WAIST ASSISTIVE WEARABLE POWERED EXOSKELETON FOR ARMED PERSONNEL

BTP REPORT PHASE I

submitted by

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under the Guidance of

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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 (Roll No. 131701018)*** 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.

M. Santha

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ABSTRACT

Armed Personnel works in a harsh environment, extreme temperatures, and walk on uneven terrains for miles with a heavy backpack. 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. The exoskeleton is a wearable device that enhances the strength and the performance of the operator. Exoskeletons are collaborative, hence they are evolving rapidly in all the fields, medical, military, industrial, and civilian. In this project, we aim to design a lower extremity, waist-assistive powered exoskeleton for the enhancement of strength and agility of the military personnel carrying heavy payloads.

Keywords: Exoskeleton, Lower Extremity, Payload, Strength, Waist-assistive

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1 INTRODUCTION

An exoskeleton is a rigid, external, and supporting cover of the body used for protection and strength enhancement. It is a wearable device that contains a framework wrapping the user's body. An exoskeleton consists of a frame that plays a similar role as of 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 the 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.

1.1 LITERATURE REVIEW

The very first exoskeleton was built in 1890 by Nicholas Yagn [5]. 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 [2]. 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 [6]. Later, many exoskeletons have been developed such as HULC, SuitX, HAL, and so on. Exoskeletons are slowly emerging outside of labs to medical patients, rehabilitation centers, and the military. 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.

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 [1]. 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 on the existing exoskeletons and design an exoskeleton that could enhance the strength of the personnel.

1.3 OBJECTIVES

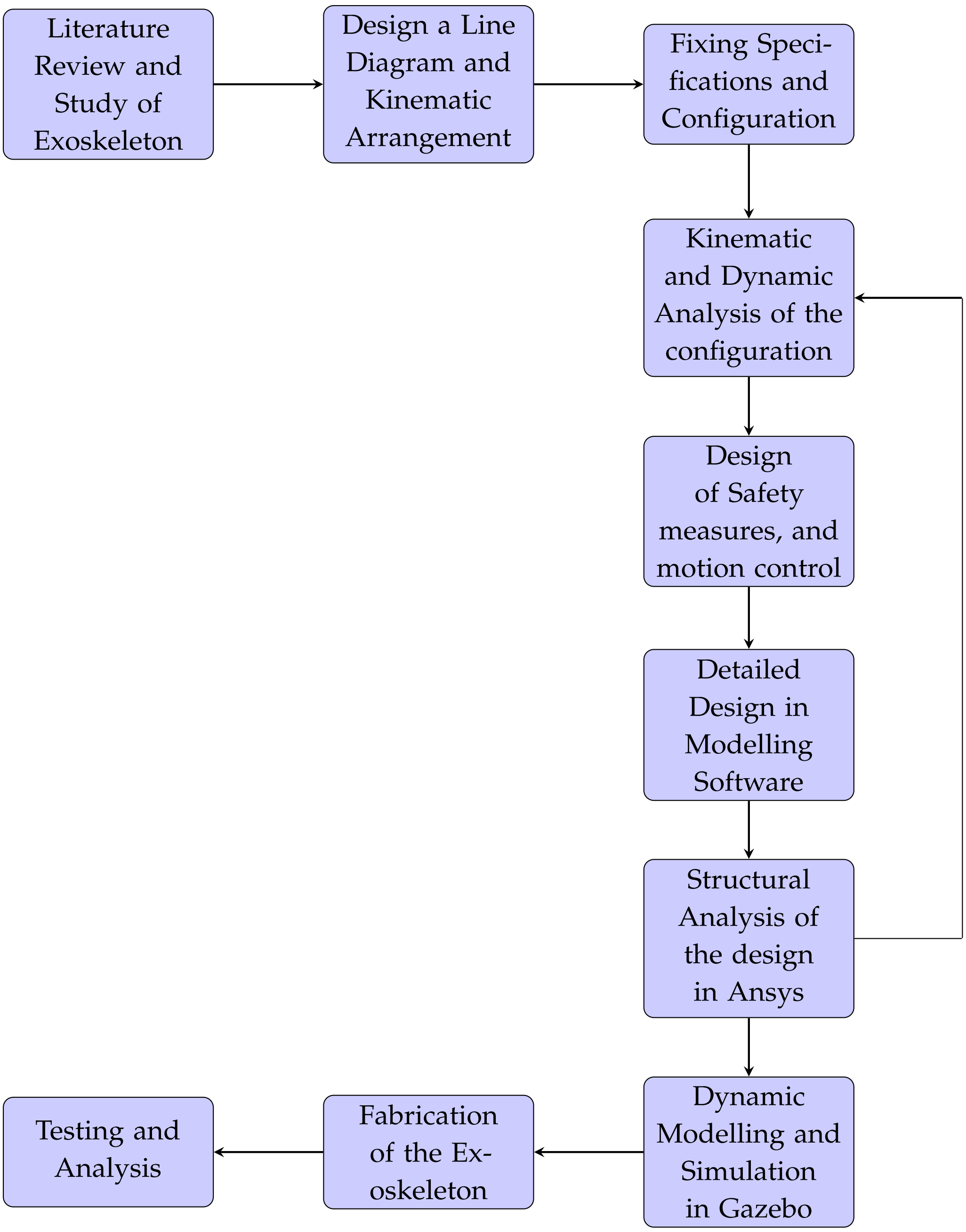
The primary objectives of the project are mentioned below:

1. To design a waist assistive lower extremity exoskeleton to enhance the strength of armed personnel
2. Structural Analysis of the framework in FEM
3. To develop a dynamic model for the exoskeleton and simulate it in Gazebo
4. To fabricate and test the designed exoskeleton

1.4 METHODOLOGY

The methodology of the project and the approach to the project is depicted in the flow chart 1.1.

Figure 1.1: Flow Chart for the methodology



2 THEORETICAL BACKGROUND

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, 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 hips to toes, whereas the upper body covers the rest of the body. The lower body has a hip, knee, and ankle joints. Every joint has some extent to which the joint can be moved. It is termed as Range of Motion. Active range of motion is the range of motion when no external force is applied to the joint, whereas the 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.

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.

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 [3]. 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 FORCE ANALYSIS

Forces experienced by the frame can either be internal or external. However, the analysis of internal forces is performed in simulation software. External forces are the forces exerted by the operator, by the joints, by the payload, and by the floor. Force analysis is essential to estimate the gait. Dynamic force analysis is performed when the system is moving. However, owing to the complex calculations, static force analysis is performed. The error can be rectified by multiplying the static forces by a factor of 2. Static force analysis is performed by considering all the worst-case scenarios.

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°	

2.5 STATIC BALANCE

Static balance is essential in designing an exoskeleton. Hence, it is important to find out Zero Moment Point(ZMP) to avoid the imbalance of the exoskeleton. ZMP is a contact point on foot, where all the forces balance and don't produce any moment in a horizontal direction. Sum of the moments and forces due to horizontal inertia and gravity nullifies at the ZMP.

2.6 GAIT ANALYSIS

Human gait refers to locomotion achieved through the movement of human limbs [4]. Differences in human gait and exoskeleton gait arises 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.

