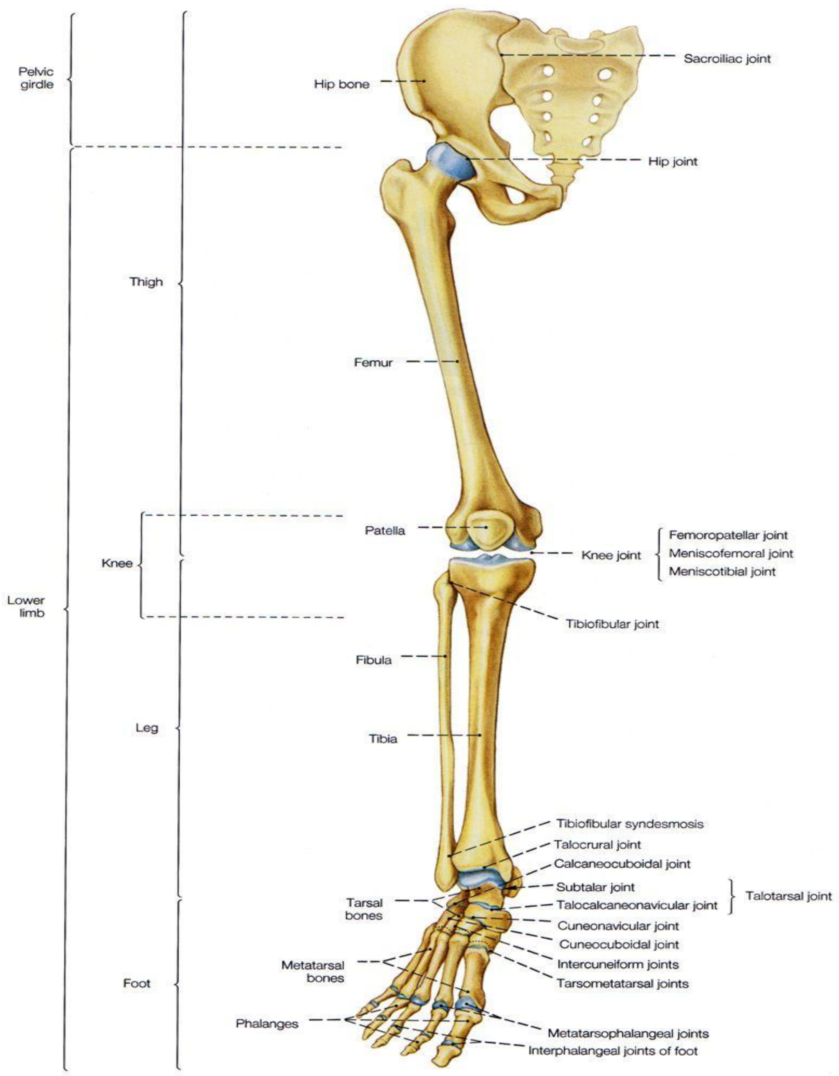


Figure 2 Lower Limb

1.3.1 Hip

The hip joint is the body's second most weight support joint after the knee because it is supported by many ligaments and surrounded by strong muscles that prevent dislocation and holding the joint together. It allows the body to carry out stable locomotion even in straight line due to its spherical shape allowing three degrees of freedom (DoF). The hip joint is attached with the pelvis in a structure of ball and socket where the pelvis acts as a socket surrounding the femur head. Hip joint can move in three different range of motions:

• Flexion-extension: The flexion is the motion that moves the thigh forward and upward with a range of motion up to 120 degrees. Extension is the opposite movement to flexion.

• Abduction-adduction: abduction is the movement of the lower limb away from the body centre with a range of motion up to 40 degrees. Adduction is the opposite movement with range of motion between 30 and 35 degrees.

• Medial-lateral rotation: medial and lateral rotation is the movement around femur bone axes with a range from 15 to 30 degrees for the medial and lateral rotation up to 60 degrees.

1.3.2 Knee

The knee joint is known as synovial hinge joint or condyloid joint, and it links the tibia and femur bones. The knee joint has the most restraints compared with other body joints, protected by strong muscles. It is deemed as the biggest and strongest joint in the human limbs as it plays vital part in walking and standing motions and supports body weight bearing. The knee joint's main movements are active in the sagittal plane, however, small rotations are achievable when knee in flex motion. These motions are:

• Flexion-extension: flexion is the motion when the leg is approaching the thigh while in the same plane; the range of motion is up to 160 degrees depending on the hip movement condition. Extension is the opposite movement with range of motion from 0-10 degrees.

• Medial-lateral rotation: medial is an internal rotation and happens at the end of extension stage which takes the knee to locked position to maintain stability with a range of motion of 10 to 15 degrees. Medial is external rotation and happens at the beginning of flexion stage with range of motion of 30 to 50 degrees based on knee flexion level.

1.3.3 Ankle

The ankle is a synovial joint located between lower end of the leg and upper part of the foot. The assembly of ankle and foot contains 26 bones linked by 30 joints and supported by 100 muscles. During walking the foot and ankle play crucial part in lower limb stability, where the foot works as shock-absorber transferring force between the lower limbs and the ground and acting as solid pedal to apply force while walking on uneven surface levels. There are two movements for the ankle joint in the transverse plane:

• Dorsal-plantar flexion: dorsal flexion is the movement where the ankle rotates the foot towards the inner surface of the leg with a range of motion up to 20 degrees. Plantar flexion movement happens the when heel is off the ground and the toe is on the ground with range of motion from 40 to 50 degrees.

