WAIST ASSISTIVE WEARABLE POWERED EXOSKELETON FOR ARMED PERSONNEL

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CERTIFICATE

This is to certify that the thesis titled ***Waist Assistive Wearable Powered Exoskeleton for Armed Personnel***, submitted by ***Nellipudi Poojitha Reddy*** for the award of the degree of ***Bachelor of Technology*** of ***Indian Institute of Technology Palakkad***, is a record of bonafide work carried out by her under my guidance and supervision at ***Department of Mechanical Engineering, Indian Institute of Technology Palakkad***. To the best of my knowledge and belief, the work presented in this thesis is original and has not been submitted, either in part or full, for the award of any other degree, diploma, fellowship, associateship or similar title of any university or institution.

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ABSTRACT

Armed Personnel works in a harsh environment, extreme temperatures, and walk on uneven terrains for miles with heavy loads. Therefore, it reduces the efficiency of the personnel on the battlefield leading to the loss of several lives. Hence, the armed personnel needs strength to enhance their performance and efficiency by decreasing their effort to walk and carry the heavy loads on uneven terrains. An exoskeleton is a wearable device that enhances the strength and the performance of the operator. The primary objective of the project is to design a lower-extremity exoskeleton to support the waist and lower body of the operator while walking.

Human walking simulation is an important component while designing an exoskeleton. However, it is extremely difficult to simulate the motion due to complex joint parameters. Complexities involved with the walking motion can be simplified by considering only flexion/extension joints. A 2-D kinematic model of the exoskeleton was assumed to calculate the joint angles while walking. Two methods were implemented to stabilize the walking phenomena. The first method involved pre-planning the cycloid trajectory of the foot and then solving inverse kinematics using the Newton-Raphson method. Whereas, the second method involved the calculation of the Zero-Moment Point along with the trajectory generation. Despite having a common second step, the latter method performed stabilized walking pattern compared to the cycloid trajectory method.

Forward and Inverse Kinematics were performed based on the assumed kinematic arrangement. Walking simulation algorithms were implemented in MATLAB. It is observed from the simulation that the cycloid trajectory method had stable walking for smaller steps, whereas, it had highly unstable walking for larger steps. The trajectory planning method performed stable walking similar to human walking even for the larger steps. Also, a 3-D CAD model of the exoskeleton was designed based on the assumptions and the requirements.

Keywords: Exoskeleton, Zero-Moment Point, Cycloid Trajectory method, Trajectory Planning, Newton-Raphson method, Inverse Kinematics

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INTRODUCTION

An exoskeleton is a wearable device wrapped around the person which adds external support, rigidity, and provides strength. It consists of a frame that plays a similar role as the bones in a human body. The links are connected using rotary joints that can either be passive or powered. Exoskeletons are mainly classified based on the framework, power, and extremity. The framework can either be rigid or soft. However, in this project, a rigid body framework will be designed because of its versatility.

Exoskeletons are evolving rapidly in all fields. They are being used in rehabilitation centers to treat paraplegics, in hospitals, in industries to reduce the worker's effort, and in the military. However, the main focus of the project is to design an exoskeleton for military purposes. Armed personnel gets exhausted by carrying heavy loads for miles on uneven terrains, thereby, reducing the efficiency of the main mission. A wearable exoskeleton powers the joints and reduces the load experienced by the pilot. Hence, a powered exoskeleton can help military personnel to enhance strength and performance. In this project, kinematic analysis of the exoskeleton was performed and the walking motion was stabilized by implementing various algorithms. In addition to that, a 3-D CAD model was designed based on the assumptions and requirements.

1.1 LITERATURE REVIEW

The very first exoskeleton was built in 1890 by Nicholas Yagn [8]. It was a passive exoskeleton with mechanical elements such as springs, bucklings, and resilient connections to support the weight of the body. The first powered exoskeleton(Hardiman) was designed and fabricated by General Electric in 1971. It was designed to lift 1500 pounds to a height of 6ft [4]. It had 15 DoF on each side with bilateral control and works based on a master-slave system. However, Hardiman had failed because of its complex motion, overcontrol, and safety issues.

There have been a lot of developments in powered exoskeletons after Hardiman. However, none of them have made a significant change in terms of control and flexibility, until the BLEEX exoskeleton by the University of California, Berkeley. BLEEX is a lower extremity exoskeleton with 7 DoF on each side powered by linear hydraulic actuators [9]. Later, many exoskeletons were developed, however, there are many limitations to the exoskeleton in terms of comfort, weight, cost, and complex restricted motion. A lot of research is going on to make the gait motion smooth, to increase the wearer's comfort by replacing rigid links with tendons and soft links, and to reduce the weight of the exoskeleton.

Motion planning is extremely important for the powered exoskeletons. Therefore, human walking must be imitated to implement it in the exoskeleton. From the literature review, it is observed that most of the exoskeletons assume cycloid motion for walking simulation. It is considered the best approximation by most scientists and researchers, however, the cycloid trajectory method is stable only for baby steps. Unstable motion is observed in the case of longer steps. Hence, new methods such as ZMP-CPG methods are being developed to stabilize the walking motion for longer steps.

1.2 MOTIVATION BEHIND THE WORK

Exoskeletons are being researched and developed rapidly all over the world, however, the level of research going on for the development of exoskeletons in India is quite low compared to the other countries. Recently, DRDO has taken an initiative to develop and fabricate an exoskeleton for military purposes [3]. Premier Institutions, companies, and industries are researching extensively on the problem statement to develop an exoskeleton. Developing an exoskeleton will increase military power and it is the strongest weapon to the nation's development. Hence, we have chosen the problem statement to research the existing exoskeletons and design an exoskeleton that could enhance the strength of the personnel.

1.3 OBJECTIVES

The primary objective of the project is to design a waist assistive lower extremity exoskeleton to enhance the strength of armed personnel. It involves various sub-tasks which are listed below.

1. To perform kinematic analysis based on the assumed arrangement
2. To develop an algorithm to simulate human walking
3. To stabilize the walking pattern of biped in real-time environments
4. To implement the stabilized walking pattern of biped in the exoskeleton
5. To design a 3-D CAD model of the exoskeleton

2 THEORETICAL BACKGROUND

An exoskeleton is a wearable device that can be used for protection, support, and strength enhancement. The fundamental components of the exoskeleton are frame, joints, and fixtures. Joints are controlled using either hydraulic, pneumatic actuators, or electric motors. Fixtures are attached to the exoskeleton to rigidly connect the exoskeleton to the operator. In this chapter, the theoretical background required to design an exoskeleton will be discussed.