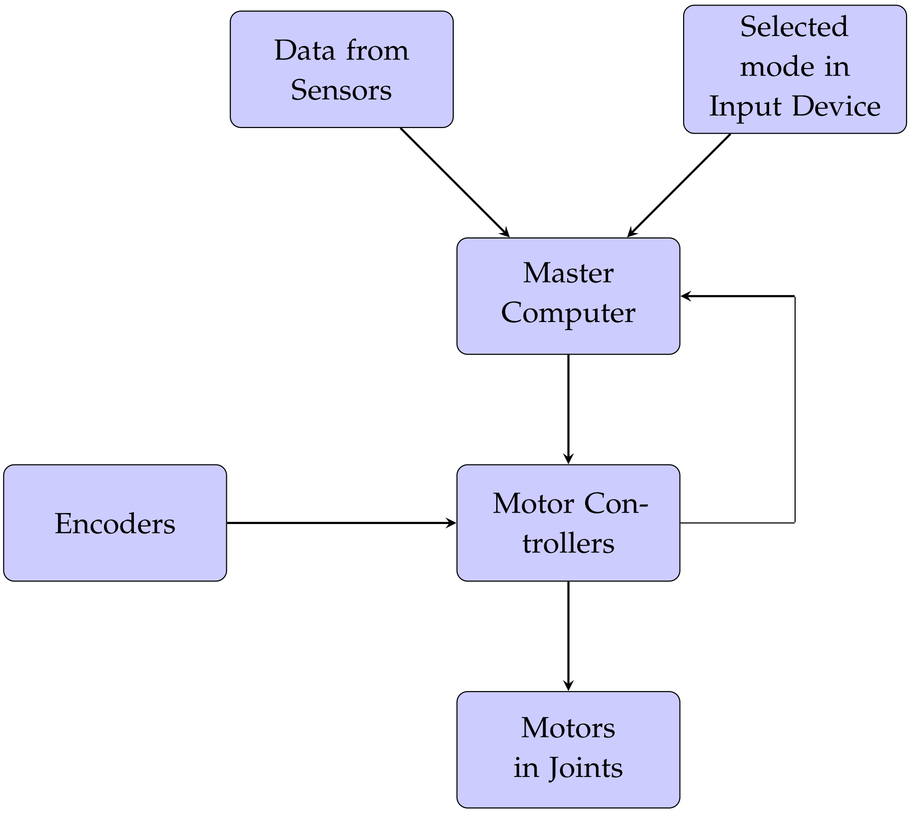
2.7 GAIT CONTROL

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.

2.8 DATA ANALYSIS IN EXOSKELETON

Data needs to be actively collected, analyzed, and distributed by the master computer to the controllers to achieve the desired trajectory. As shown in the flowchart 2.1, the master computer collects the data from the sensors, input device, and motor controllers. The data received are analyzed, calculated, and sent back to the motor controllers.

Figure 2.1: Data Analysis by Master Computer



2.9 SAFETY MEASURES

Safety is the utmost priority when it comes to the exoskeleton. Safety measures need to be taken to avoid the danger caused by the exoskeleton. The following precautions must be taken to ensure safety.

1. Emergency button to disable the high voltage power supply to the motors
2. Frame should be designed in such a way that the pilot doesn't end up in an uncomfortable position
3. Measure to shut down the system in the case of overheating
4. Gait needs to be checked at every instant so that trajectories don't exceed the maximum speed and acceleration of the joints.
5. When the joint reaches the limit, it is not supposed to move with maximum velocity in the direction of the limit.

3 WORK PROGRESS : KINEMATIC ANALYSIS

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 has been assumed to calculate the joint angles and trajectories. The figure 3.1 represents the exoskeleton in the double stance phase. It is assumed to have 6-links with 5 active joints at hip, knee & ankle. We analyze the simplified model to determine the pose and configuration of the exoskeleton.

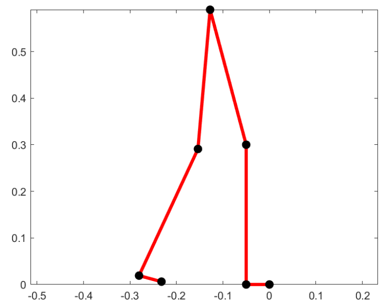


Figure 3.1: Simplified 2-D Exoskeleton Model

3.1 FORWARD KINEMATICS

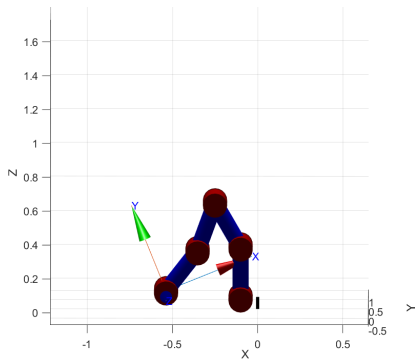


Figure 3.2: Line Diagram of the 2-D Exoskeleton

Line Diagram specifies the arrangement of the links and joints in a simplified model. Figure 3.2 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.