1.4 Kinematic properties of human lower limb

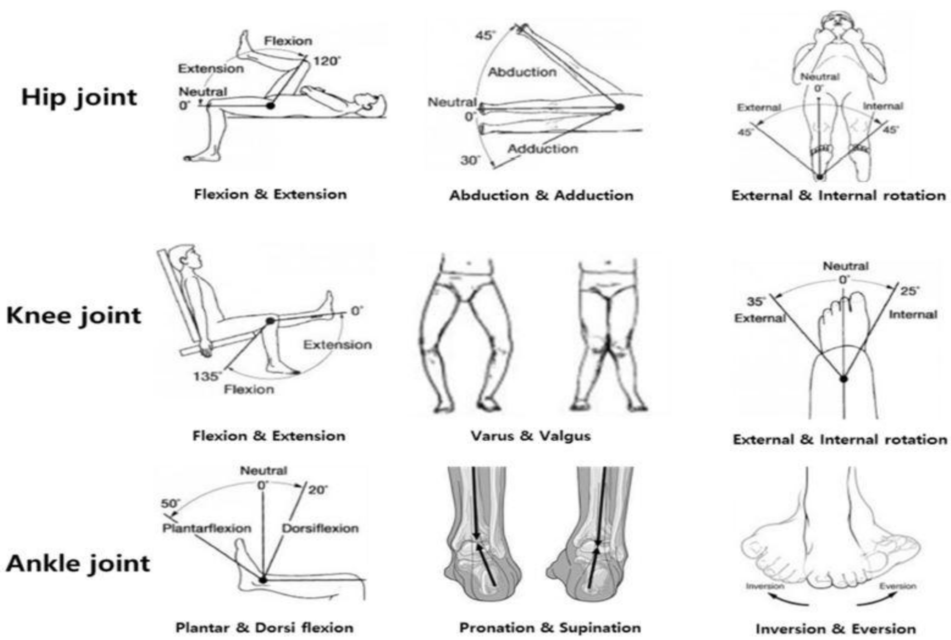


Figure 3 Range of Motion of lower limb

Table 1 Kinematics Properties of human lower limb joints

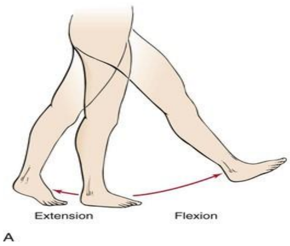
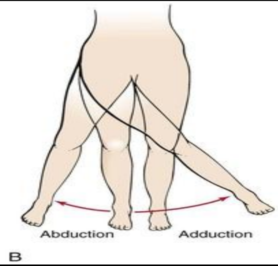
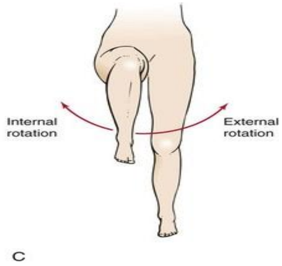
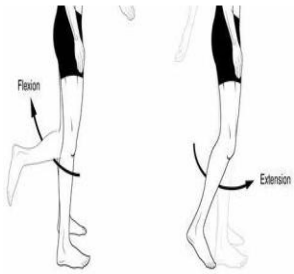
<table>
<tr><th>Joint</th><th>DoF</th><th>Motion</th><th>RoM (deg)</th></tr>
<tr><td rowspan="3">Hip</td><td rowspan="3">3</td><td>
</td><td>140/15</td></tr>
<tr><td>
</td><td>40/30-35</td></tr>
<tr><td>
</td><td>15-30/60</td></tr>
<tr><td>Knee</td><td>2</td><td>
</td><td>120-140/0-10</td></tr>
<tr><td>Ankle</td><td>1</td><td>
</td><td>40-50/20</td></tr>
</table>

Table 1 depicts different joints kinematics properties of human lower limb. In which varies joints permeable range of motion with name of different motion and pictures are mentioned, these will help to design exoskeletons body and motion planning of exoskeleton according wearers comfort.

Chapter 2: Modeling of an exoskeleton system

2.1 Gait analysis by using kinovea software

Gait is a pattern of limbs movement while human pursues locomotion; gait pattern varies from human to human as they have different biomechanical properties.

One human gait cycle can be formed by different phase modes as shown in below figure 4. That's known as stance phase and swing phase, in stance phase leg stays in contact with floor and in swing phase foot stays in swing.

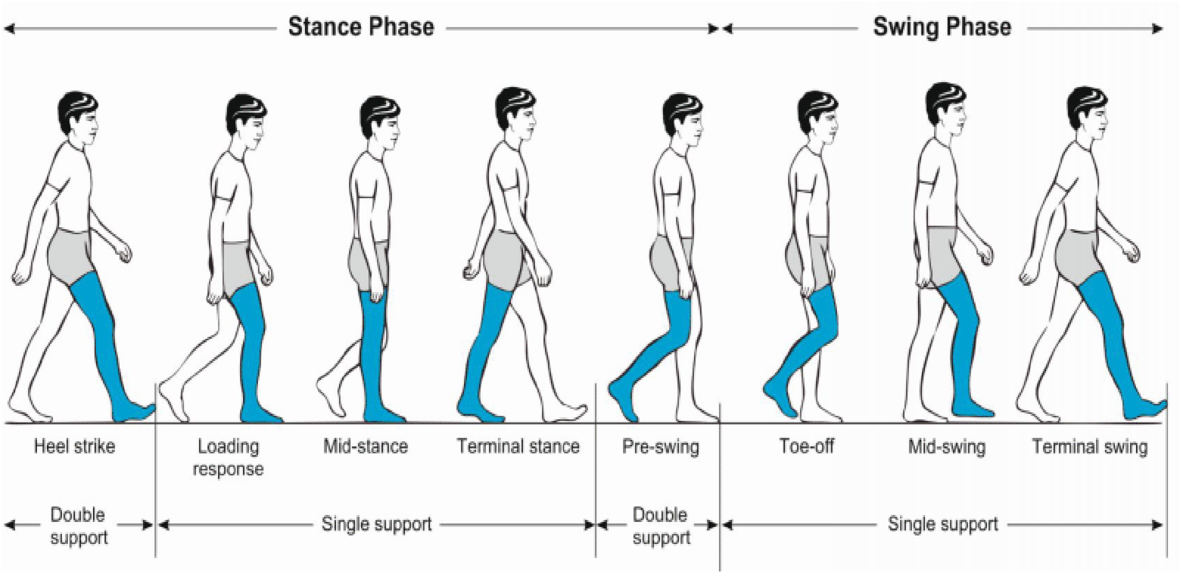


Figure 4 Human Gait

Human body can be define into three planes for analyzing purposes fist sagittal plane which is used for human gait analysis it's what shown in the figure 4, other two planes are transverse plane which is passes in between from torso and lower limb, frontal plane cuts the body into two parts from the head to toes refer figure 5.

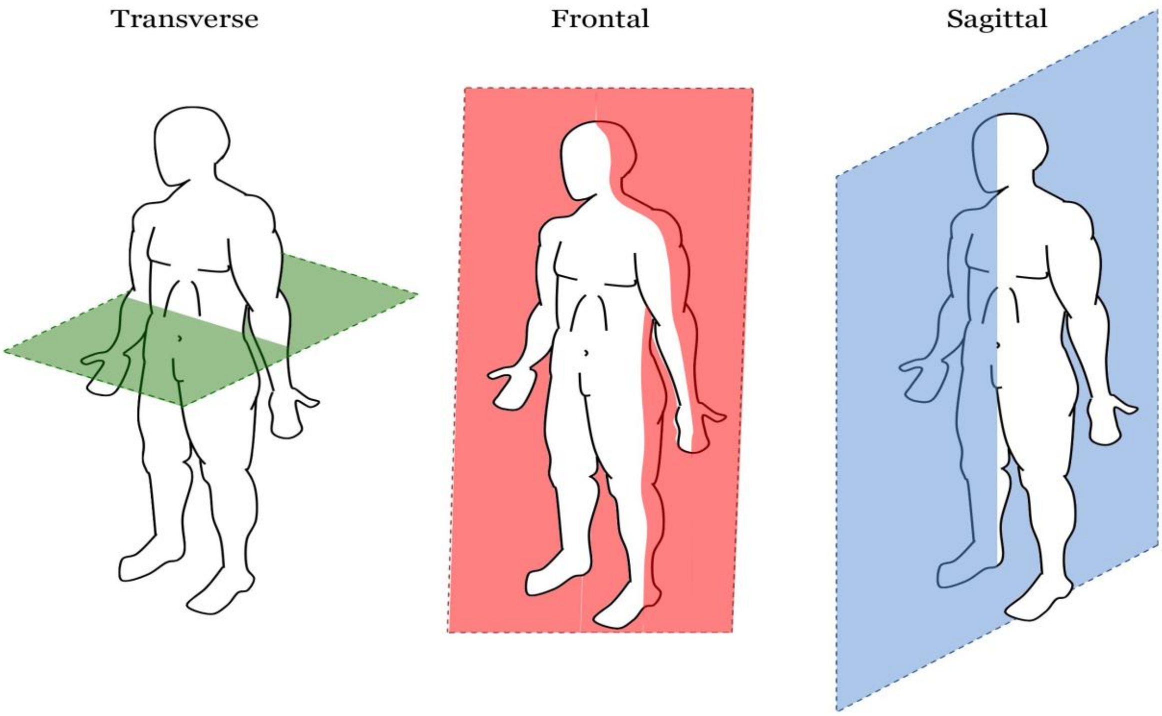


Figure 5 Human Body Planes

Gait analysis is the process to analyze kinematics data of a particular person for walking, different software such as Dartfish, Kinovea can be use for gait analysis. Here we analyzed the gait of a person having 60kg weight and by using kinovea software. We plotted hip and knee joint values with respect to time. Some illustration shown in figure 6 in which hip joint and knee joint angle are shown and trajectory of joint shown in figure 7.