2.1 EXOSKELETON TERMINOLOGY

The human body is divided into the lower body and upper body. The lower body extends from the hips to the toes, whereas the upper body covers the rest of the body. The lower body has hip, knee, and ankle joints. Every joint has some extent to which the joint can be moved. It is termed Range of Motion. Active range of motion is the range of motion when no external force is applied to the joint, whereas passive range of motion is the range of motion when an external force is applied to the joint. While designing the exoskeleton, we consider the passive range of motion for human joints. Table 2.1 tabulates the range of motion exerted by the joints in the lower body.

Table 2.1: Passive range of motion for the joints in lower body

Type of Joint	Movement	Passive Range of Motion	Plane of Rotation
Hip Joint	Flexion	140°	Sagittal Plane
	Extension	20°	
	Abduction	50°	Frontal Plane
	Adduction	30°	
	Endo-rotation	30°	Transverse Plane
	Exo-rotation	40°	
Knee Joint	Flexion	150°	Sagittal Plane
	Extension	10°	
	Endo-rotation	10°	Transverse Plane
	Exo-rotation	40°	
Ankle Joint	Plantar Flexion	50°	Transverse Plane
	Dorsi Flexion	30°	

2.2 KINEMATIC ARRANGEMENT

A basic and foremost step to design an exoskeleton is to design a frame. Line Diagram is the representation of joints and links. Links are represented using line segments, connecting the joints. The kinematic arrangement is the representation of axes for all the joints. Frame kinematic arrangement is essential for kinematic and dynamic analysis of the exoskeleton.

Figure 2.1 represents the coordinate system for every frame in the given configuration. Frame 0 represents the base of the exoskeleton, whereas frame 6 represents the end-effector. While walking,

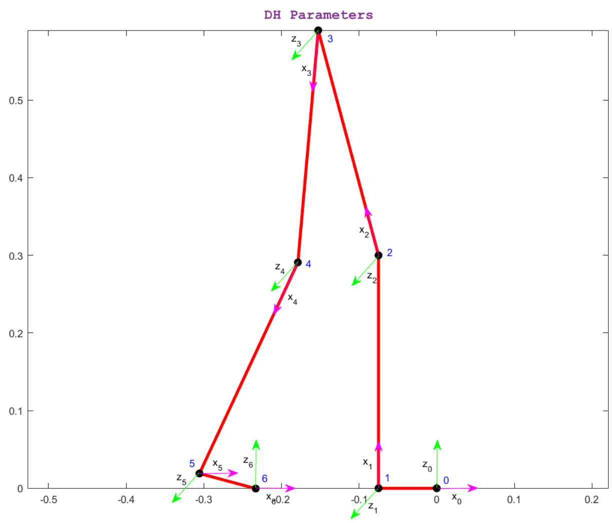


Figure 2.1: Kinematic Arrangement of the 2-D Exoskeleton

the human body exhibits swing and stance phases alternatively. Hence, the foot tip of the left leg(stance phase) is assumed as the base and the foot tip of the right leg(swing phase) is assumed as the end-effector in the given configuration.

2.3 DH PARAMETERS

Denavit–Hartenberg parameters (also called DH parameters) are the four parameters associated with a particular convention for attaching reference frames to the links of a spatial kinematic chain, or robot manipulator [6]. DH parameters are the combination of link twist angle, link length, joint angle, and joint distance. The transformation matrix, which can be found using DH parameters, transforms the position of a point from a non-inertial frame to an inertial frame.

2.4 GAIT ANALYSIS

Human gait refers to locomotion achieved through the movement of human limbs [7]. Differences in human gait and exoskeleton gait arise due to the difference in the number of joints and range of motion. Human gait is too complex to achieve, even if it is achieved, the disturbance created by the operator would be unpredictable. To analyze the gait, the trajectory needs to be designed for the foot and inverse kinematics must be performed on the other active joints. It can also be analyzed by simulating the dynamic model of the exoskeleton.

2.5 GAIT CONTROL

A Control system is essential to achieve the desired gait trajectory for the exoskeleton. Feed-forward or feedback control can be used in the control system. However, the possible disturbance in the exoskeleton cannot be estimated in advance, because the disturbance created by the operator would be unpredictable. Hence, feedback control is preferred over feed-forward control.

3 PROBLEM FORMULATION & METHODOLOGY

Kinematics deals with the relationship between configurational space and task space. It helps in analyzing the motion without considering the forces that resulted in the motion of the body. Kinematics can be classified into two sub-sections: Forward Kinematics & Inverse Kinematics. Forward kinematics determine the position & orientation of the end-effector w.r.t the inertial frame for the given configuration of the exoskeleton, whereas inverse kinematics determine the joint angles of the exoskeleton for the given configuration of end-effector.

Model : A 2-D kinematic model of the exoskeleton was assumed to calculate the joint angles and trajectories. The biped model represents the exoskeleton in the double stance phase. It is assumed to have 6-links with 5 active joints at the hip, knee & ankle. We analyze the simplified model to determine the pose and configuration of the exoskeleton.

Motion planning is important for powered exoskeletons. Therefore, human walking must be imitated to implement it in the exoskeleton. In this chapter, various methods to stabilize the walking motion will be discussed.

3.1 CYCLOID TRAJECTORY METHOD

We assume the trajectory of the foot tip of the swing leg to be cycloid. Cycloid motion reduces the impact on the foot due to ground(jerk) by superposing the sinusoidal and linear equations.

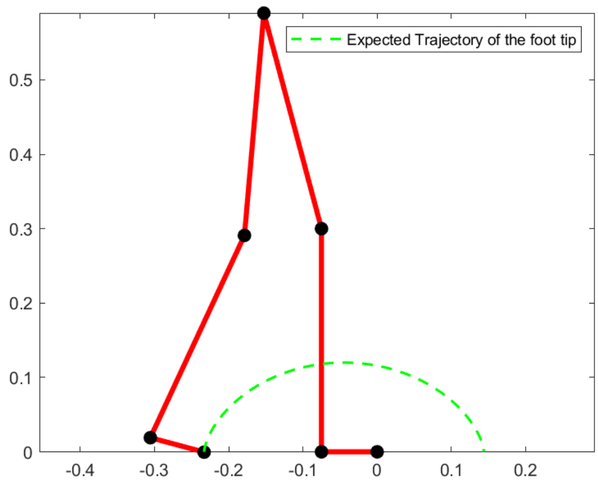


Figure 3.1: Cycloid trajectory at the tip of the foot

Consider the left leg to be at stance phase as shown in figure 3.1. Assuming the base at the left foot tip, we calculate the DH parameters for the initial assumed configuration. Forward kinematics gives the position of the end effector, left foot tip, w.r.t the base. Assuming the cycloid trajectory of the foot tip gives the configuration of the end-effector resulting in an inverse kinematic problem.

Joint angles at the hip, knee, and ankle can be found from the Newton Raphson method. As the right leg reaches the end of the cycloid position, it changes to the stance phase. Similarly, the left leg changes to the swing phase, and the right foot tip follows the cycloid trajectory leading to the completion of the gait cycle. In this way, each foot tip follows a cycloid trajectory alternatively resulting in walking motion.

