A REPORT ON

DESIGN AND CONTROL OF ACTIVE UPPER BODY EXOSKELETON

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Abstract

Soldiers often have to carry out repetitive tasks like loading and unloading a truck. Constant lifting of such heavy loads puts stress on the arms, back and hips and can be detrimental to the soldier's health. An upper body exoskeleton is the proposed solution to this problem. The exoskeleton will provide assistance to the soldier while carrying out the lifting and unloading tasks. The assistance will be provided with the help of actuators and other assistive sensors.

To determine the different ranges for the different joints involved in the motion and the values of torque and forces, the motion capture of 100 soldiers was studied at different walking speeds and with different weights. The simulation of the activity was carried out using Simulink in Matlab.

Based on the inferences drawn from studying the data, various sensors and actuators were selected to be used in the exoskeleton.

Ideally the exoskeleton should be able to move in perfect harmony with the wearer but practically this is not possible to achieve. Therefore the best we can do is aim to reduce the error as much as possible and prevent the exoskeleton from acting out sporadically causing harm to the wearer.

Using the data we were able to arrive at the expected torque and power of the actuator we would need for the exoskeleton. The required power was found to be around 50.5 W considering a factor of safety of around 1.5. Along with this a control system using the genetic algorithm to tune the PID is also presented.

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Nomenclature

$\boldsymbol{\tau}_i$ = Input torque of the motor in N-m
$\boldsymbol{\tau}_o$ = Output torque in N-m
ω_a = Rotational velocity of armature
$\Omega_a(s)$ = Laplace transform of ω_a
B = Damping coefficient
GR = Gear Ratio
i_a = Current through the armature coil
$I_a(s)$ = Laplace transform of i_a
J = Rotor inertia
K_t = Torque Constant
K_v = Speed/Velocity Constant
L_a = Inductance due to armature coil in series
N_i = Input speed of motor in rpm
N_o = Output speed in rpm
P = Power
R_a = Resistance due to armature coil
$T_{\omega 1}$ = Torque due to rotational acceleration of the rotor
T_{ω} = Torque due to rotational velocity of the rotor
T_e = Electromagnetic Torque
T_L = Torque due to mechanical load
$T_L(s)$ = Laplace transform of T_L
V_a = Voltage Source-across armature coil
$V_a(s)$ = Laplace transform of V_a
V_c = Back EMF
V_{La} = Voltage across inductor
V_{Ra} = Voltage across resistance

Abbreviations

DOF = Degrees of Freedom
FOS = Factor of Safety
HAL = Hybrid Assistance Robot
DARPA = Defence Advanced Research Projects Agency
ROM = Range of Motion
AI = Artificial Intelligence
COR = Centre of Rotation
DPL = Double Parallelogram
IMU = Inertial Measurement Unit
AA = Abduction and adduction
EF = Extension and flexion
IE = Internal and external rotation
PS = Pronation and supination
RU = Ulnar and radial movement/deviation
EMG = Electromyography
sEMG = Surface electromyography
phRI = Physical human robot interaction
FSR = Force sensitive resistors

Chapter 1-Introduction

An exoskeleton is an external skeleton which supports and protects an animal's body and is found commonly in nature in insects like grasshoppers and cockroaches. Taking inspiration from nature mankind has endeavored to build similar exoskeletons for themselves to enhance our physical capabilities.

Exoskeletons designed for humans are designed to work in tandem with the wearer and provide assistance, decrease effort and increase their strength. The main aim of an exoskeleton in the defense domain is to reduce fatigue and injuries experienced by the troops thereby increasing overall productivity.

Exoskeletons can be categorised based on their structure, body part focused on, the action, power technology, purpose and the domain of application. A more elaborate classification is as follows:

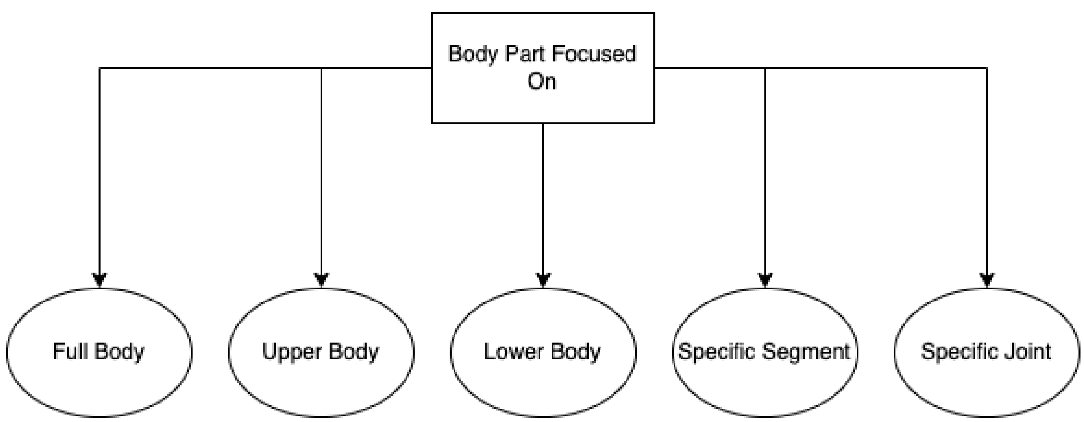

Fig 1. Classification of exoskeleton based on body part of focus

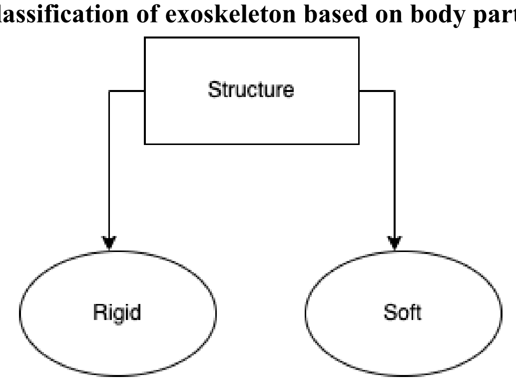

Fig 2. Classification of exoskeleton based on structure

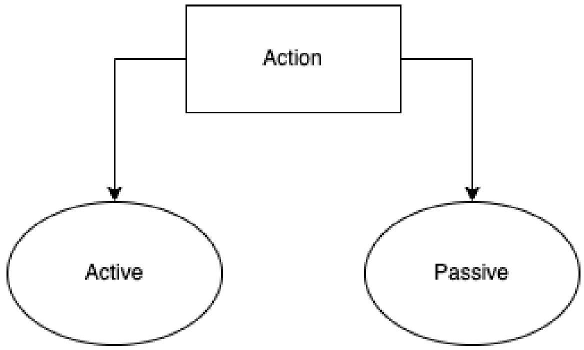

Fig 3. Classification of exoskeleton based on action

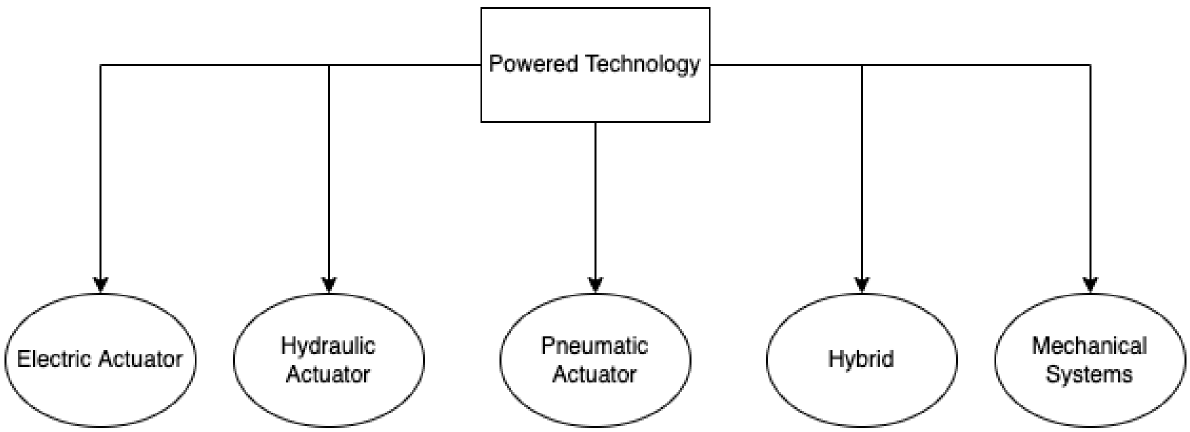

Fig 4. Classification of exoskeleton based on the powering technology

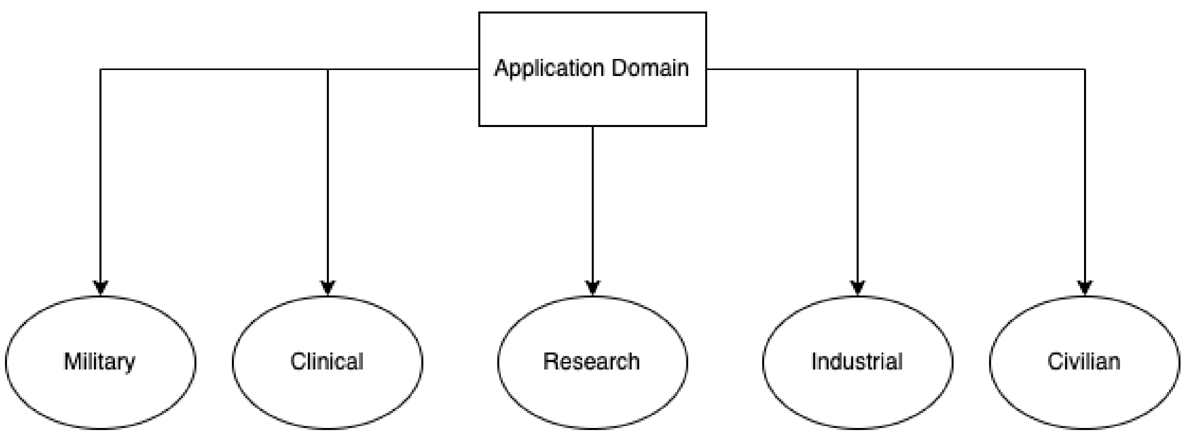

Fig 5. Classification of exoskeleton based on the domain of classification

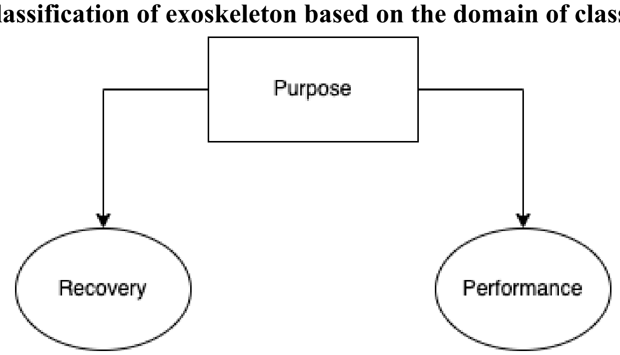

Fig 6. Classification of exoskeleton based on the purpose

The major classification is based on the action, i.e., between active and passive exoskeletons[1]. The active exoskeletons provide assistance using actuators and controllers and run on an external source of power, whereas the passive exoskeletons assist the wearer using springer and damper systems and do not require any external power to operate.
Despite the active exoskeletons being more complex to build than the passive ones, they are preferred over passive exoskeletons due to their ability to provide an accurate amount of assistance depending on factors like load and the wearer's ability to lift[1]. This provides a more smooth and less restrictive movement.
Another major classification is based on the structure being rigid or flexible. While rigid exoskeletons are easier to make, flexible exoskeletons can be worn more comfortably and for long periods of time.

Some of the major use cases of the exoskeleton are in the medical, manufacturing and defence industries.
The medical industry has found exoskeletons to be very useful in rehabilitation therapy in aiding patients who have lost function of their limbs partially or completely[2].
The manufacturing industry has introduced exoskeletons in their factory divisions to provide assistance to workers carrying out repetitive tasks which could be injurious to their bodies in the long run. For example a worker deployed in warehouses to shift heavy objects from one point to another would find it easier to carry out the task with assistance from an exoskeleton.
Exoskeleton deployment in the defence industry is still relatively new. This is because it is difficult to develop an exoskeleton which can be deployed in active combat situations without risk of malfunction[2]. Mostly the development of exoskeletons in the defence industry are aimed at reducing fatigue experienced by a soldier and allowing them to carry heavier payloads for longer distances.

1.1 History

The earliest known exoskeleton-like device was developed by a Russian engineer Nicholas Yagin in 1890 for the purpose of assistance in movement. The exoskeleton was passive in nature, i.e. it wasn't functioning on power acquired from external sources and required the wearer to provide the power[1].

The next famous exoskeleton was developed in 1917 by American inventor Leslie C. Kelley. Kelley called his device the pedometer and it operated on steam power with artificial ligaments acting in sync with the wearer's movements. This was the first active exoskeleton based on historical records.