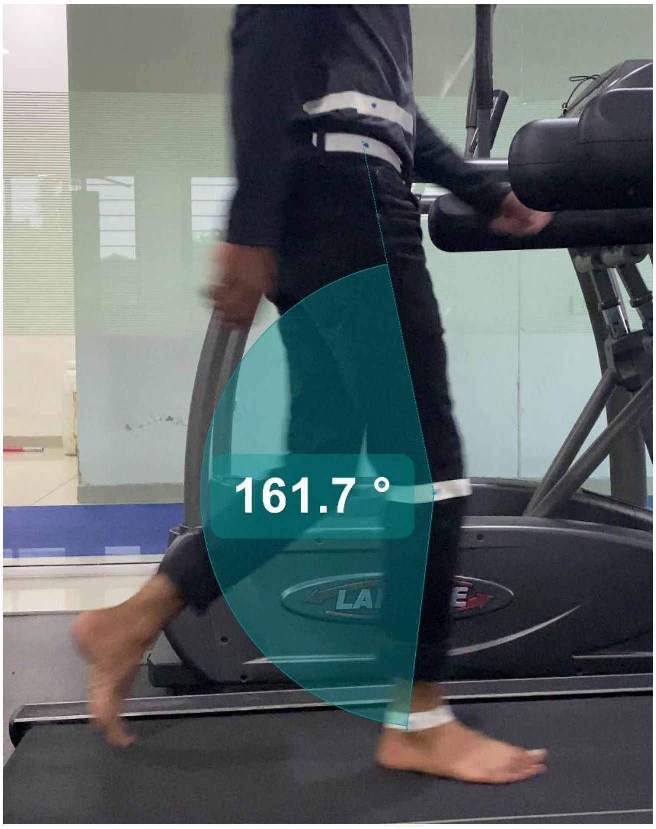


Figure 7 (A) Knee joint analysis and (B) Hip joint analysis

Figure 8 Knee joint trajectory

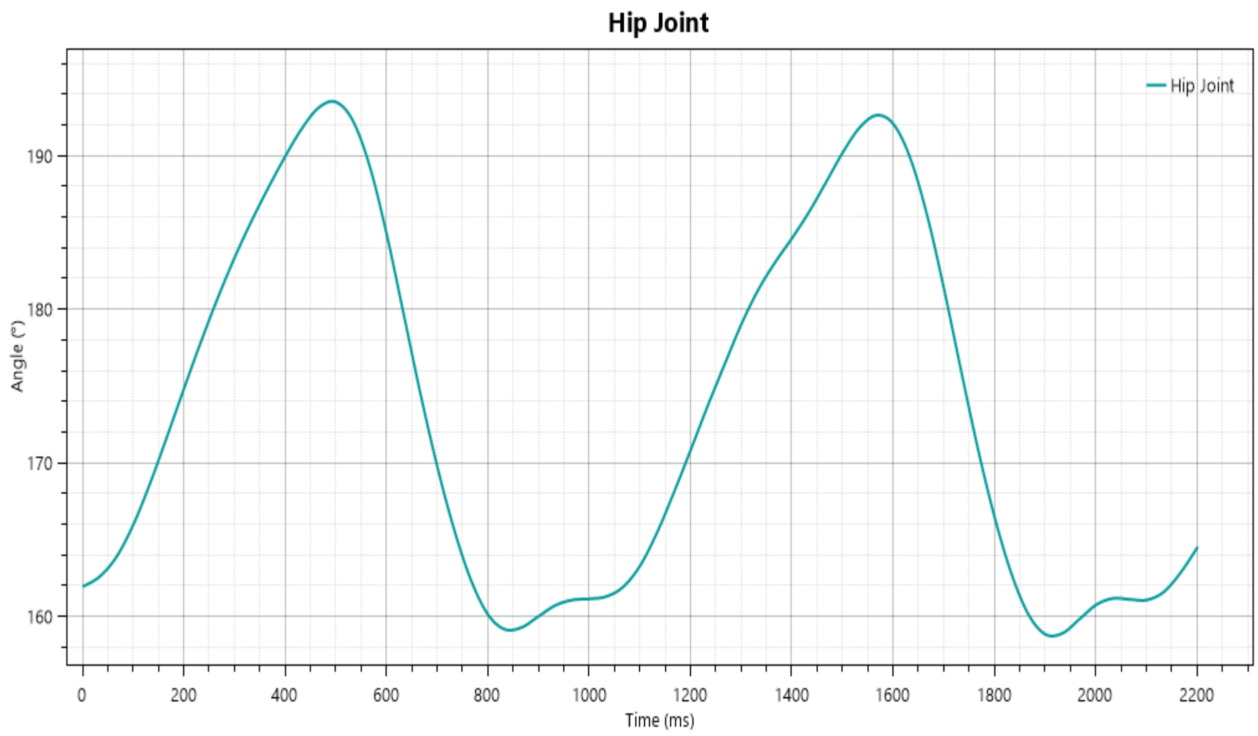


Figure 9 Hip joint trajectory

These joint trajectories can be use to get joint torque requirement and simulate musculoskeletal model in opensim software. Also, these trajectories can be used to provide joint data input in PID to perform gait execution by exoskeleton.

2.2 Torque calculation and selection of motor and gear design

Human body actuates joint by giving required torque to that joint and pursues intended motion of body parts, giving force or torque and achieving that motion is known as forward dynamics for calculating how much torque requires at each joints to pursues specific movement is known as inverse dynamics.

By inverse dynamics we will get to know how much torque is required for each joint like hip, knee and ankle joint. [1] Refers that human with height of 180cm and 80kg weight needs approximately 60Nm torque for hip joint and 40Nm torque at knee joint. For reducing human effort exoskeleton applies external forces by actuators that are mounted in exoskeleton.

Actuators need to select in such a way that most likely satisfy torque requirement of different joints. RS-550 high torque motor coupled with p60 planetary gearbox is selected which can produce 7.128Nm torque.