Cycloid trajectory is given by,

$$x = a * (\phi - \sin(\phi))$$
$$y = a * (1 - \cos(\phi))$$

where,

ϕ is the angle made with vertical line

$a = \frac{StepLength}{2\pi}$

3.2 ZERO MOMENT POINT METHOD

Human gait can be divided into two cycles in a single walking cycle: single support phase and double support phase. In a single support phase, one leg is in contact with the ground whereas the other leg swings across the stance leg. In a double support phase, the swing and stance leg interchange the positions while both being in contact with the ground. Center of gravity plays an important role in maintaining the static stability of a biped. CoG must always fall in the support polygon within the legs to maintain static stability. In order to maintain dynamic stability, the center of pressure(CoP) should strictly be inside the support polygon. Zero-moment point(ZMP) or CoP is defined as the point on the ground at which the resultant of ground reaction forces act[1]. The coordinates of ZMP are obtained by using the below equations

$$x_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i\ddot{x}_i z_i - \sum_{i=1}^{n} I_{iy}\ddot{\Omega}_{iy}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{3.1}$$

$$y_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i\ddot{y}_i z_i - \sum_{i=1}^{n} I_{ix}\ddot{\Omega}_{ix}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{3.2}$$

where, m_i = mass of link and respective inertial component $I_{ix}\&I_{iy}$

Ω_{ix}, Ω_{iy} = absolute angular accelerations of the link

(x_i, y_i, z_i) = coordinates of CoM of link i

In the single support phase, ZMP should be located inside the stance foot region, whereas, in the double support phase, ZMP should fall within the supported region. In the ZMP method, center of pressure point is found at every instant of time and adjusted accordingly to stabilize the walking.

3.3 TRAJECTORY PLANNING

For ZMP to fall within the support polygon, trajectories of the joints must be defined. Hence, we can consider biped as two 2R manipulators: stance and swing leg. For hip trajectory, stance ankle joint is considered as the base and hip is considered as the end effector. For ankle trajectory of the swing leg, hip joint is considered as the base, and ankle is considered as the end effector. For a biped walking on a sagittal(x-z) plane, the motion of the stable leg is assumed to be an inverted pendulum[2]. In addition, we assume the biped does not fold the stable leg while walking and the foot to be always parallel to the ground. Hence, the walking sequence can be determined by computing trajectories of hip, ankle, and knee joints.

3.3.1 *Swing Leg's Trajectory*

Ankle Trajectory : We define the ankle joint trajectory of swing leg as follows[5]

$$x_A(t) = x_i + \left(\frac{3x_f}{t_f^2}\right)t^2 - \left(\frac{2x_f}{t_f^3}\right)t^3 - x_i + \frac{x_f}{2} \tag{3.3}$$

$$\begin{aligned} z_A(t) = &- kx_i(x_f + x_i)^2 + k(x_f + x_i)(x_f + 3x_i)(x_A(t) + (x_i + \frac{x_f}{2})) \\ &- k(2x_f + 3x_i)(x_A(t) + (x_i + \frac{x_f}{2}))^2 + k(x_A(t) + (x_i + \frac{x_f}{2}))^3 \end{aligned} \tag{3.4}$$

$$\begin{aligned} \text{where, } k &= \frac{h}{(x_m - x_i)(x_m - x_i - x_f)^2} \\ (x_i, z_i) &= \text{Coordinates of ankle joint of stance leg at time } t_0 \\ (x_i + x_f, z_f) &= \text{Coordinates of ankle joint of stance leg at time } t_f \\ x_m &= \text{x coordinate of ankle joint at maximum vertical height} \\ h &= \text{Step height} \end{aligned}$$

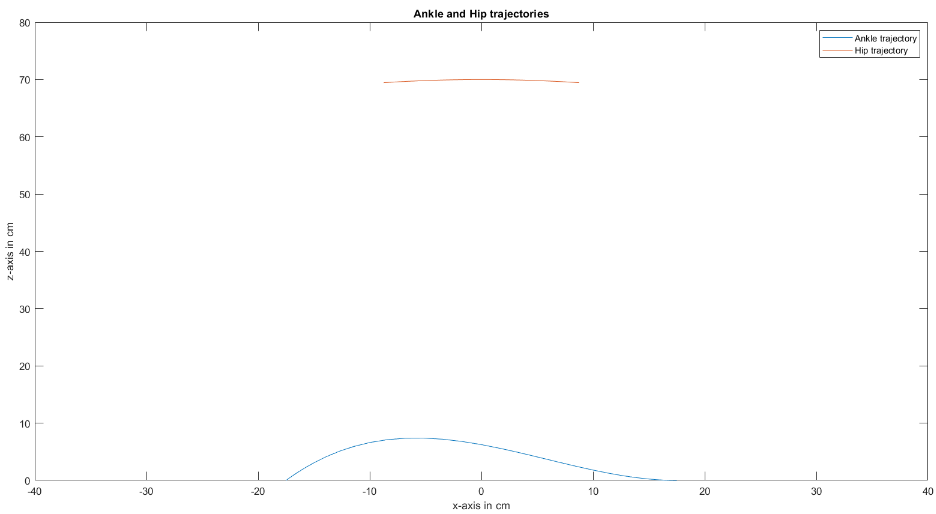


Figure 3.2: Ankle and Hip trajectories

3.3.2 *Stance Leg's Trajectory*

Hip Trajectory : We define the hip joint trajectory of stance leg as follows

$$x_H(t) = \frac{x_f}{4} + v_s t + (\frac{v_e - v_s}{2t_f} - 1.5rt_f)t^2 + rt^3 \tag{3.5}$$