Kinematic arrangement defines the coordinate systems & convention for the given configuration to develop mathematical quantities that represent position and orientation. Figure 3.3 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, the human body exhibits swing and stance phases alternatively. Hence, the foot tip of the left leg(stance phase) is

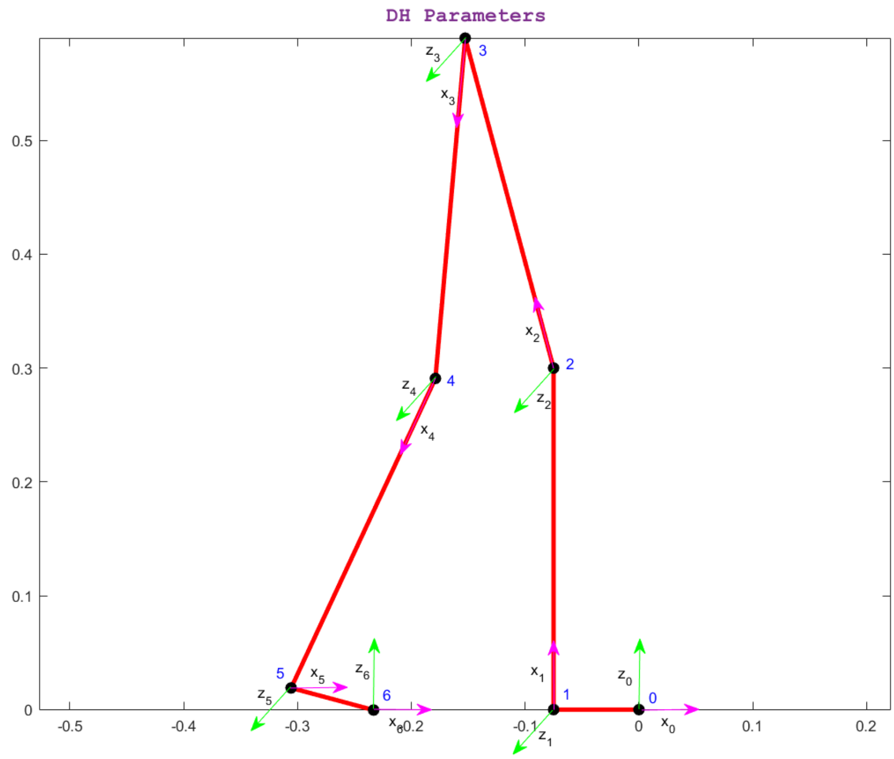


Figure 3.3: Kinematic Arrangement of the 2-D Exoskeleton

Table 3.1: 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	$-\pi/2$

assumed as the base and the foot tip of the right leg(swing phase) is assumed as the end-effector in the given configuration.

3.1.1 *DH Parameters*

DH parameters for the assumed kinematic arrangement are given by the table 3.1, 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.

3.1.2 *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 matrices are defined below:

$$T_1^0 = \begin{bmatrix} -\sin(q_1) & \cos(q_1) & 0 & -a_0 \\ 0 & 0 & -1 & 0 \\ -\cos(q_1) & -\sin(q_1) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.1}$$

$$T_2^1 = \begin{bmatrix} \cos(q_2) & -\sin(q_2) & 0 & a_1 \\ \sin(q_2) & \cos(q_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

$$T_3^2 = \begin{bmatrix} \cos(q_3) & -\sin(q_3) & 0 & a_2 \\ \sin(q_3) & \cos(q_3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.3}$$

$$T_4^3 = \begin{bmatrix} \cos(q_4) & -\sin(q_4) & 0 & a_2 \\ \sin(q_4) & \cos(q_4) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.4}$$

$$T_5^4 = \begin{bmatrix} -\sin(q_5) & \cos(q_5) & 0 & a_1 \\ -\cos(q_5) & -\sin(q_5) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.5}$$

$$T_6^5 = \begin{bmatrix} 1 & 0 & 0 & a_0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.6}$$

From equations 3.1, 3.2, 3.3, 3.4, 3.5 & 3.6, we can find the transformation matrix of the end-effector w.r.t the base.

$$T_6^0 = T_1^0 * T_2^1 * T_3^2 * T_4^3 * T_5^4 * T_6^5$$

$$T_6^0 = \begin{bmatrix} \text{-}\cos(q_1+q_2+q_3+q_4+q_5) & 0 & \sin(q_1+q_2+q_3+q_4+q_5) & \sigma_1 \\ 0 & 1 & 0 & 0 \\ \text{-}\sin(q_1+q_2+q_3+q_4+q_5) & 0 & \text{-}\cos(q_1+q_2+q_3+q_4+q_5) & \sigma_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.7}$$

$$P_6^0 = \begin{bmatrix} \sigma_1 \\ 0 \\ \sigma_2 \end{bmatrix} \tag{3.8}$$

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, $P_{end}^{base} = T_6^0 * P_{end}$

3.2 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, 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.