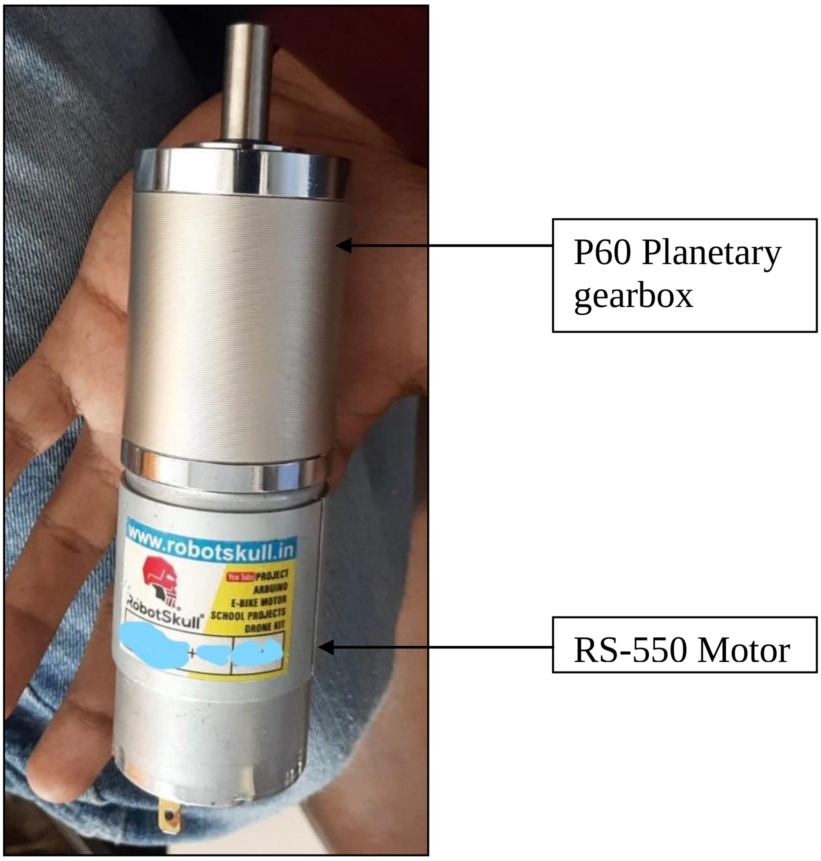


Figure 10 RS-550 motor with P60 planetary gearbox

RS-550 DC motor with P60 planetary gearbox can produce 7.128Nm torque which is not sufficient for our requirement of torque for hip and knee joint. So, external spur gears with reduction ratio of 9:1 and 5:1 is designed hip and knee joint, for hip joint 2 layer compound gears is designed each has 3:1 gear-ratio.

Peak output torque for hip and knee joint,

Peak torque at hip joint = 7.128 x 9 = 64.152 Nm

Peak torque at knee joint = 7.128 x 5 = 35.64 Nm

Now, it satisfies torque requirement for our hip and knee joint.

Spur gears for hip joint has 1.25 module with 25 teeth for driver gear(which is connected to motor shaft) and driven gear for first layer of compound gear has 75teeths and that 75teeths gear is connected to 25teeths gear and that connects to 2nd layer output gear with having 75teeths.

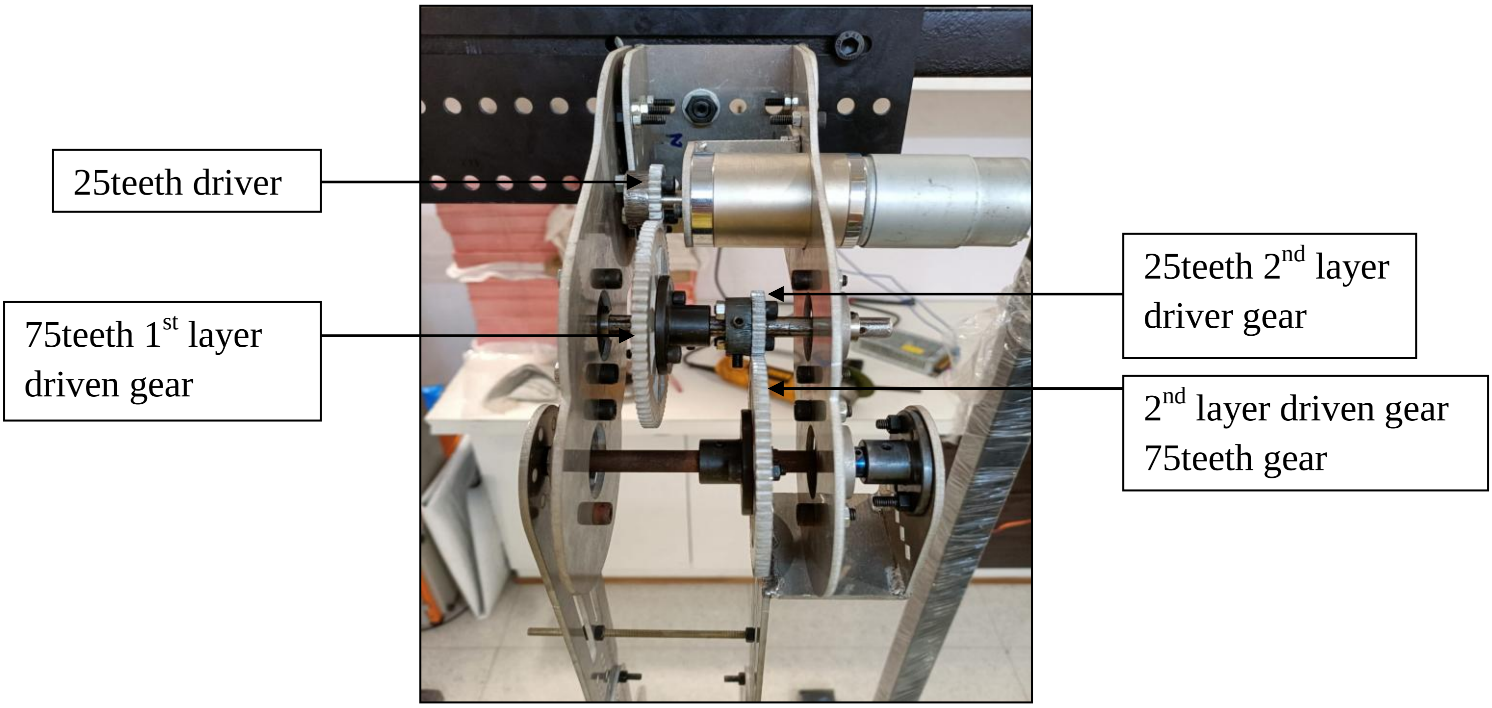


Figure 11 Hip joint, 9:1 compound gear

In knee joint one 25 teeth gear is driver gear and driven gear with 125 teeth is connected and gets 5:1 reduction ratio.