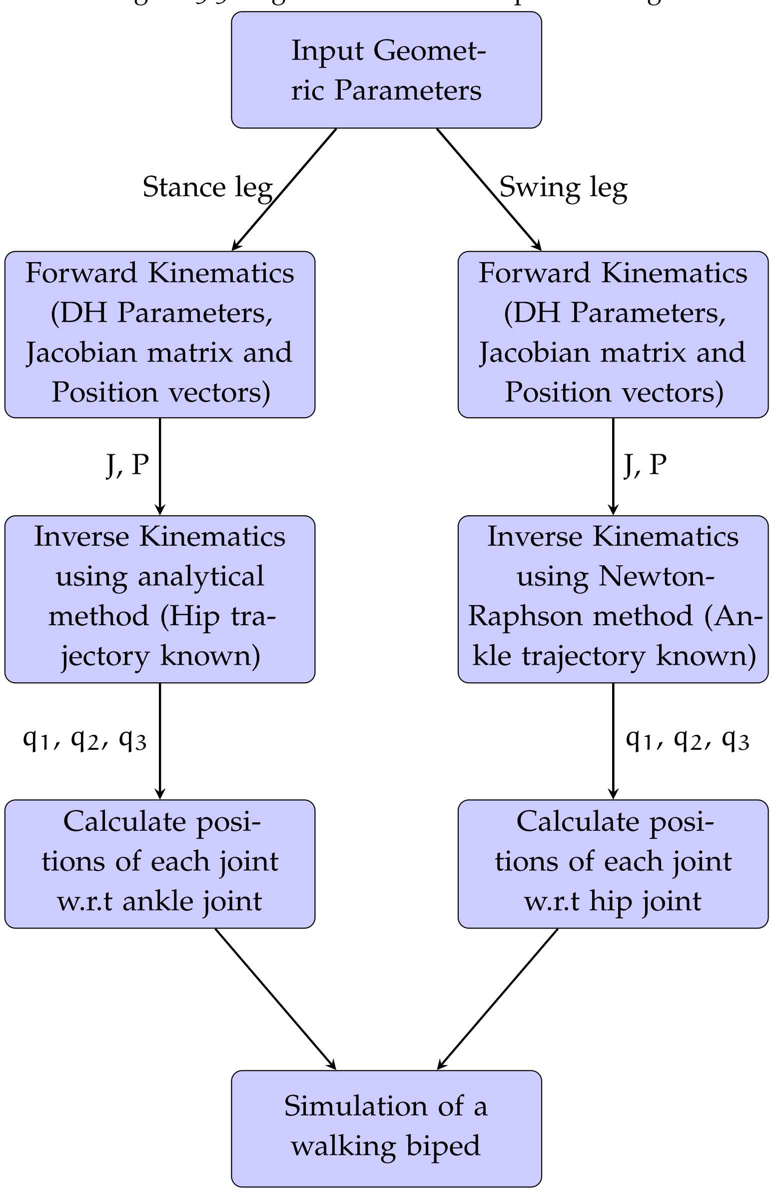
$$z_H(t) = \sqrt{(l_1 + l_2)^2 - (x_H(t))^2} \tag{3.6}$$

$$\begin{aligned}
\text{where, } r &= -2\left(\frac{xf}{2t_f^3} - \frac{v_s + v_e}{2t_f^2}\right) \\
v_s &= \text{Velocity of hip at } t_0 \\
v_e &= \text{Velocity of hip at } t_f \\
l_1 \,\&\, l_2 &= \text{Length of shank and thigh}
\end{aligned}$$

3.3.3 *Biped walking algorithm using trajectory planning*

As shown in 3.3, we input the geometric parameters such as shank, thigh, and step lengths to simulate the walking motion of biped. Forward and inverse kinematic analysis are performed to calculate the positions of joints w.r.t the reference frame.

Figure 3.3: Algorithm for stable biped walking



3.4 ZMP-CPG METHOD

Trajectory planning method is highly inefficient on rough terrains and inclined surfaces. Pre-planned trajectories are highly unstable in unknown environments and hence they cannot be implemented in real-time walking. Hybrid methods such as ZMP-CPG(Zero Moment Point-Central Pattern Generator) can be very useful in unknown environments. CPG method generates a periodic pattern that mimics human beings. It creates rhythmic motion control that generates desired motion using phase resetting. However, this method is really difficult to implement in real-time environments due to complexities involving a large number of parameters. ZMP method is widely used, however, it is not very efficient due to pre-planned trajectories. It works by adjusting CoM positions with defined trajectories. Hence, a hybrid method such as the ZMP-CPG method generates the periodic patterns by taking feedback from ZMP positions.

3.5 KINEMATIC ANALYSIS OF THE EXOSKELETON

Various methods were discussed in sections 3.1, 3.2 & 3.3 for stabilizing the walking simulation. However, all the above methods should be kinematically solved to implement the algorithms. Hence, we perform forward and inverse kinematics to the simplified biped model.

3.5.1 *Forward Kinematics*

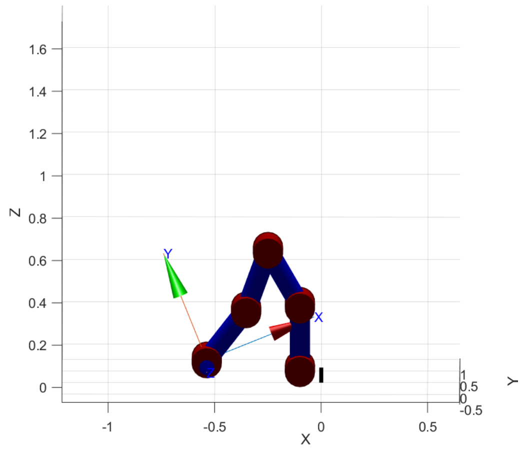


Figure 3.4: Line Diagram of the 2-D Exoskeleton

Line Diagram specifies the arrangement of the links and joints in a simplified model. Figure 3.4 represents the line diagram of the exoskeleton with 5 active joints and the flexion/extension joints at the hip coincide with each other to form a 2-D simplified model.

3.5.1.1 *DH Parameters*

DH parameters for the assumed kinematic arrangement are given by the table 4.1, where θ_k and d_k represents joint angle and joint distance respectively, whereas a_{k-1} and α_{k-1} represents link length and link twist angle respectively. The transformation matrix can be found from the DH parameters. When the position matrix of the end-effector in the non-inertial frame is multiplied with the transformation matrix, the result gives the position of the end-effector w.r.t the base.

Table 3.1: DH Parameters for n-linked manipulator

Link	θ_k	d_k	a_{k-1}	α_{k-1}
1	θ_1	d_1	a_1	α_1
2	θ_2	d_2	a_2	α_2
3	θ_3	d_3	a_3	α_3
4	.	.	.	.
5	.	.	.	.

3.5.1.2 *Transformation Matrices*

Transformation matrices can be found using DH parameters for each link and it helps in converting the position of each joint w.r.t the base. The general form of transformation matrix is defined as:

$$T_k^{k-1} = \begin{bmatrix} \cos(\theta_k) & \text{-}\sin(\theta_k) & 0 & a_{k-1} \\ \sin(\theta_k)\cos(\alpha_{k-1}) & \cos(\theta_k)\cos(\alpha_{k-1}) & \text{-}\sin(\alpha_{k-1}) & \text{-}\sin(\alpha_{k-1})d_k \\ \sin(\theta_k)\sin(\alpha_{k-1}) & \cos(\theta_k)\sin(\alpha_{k-1}) & \cos(\alpha_{k-1}) & \cos(\alpha_{k-1})d_k \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.7}$$