3.2.1 *Jacobian Matrix*

Jacobian matrix determines the relationship between the joint velocities and end-effector velocities of the exoskeleton.

$$J = \begin{bmatrix} \frac{\partial P_6^0}{\partial q_1} & \frac{\partial P_6^0}{\partial q_2} & \frac{\partial P_6^0}{\partial q_3} & \frac{\partial P_6^0}{\partial q_4} & \frac{\partial P_6^0}{\partial q_5} \end{bmatrix} \tag{3.9}$$

From equations 3.8 and 3.9, Jacobian matrix for the designed kinematic arrangement is given by,

$$J = \begin{bmatrix} \sigma_1 - \sigma_7 - a_1 \cos(q_1) - \sigma_3 - \sigma_5 & \sigma_1 - \sigma_7 - \sigma_3 - \sigma_5 & \sigma_1 - \sigma_3 - \sigma_5 & \sigma_1 - \sigma_3 & \sigma_1 \\ 0 & 0 & 0 & 0 & 0 \\ -\sigma_4 - \sigma_8 - a_1 \sin(q_1) - \sigma_2 - \sigma_6 & -\sigma_4 - \sigma_8 - \sigma_2 - \sigma_6 & -\sigma_4 - \sigma_2 - \sigma_6 & -\sigma_4 - \sigma_2 & -\sigma_2 \end{bmatrix}$$