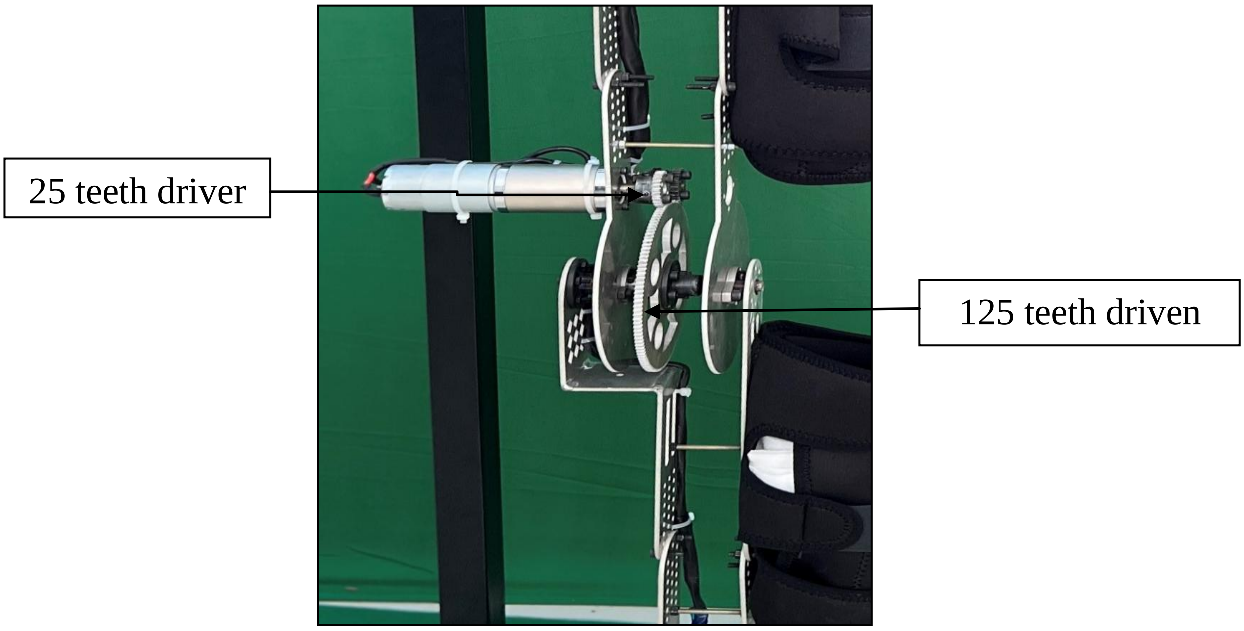


Figure 12 Knee Joint 5:1 ratio gear

2.3 Frame design of exoskeleton and strength analysis

Exoskeletons directly wear by humans means it directly gets in contact with human body. So, exoskeletons need to be comfortable and not every human body has same size in term of thigh ankle and shank. So, design of frame should be adjustable according to wide variety of humans.

We designed thigh and shank module according to that it can be adjust as human body parameters.

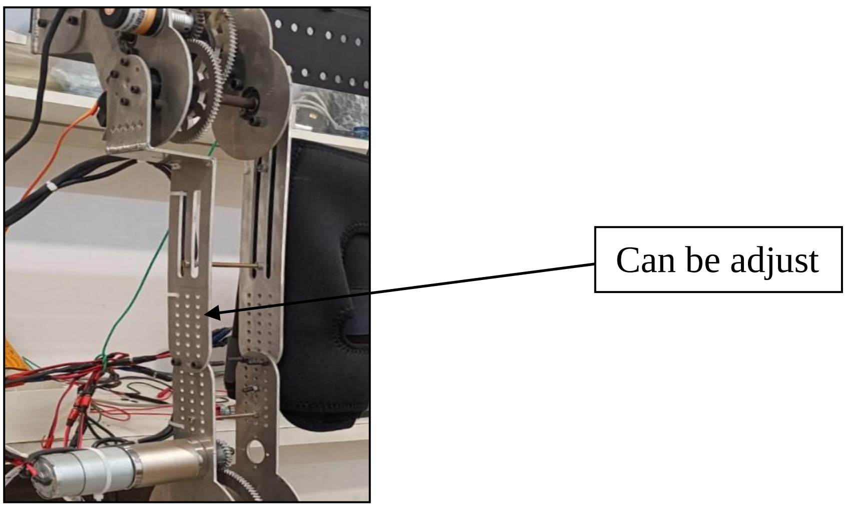


Figure 13 Adjustable thigh module

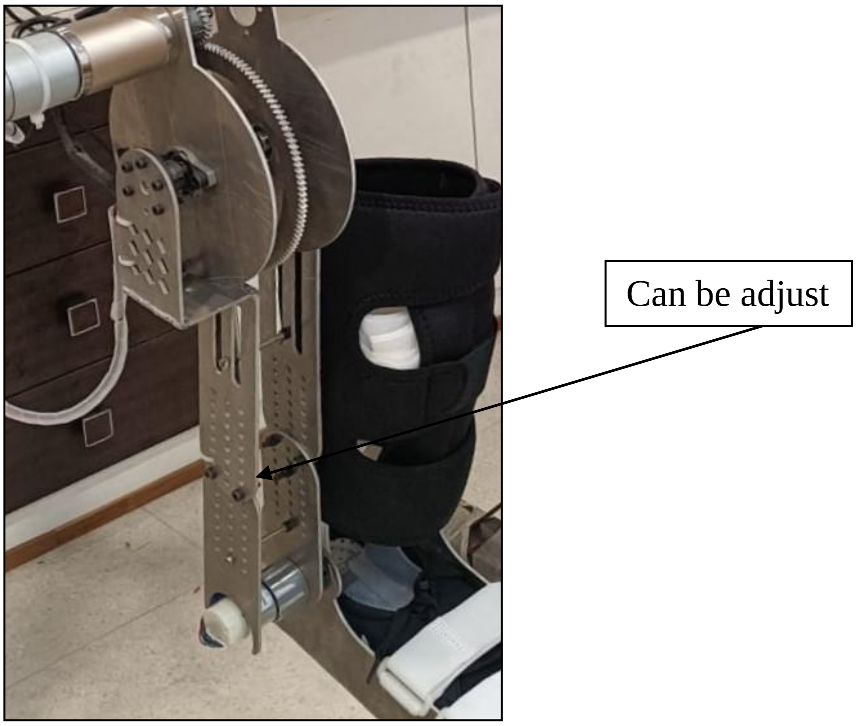


Figure 14 Adjustable shank module

Frame that holds gears and provides space for encoders is designed using solidworks software and different parts are cut through laser and water jet cutting machine.