From the equation 3.7, transformation matrix can be calculated for every link in table 4.1 i.e., $T_1^0, T_2^1, T_3^2, T_4^3$ and so on. Transformation matrix of the end-effector w.r.t the base for the n-linked manipulator is given by,

$$T_n^0 = T_1^0 * T_2^1 * ..... * T_n^{n-1}$$

Consider a 6-linked biped model as shown in figure 3.4, the transformation matrix of the end-effector w.r.t the inertial frame for the configuration is given by,

$$T_6^0 = \begin{bmatrix} \text{-}\cos(q_1+q_2+q_3+q_4+q_5) & 0 & \sin(q_1+q_2+q_3+q_4+q_5) & \sigma_1 \\ 0 & 1 & 0 & 0 \\ \text{-}\sin(q_1+q_2+q_3+q_4+q_5) & 0 & \text{-}\cos(q_1+q_2+q_3+q_4+q_5) & \sigma_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.8}$$

$$P_6^0 = \begin{bmatrix} \sigma_1 \\ 0 \\ \sigma_2 \end{bmatrix} \tag{3.9}$$

where,

$$\sigma_1 = -a_0 - a_1\sin(q_1+q_2+q_3+q_4) - a_2\sin(q_1+q_2) - a_1\sin(q_1) \\ - a_0\cos(q_1+q_2+q_3+q_4+q_5) - a_2\sin(q_1+q_2+q_3)$$

$$\sigma_2 = a_1\cos(q_1+q_2+q_3+q_4) + a_2\cos(q_1+q_2) + a_1\cos(q_1) \\ - a_0\sin(q_1+q_2+q_3+q_4+q_5) + a_2\cos(q_1+q_2+q_3)$$

Hence, position of the end-effector, tip of the foot, w.r.t the base is given by, $P_{end}^{base} = T_6^0 * P_{end}$

3.5.2 *Inverse Kinematics*

Inverse Kinematics is essential to determine the joint parameters as the exoskeleton will be controlled in task space. There are two major ways to determine the joint parameters in inverse kinematics: Analytical methods & Numerical methods. Inverse kinematics problem must be solved to control the configuration of the end-effector in the task space. Analytical method results in multiple solutions/configurations for the same end-effector pose, however, the numerical method results in a single convergent solution/configuration which is desirable. Hence, in the project, we will be using one of the numerical methods, the Newton-Raphson method, to determine the configuration of the exoskeleton for the given pose. However, to determine the solutions with the numerical method, one must understand the Jacobian matrix.

3.5.2.1 *Jacobian Matrix*

Jacobian matrix determines the relationship between the joint velocities and end-effector velocities of the exoskeleton. For a n-linked manipulator, Jacobian matrix is defined as,

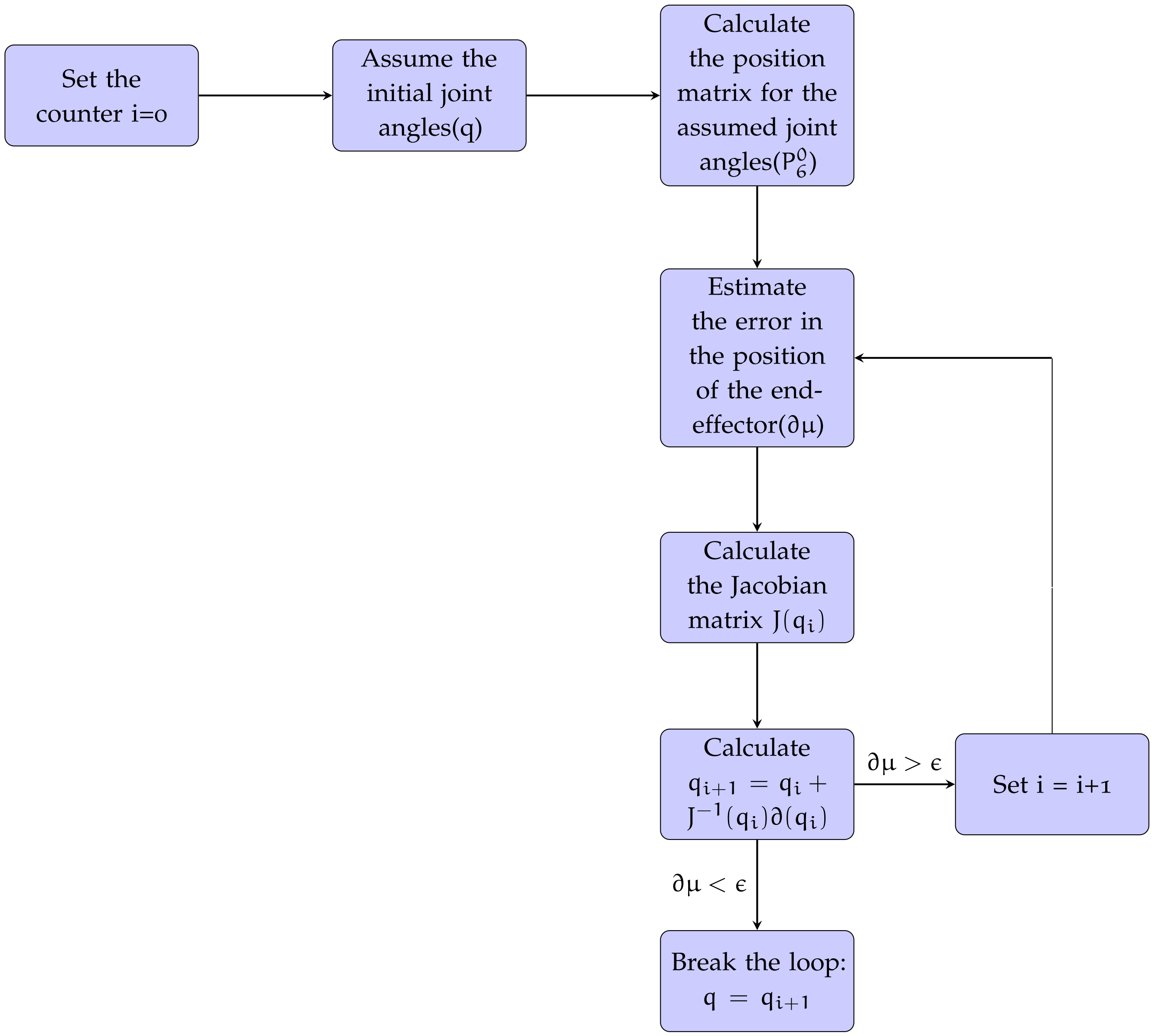
$$J = \begin{bmatrix} \frac{\partial P_n^0}{\partial q_1} & \frac{\partial P_n^0}{\partial q_2} & \frac{\partial P_n^0}{\partial q_3} & \frac{\partial P_n^0}{\partial q_4} & . & . & . & . & \frac{\partial P_n^0}{\partial q_n} \end{bmatrix} \tag{3.10}$$

From equations 3.9 and 3.10, the Jacobian matrix for the designed kinematic arrangement can be calculated.