where,

$$\sigma_1 = a_0 \sin(q_1 + q_2 + q_3 + q_4 + q_5)$$

$$\sigma_2 = a_0 \cos(q_1 + q_2 + q_3 + q_4 + q_5)$$

$$\sigma_3 = a_1 \cos(q_1 + q_2 + q_3 + q_4)$$

$$\sigma_4 = a_1 \sin(q_1 + q_2 + q_3 + q_4)$$

$$\sigma_5 = a_2 \cos(q_1 + q_2 + q_3)$$

$$\sigma_6 = a_2 \sin(q_1 + q_2 + q_3)$$

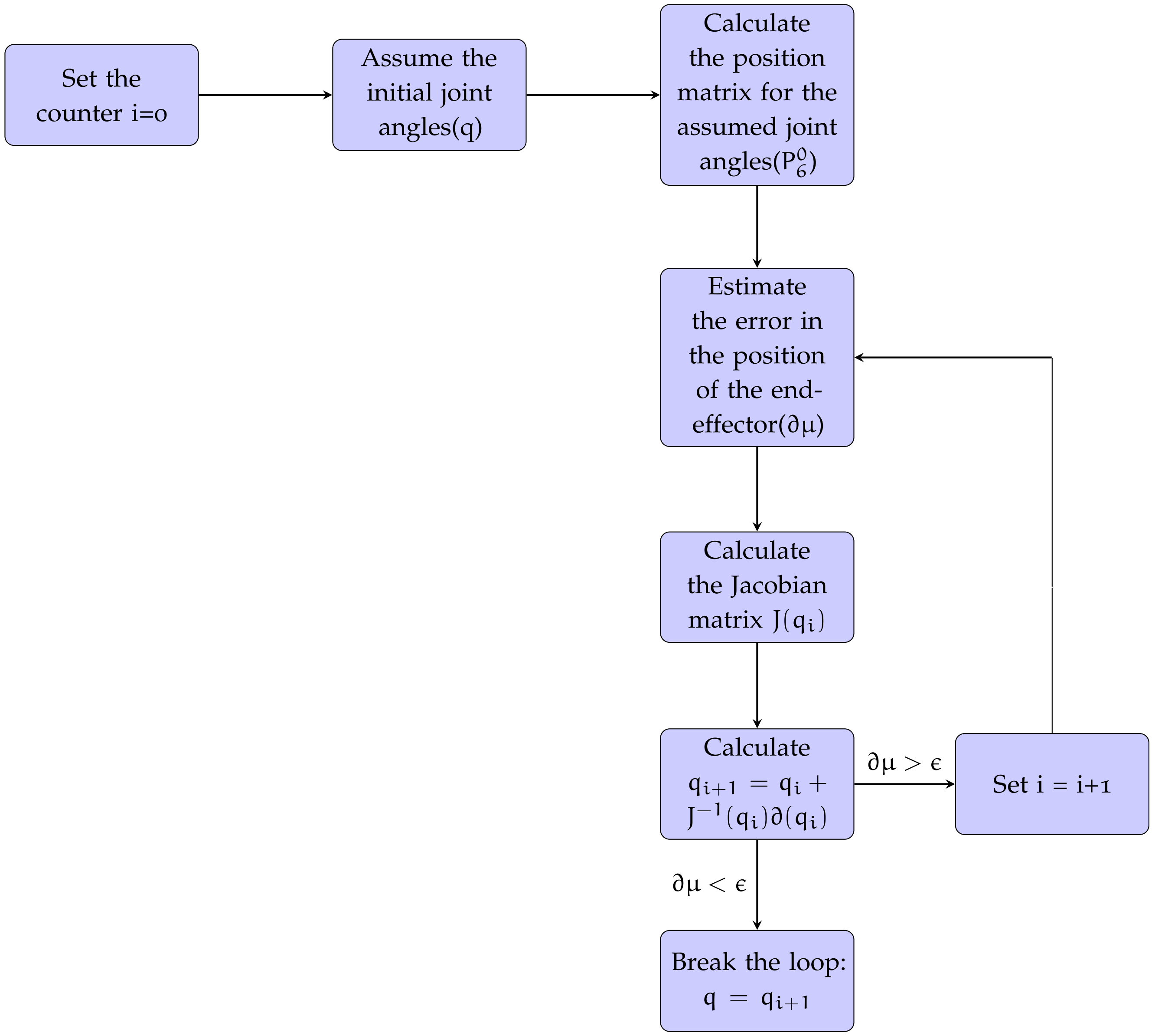
$$\sigma_7 = a_2 \cos(q_1 + q_2)$$

$$\sigma_8 = a_2 \sin(q_1 + q_2)$$

3.2.2 *Newton Raphson Method :*

The most common method to find the inverse kinematic solution is the Newton Raphson method. In this iterative method, we assume 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 3.4.

Figure 3.4: Newton Raphson Algorithm



3.3 GAIT TRAJECTORY

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. Consider the left leg to be at stance phase as shown in figure 3.5. 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

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

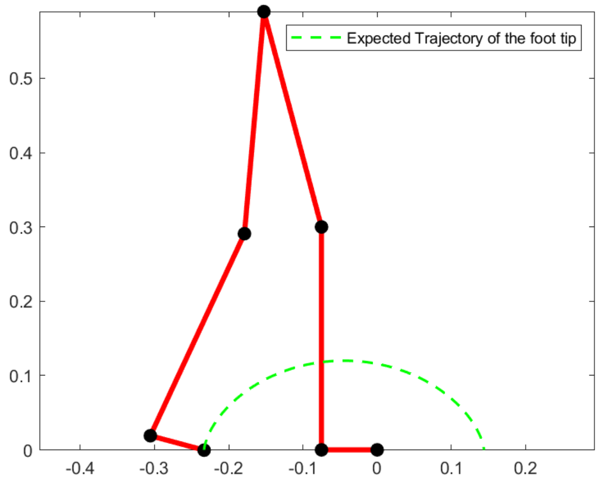


Figure 3.5: Cycloid trajectory at the tip of the foot

3.4 CONCLUSION

Forward and inverse kinematic analysis have been performed and the walking motion of the exoskeleton in 2-D has been simulated. In phase II, we would work on the dynamic analysis of the exoskeleton and model it in CAD.

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