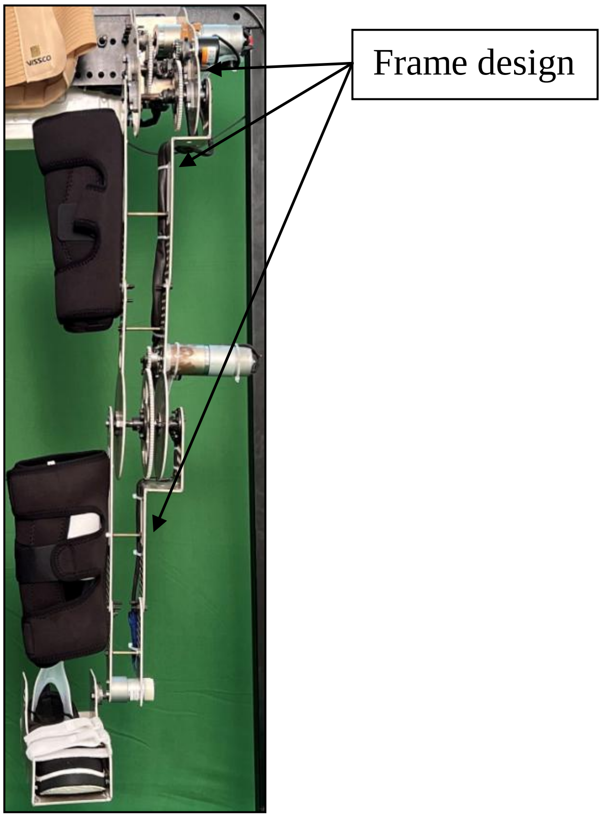


Figure 15 Frame

2.3.1 Solidworks design

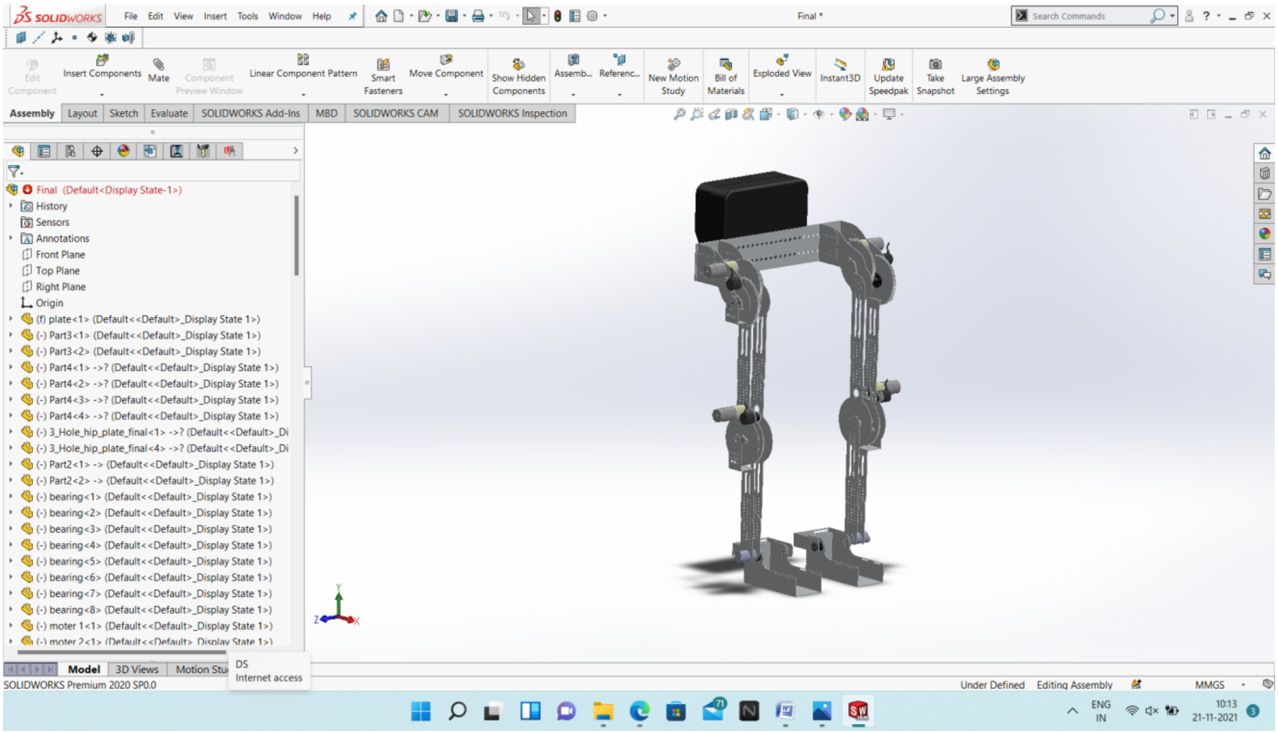


Figure 16 Solidworks design

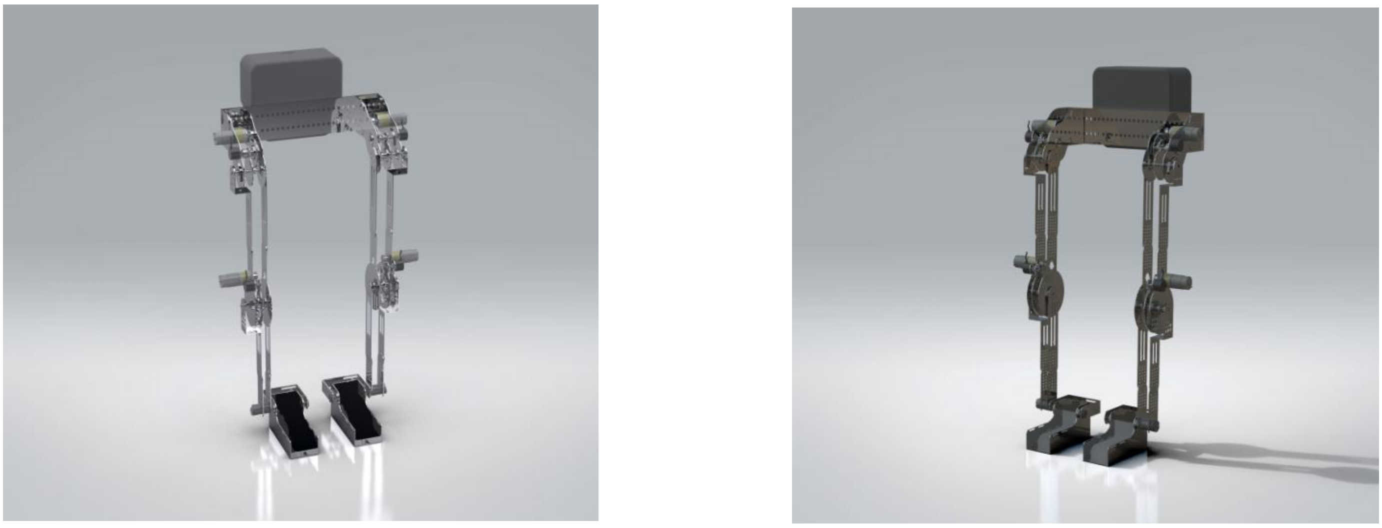


Figure 17 Solidworks visualize professional

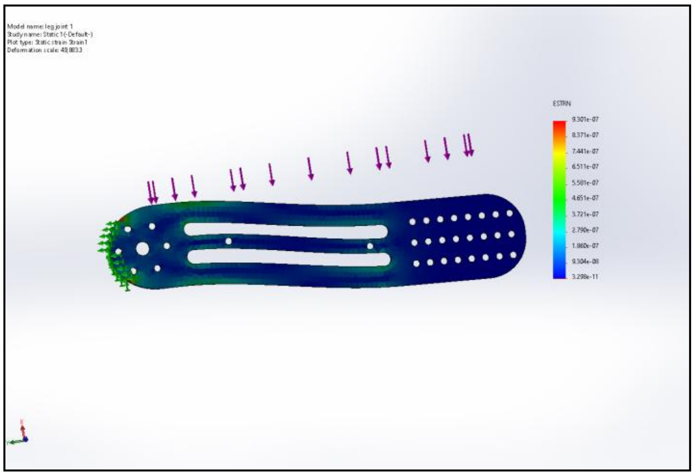
2.3.2 Strength analysis and material selection for body or frame

When human pursues motion while wearing exoskeleton it is totally rely on exoskeleton due to that frame of exoskeleton need to be strong enough to sustain force that is applied by wearers body.

Apart of that exoskeleton wears by paraplegic patient or some highly laborious working human because of that body of exoskeleton need to be light weight so, wearers don’t get tiered by wearing exoskeleton.

Strength analysis and weight analysis of different materials done on solidworks software. After that robust and light weighted aluminum alloy 6082 is selected that uses in light and strong machines such as space crafts, aero planes etc..

Results of strength analysis and weight are shown below.