3.5.2.2 *Newton Raphson Method :*

The most common method to find the inverse kinematic solution is the Newton Raphson method. In this iterative method, we assume the initial configuration/joint angles of the exoskeleton to find the zeroes of the transformation matrix. The algorithm for the Newton Raphson method is shown in the flow chart 3.5.

Figure 3.5: Newton Raphson Algorithm



4 RESULTS

Biped walking was simulated using various methods as discussed in chapter 3. Following geometric parameters were given as inputs to demonstrate walking :
Step length = 35 cm
Step height = 6.25 cm
Hip velocity = 2.5 cm/s
Simulation time = 10 s
Length of foot = 20 cm
Width of foot = 10 cm
Length of shank and thigh = 35 cm

4.1 CYCLOID TRAJECTORY METHOD

DH Parameters : DH parameters for the biped in cycloid trajectory method are given in the table 4.1

Table 4.1: DH Parameters

Link	θ_k	d_k	a_{k-1}	α_{k-1}
1	$\theta_1 + \pi/2$	0	$-a_0$	$\pi/2$
2	θ_2	0	a_1	0
3	θ_3	0	a_2	0
4	θ_4	0	a_2	0
5	$\theta_5 + \pi/2$	0	a_1	0
6	0	0	a_0	$-\pi/2$

4.1.1 *Configuration*

Baby Steps : An algorithm was developed to simulate the walking in a cycloid trajectory method with the help of inverse kinematics. It is observed that the walking is stable when the step length is less than the length of the foot. One of the snaps from the walking simulation is given below in figure 4.1. It can be concluded from the simulation that the CG always fall in between the foot, hence, walking is stable for smaller steps.

Longer Steps : An algorithm was developed to simulate the walking in a cycloid trajectory method with the help of inverse kinematics. It is observed that the walking is highly unstable when the step length is longer. One of the snaps from the walking simulation is given below in figure 4.2. It can be concluded from the simulation that the CG always doesn't fall in between the foot, hence, walking is unstable for longer steps.

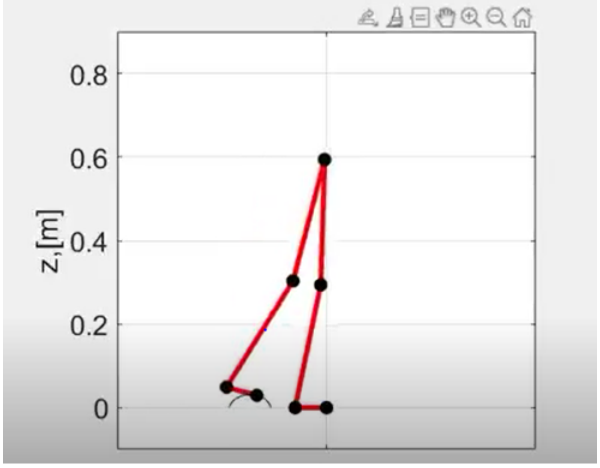


Figure 4.1: Snapshot from walking simulation - Baby steps

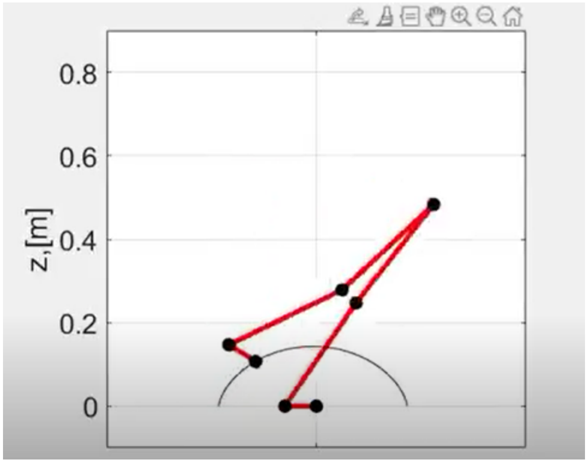


Figure 4.2: Snapshot from walking simulation - Longer steps

4.2 TRAJECTORY PLANNING METHOD

4.2.1 *Kinematic analysis of Stance Leg*

DH Parameters : DH parameters for the stance leg are given in the table 4.2

Table 4.2: DH Parameters for stance leg

Link	θ_k	d_k	a_{k-1}	α_{k-1}
1	$\theta_1 + \pi/2$	0	$-f$	$\pi/2$
2	θ_2	0	l_1	0
3	θ_3 - $\pi/2$	0	l_2	0
4	0	0	0	$-\pi/2$

Inverse Kinematics of stance leg : The hip joint of the stance leg follows a circular trajectory with the ankle joint as its center. Coordinates of the knee and hip joints w.r.t ankle joint can be calculated using inverse kinematics(analytical method). Joint positions and angles can be calculated w.r.t base at every instant as shown in figure 4.3

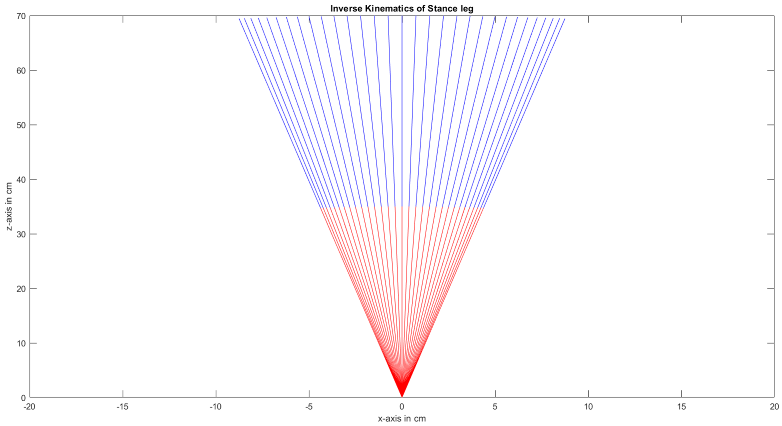


Figure 4.3: Joint positions of stance leg w.r.t base

4.2.2 *Kinematic analysis of Swing Leg*

DH Parameters : DH parameters for the swing leg are given in the table 4.3

Table 4.3: DH Parameters for swing leg

Link	θ_k	d_k	a_{k-1}	α_{k-1}
1	θ_1 - $\pi/2$	0	0	$\pi/2$
2	θ_2	0	l_2	0
3	$\theta_3 + \pi/2$	0	l_1	0
4	0	0	f	$-\pi/2$