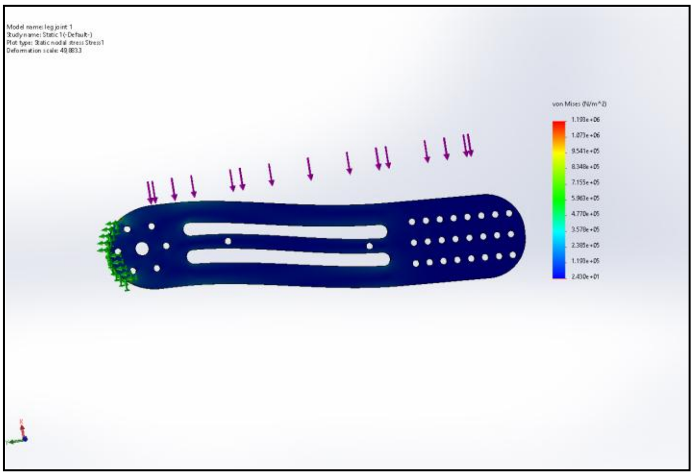


Figure 18 Stress and Strain analysis

2.4 Braces and Straps

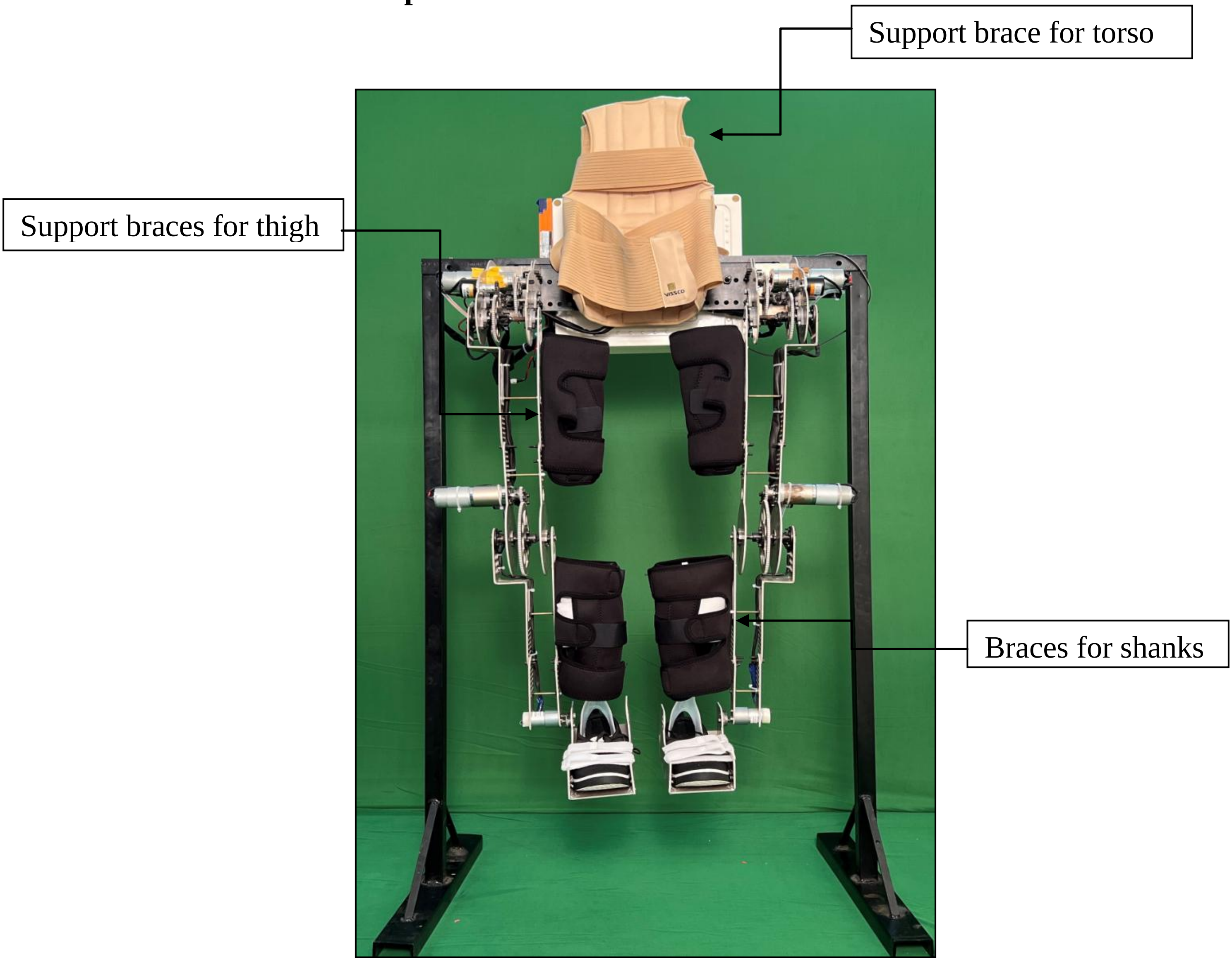


Figure 19 Support braces

Support braces for torso, thighs and shanks provided for comfort walking of any human. Wearer can wear and enjoy walking experience of exoskeleton.

Chapter 3: Control system design for exoskeleton

3.1 PID (Propositional Integral and Derivative) Control

PID control is one of the common control algorithms employed by industrial systems. PID controllers are widely used because they are simple to implement, reliable and easy to tune. Additionally, it can provide robust performance to system uncertainties and it has proven to be advantageous when the controlled model is not represented mathematically. PID control algorithm measures the difference between the actual signal of the system output and the desired signal. The difference i.e. error $e(t)$ is used as an input to the control system, where control action is generated to lower the error to almost zero. The PID controller is comprised of three tune able parameters, namely proportional k_p, integral k_i and derivative k_d as shown in Figure 15.

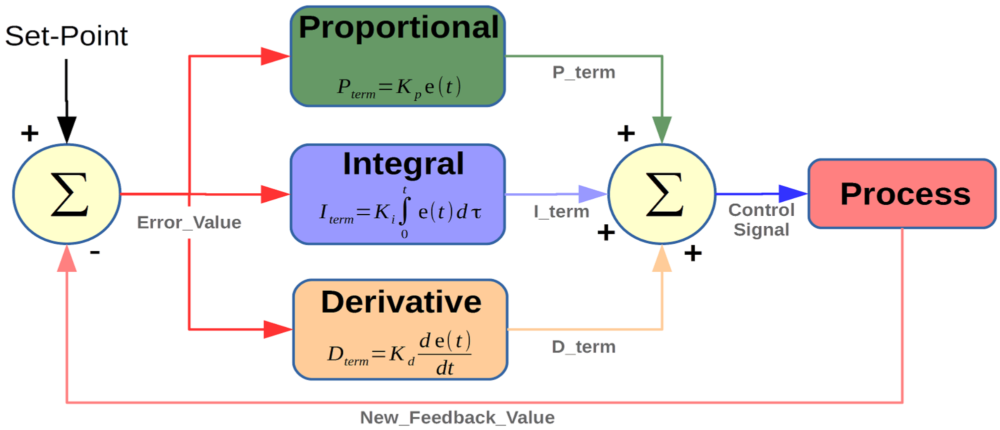
Proportional term: $k_p * e(t)$

Integral term: $\int_0^t e(x)\, dx * k_i$

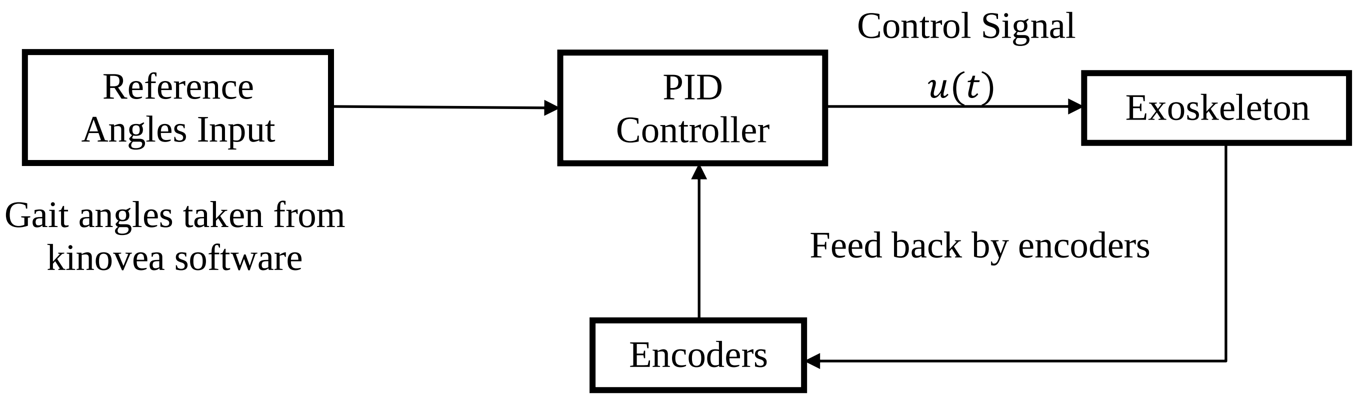
Derivative term: $k_d * \frac{de(t)}{dt}$