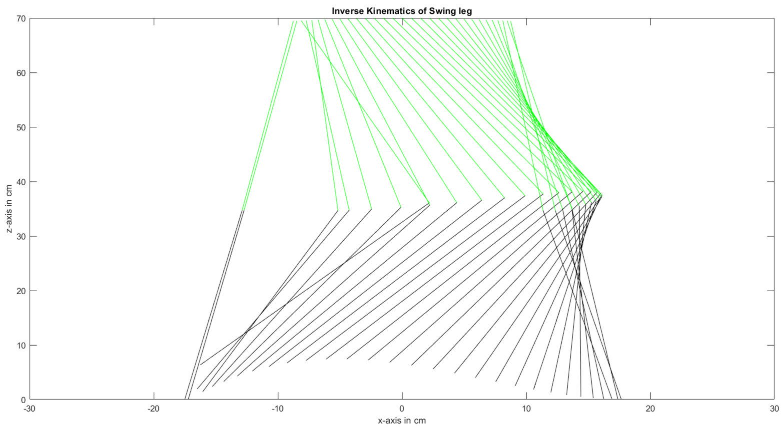


Figure 4.4: Joint positions of swing leg w.r.t base

Inverse Kinematics of swing leg : Ankle joint of swing leg follows a polynomial trajectory of the third degree. Coordinates of knee and ankle joints w.r.t hip joint can be calculated using inverse kinematics(Newton-Raphson method). Joint positions and angles can be calculated w.r.t base at every instant as shown in figure 4.4

4.2.3 *Inverse kinematics of biped*

Combined joint positions of biped w.r.t reference frame are shown in figure 4.5

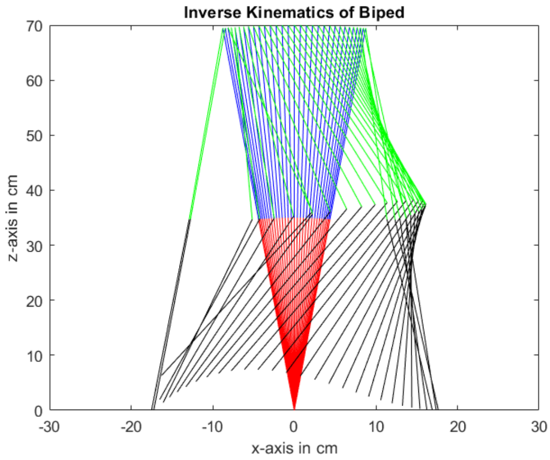


Figure 4.5: Joint positions of biped w.r.t reference frame

4.2.4 *Configuration*

An algorithm was developed to simulate the walking in trajectory planning method with the help of inverse kinematics. It is observed that the walking is stable irrespective of the step length. One of the snaps from the walking simulation is given below in figure 4.6. It can be concluded from the simulation that the CG always fall in between the foot, hence, walking is stable in this method.

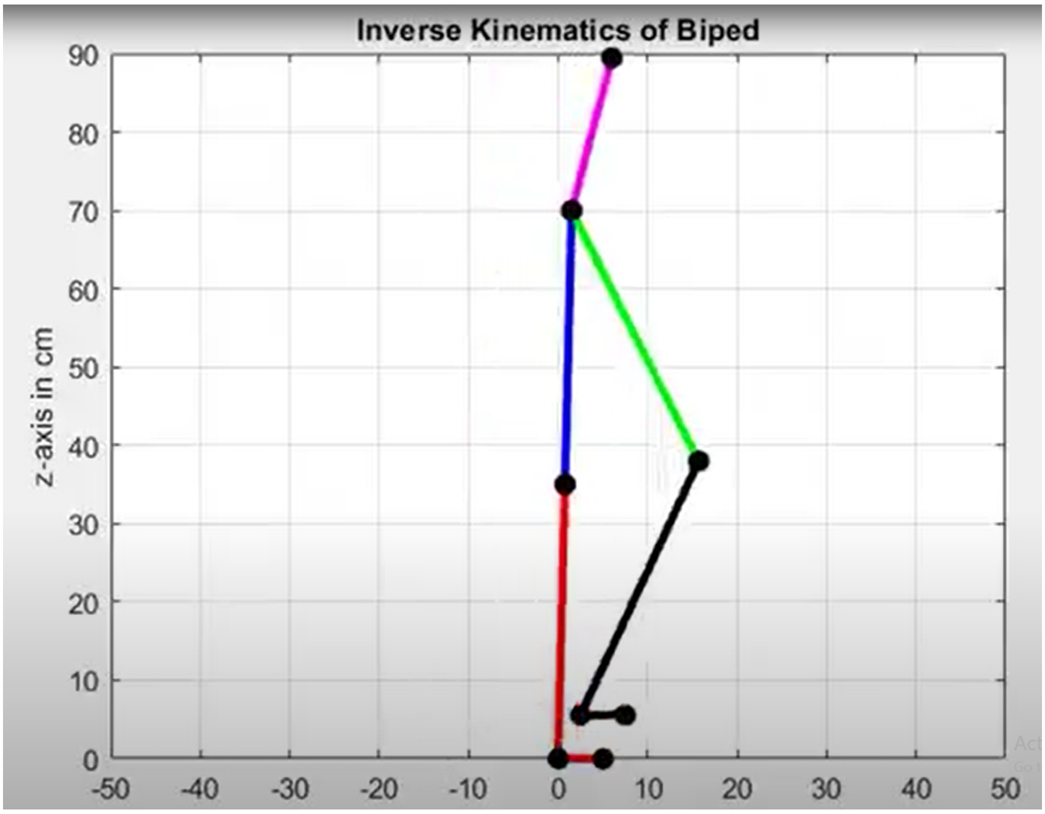


Figure 4.6: Snapshot from walking simulation - Trajectory Planning Method

4.3 CAD MODEL

As the walking simulation has been successfully stabilized, a 3-D CAD model was designed to implement the biped walking algorithm into the exoskeleton. The model was designed based on the average human size. Parameters were taken accordingly and designed an exoskeleton in Fusion 360 software.

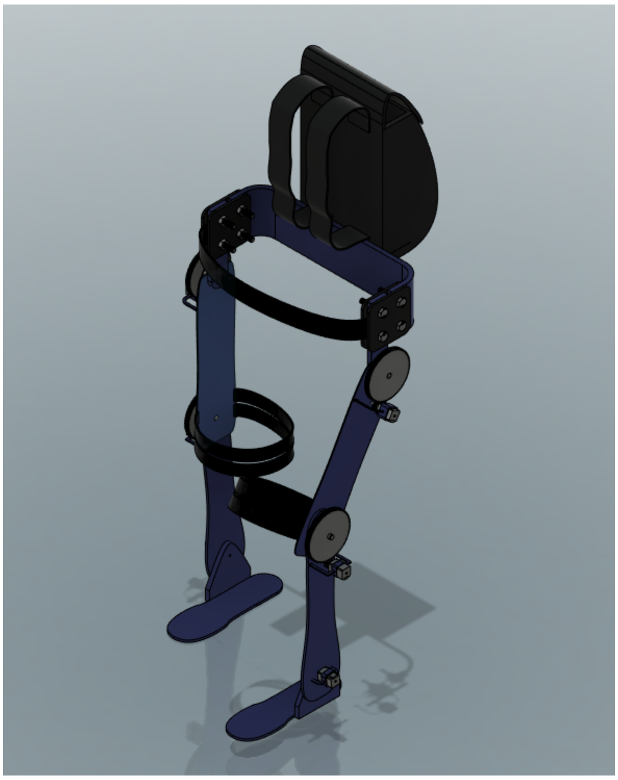
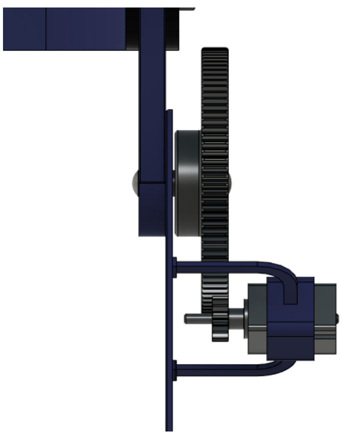
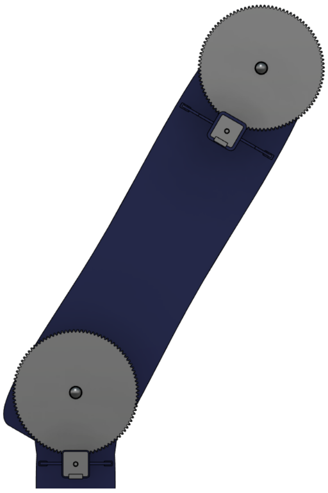


Figure 4.7: 3-D CAD model of the lower extremity exoskeleton

From the figure 4.7, designed exoskeleton has seven links with six flexion/extension joints. Each leg has three active joints with the speed reduction system using gears. The exoskeleton is designed to have a removable backpack with various compartments for sensors and payload.



(a) Front View



(b) Side View

Figure 4.8: Speed Reduction System using Gears

From the figure 4.9, it can be observed that the exoskeleton has elastic fixtures to connect the frame to the operator. Leg, knee, and ankle joints are revolute and the joint angles can be adjusted based on the requirement. Biped walking motion as discussed in the chapter 3 can be implemented in the exoskeleton with Simscape Multibody in MATLAB.

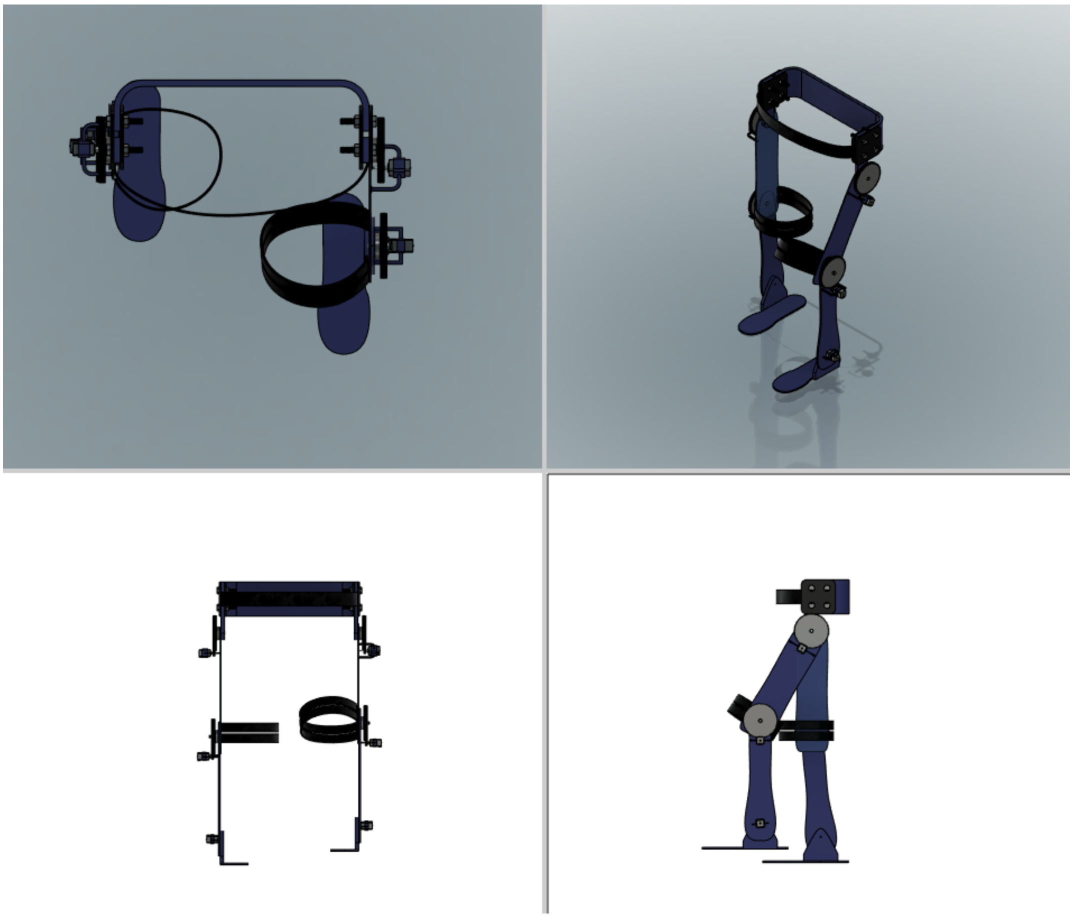


Figure 4.9: Orthogonal views of the exoskeleton

4.4 CONCLUSIONS

From the project, the following can be concluded :

1. Considering the right configuration is extremely important to analyze the kinematics and dynamics of the exoskeleton.

2. Forward and inverse kinematics were performed for various methods to stabilize the walking pattern. ZMP-CPG method proved to have stable walking on all the terrains, however, it is extremely complicated and involves various parameters. Hence, we restricted our objective to stabilize the walking on flat terrains. Therefore, the trajectory planning method resulted in stable walking irrespective of the step length among the other methods.

3. A 3-D CAD model of the exoskeleton was designed in modeling software. As the electric DC motors operate at higher speeds, a speed reduction system was designed using gears.

4.5 CONTRIBUTION

Initially as per the objectives we divided our work. There were many instances when we have done complete work and got struck due to some reasons, and, this made us to start again from the beginning and we learnt many new-things. Almost we have shared the work equally among ourselves. To be specific,

1. We together have done the Literature Review almost for two weeks
2. The main part for powered exoskeleton is motion planning in which we divided the work separately. Rithwik worked on methods to find the trajectory and I developed an algorithm for the trajectory planning accordingly.
3. Later Rithwik did the theoretical approach in calculating the kinematics of exoskeleton and I helped in analyzing even more using the forward and inverse kinematics which are the major subsections in Kinematics.
4. Later in the algorithm we found some errors in using the size of foot steps so we altered and performed the simulation for smaller steps and we repeated the simulation again.
5. Finally we developed together the CAD model of exoskeleton.

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