Control signal: $u(t) = k_p * e(t) + \int_0^t e(x)\, dx * k_i + k_d * \frac{de(t)}{dt}$

Structure of PID control



3.1.1 Control strategy for exoskeleton



PID controller in exoskeleton takes angle inputs which derived from the kinovea software and produces some input signal $u(t)$ that's goes to microcontroller in our case its arduino mega and microcontroller sends signal to motor drive which controls motor and satisfy our reference input.

Here, encoders used as feedback sensors which counts the tics and according to that microcontroller counts angle and finds error between reference value and value that is obtained by given control signal. PID controller that is coded in arduino mega.

3.2 Circuit Diagram

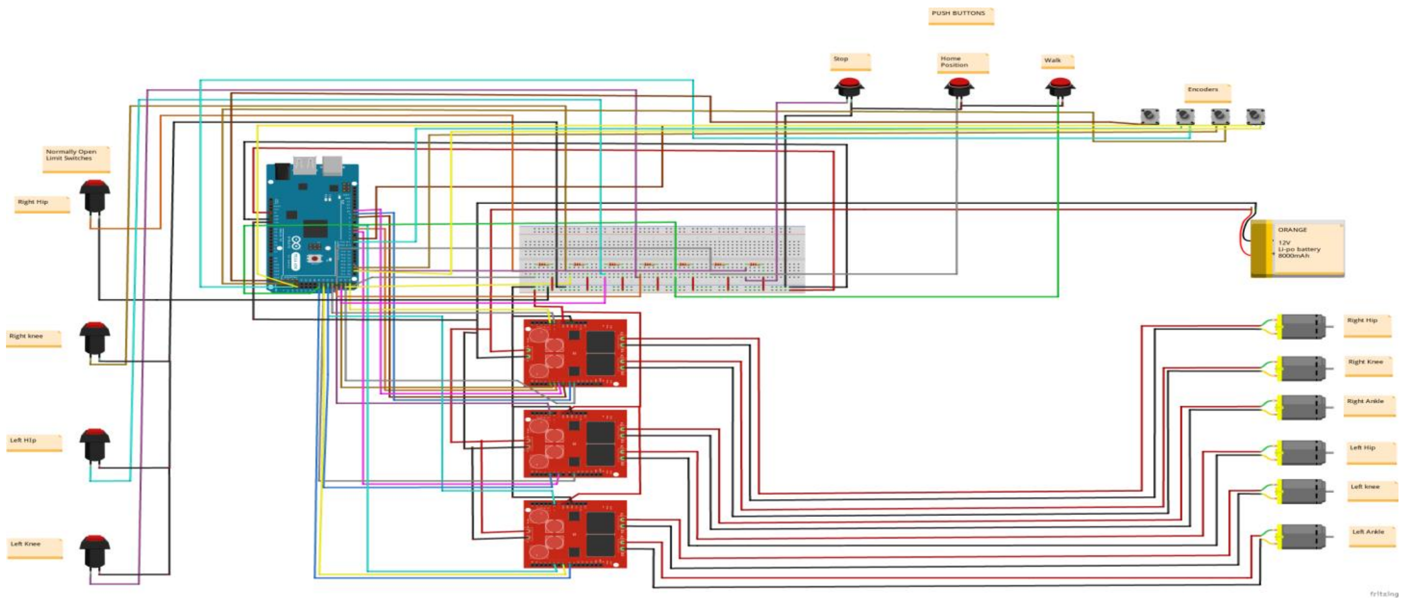


Figure 21 Circuit Diagram

Arduino mega 2560 used as microcontroller along with vnh2asp30 & vnh3asp30 motor driver for controlling 6 dc motors. Stall current of RS - 550 motor drivers is 15 ampere to sustain that vnh2asp30 motor drive is selected which can take up-to 30 ampere current. Along with that 4 limit switches used to keep exoskeleton at home position after restart. A RF(radio frequency) transmitter and receiver with 4 relay module is connected as push button switched which used to control exoskeleton from the far distance. Also a tilt sensor is provided at the top of bag that measures inclination of exoskeleton and if wearer try to initiate walking by upper body it will start walking.

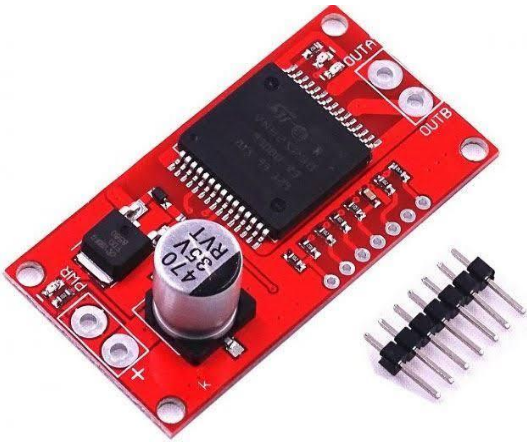


Figure 23 VNH2ASP30

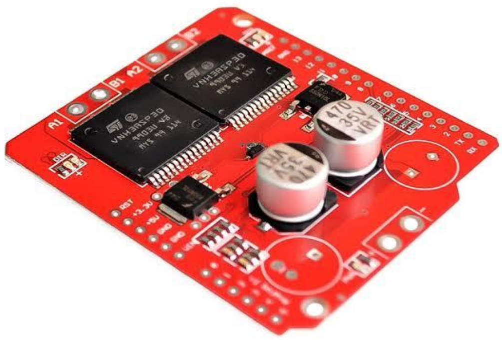


Figure 22 VNH3ASP30

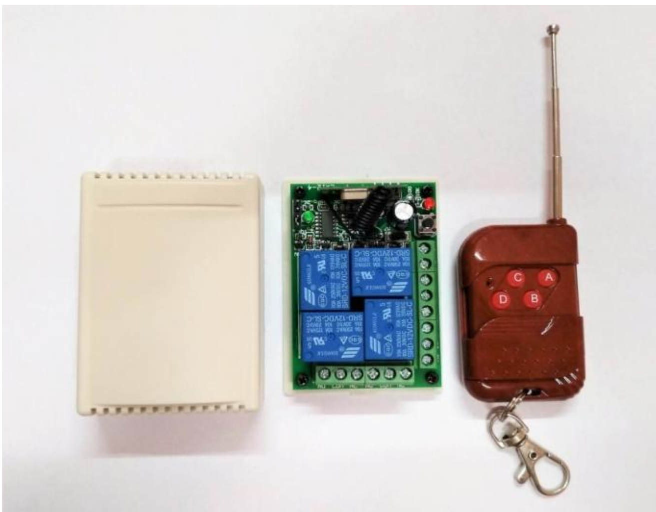


Figure 24 RC transmitter and receiver relay

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