The first modern exoskeleton was the Hardiman, co-developed by General Electric and the US Armed Forces. This suit was powered by both hydraulics and electricity and amplified the wearer's strength by a factor of 25. The suit had force feedback, enabling the wearer to feel the forces and objects being manipulated[2].

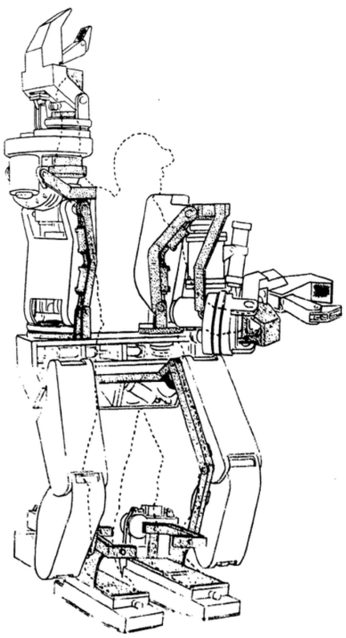

Fig 7. Prototype of Hardiman[3]

Some drawbacks of the Hardiman were as follows[3]:

- The weight of the Hardiman was around 680kg.
- There was a lot of latency between the wearers movements and the suits movements, along with a few bugs causing violent and uncontrollable motion.
- The speed of the suit was 0.76 m/s, which further limited its use in real world applications.

At about the same time in Yugoslavia, at the Mihajlo Pupin Institute active exoskeletons and humanoid robots were being developed. Legged locomotion systems were developed first, with the aim of helping in rehabilitation of paraplegics. In 1972, a pneumatically powered and electrically programmed to aid paraplegics in rehabilitation was tested at the Belgrade Orthopedic Clinic[1].

In 1997 Hybrid Assistance Robot (HAL) was being developed in Tsukuba University, Japan. The 5th version of HAL was finished in the year 2012 which is a full body exoskeleton. HAL was designed with the purpose of augmenting the strength of the wearer and assisting the elderly in their daily tasks. BLEEX, a 7 DOF lower limb exoskeleton developed in 2006 as the most prominent Defence Advanced Research Projects Agency (DARPA) project. BLEEX used hydraulic actuators and was aimed at significantly augmenting the wearer's strength. There have been many exoskeletons over the years pushing forward the research and development for applications ranging from strength augmentation to rehabilitation of limbs. Some of the most advanced exoskeletons available include SIAT-WEXv2, Harmony, etc[2].

1.2 Design Issues in Exoskeletons

Due to the mass complexity of the exoskeleton there are a few problems in building a device which could be used effectively. Some of the major design issues are:

- **Power Supply -** This is a major problem when the use case of the exoskeleton is out in the field and can’t be physically tethered to a power source. Batteries can be used but they need to be charged and replaced frequently. Also batteries have the additional risk of being prone to exploding in the battlefield. Hydrogen cells are also being considered as an alternative source of energy but the research is still at an early stage[1].
- **Skeleton Structure -** Early models of exoskeletons were built using inexpensive materials like aluminium and steel which are easy to mold. But the primary drawback of using steel is its weight. Due to the heaviness, the powered exoskeleton will require more energy to overcome its own weight thereby reducing the efficiency. Aluminium alloys are lightweight but fail through fatigue quickly. Newer exoskeletons are experimenting using carbon fiber, fiberglass and carbon nanotubes to build the skeletal structure. Soft exoskeletons are also under development which use motors and control systems which can be attached to regular clothing[1].
- **Actuators -** Joint actuators also face the challenge of being lightweight and powerful. Some of the technologies commonly used in the industry are pneumatic activators, hydraulic cylinders and electronic servomotors. Research is being done on the feasibility of elastic actuators[1].
- **Joint Flexibility -** The human anatomy is unique for each person thus making it near impossible to mimic all the degrees of freedom for a joint. Because of this exoskeleton joints are designed as a series of hinges with one degree of freedom for each of the dominant rotations[1].

- **Power Control and Modulation -** The main aim of an exoskeleton is to assist the user. Due to the uniqueness in the motion of each human being it becomes difficult to build a standardized device to provide the appropriate amount of assistance at the right time. Algorithms to tune control parameters to automatically optimize the energy cost of walking are under development. Direct feedback between the human nervous system and motorized prosthetics has also been implemented in a few high-profile cases[1].

1.3 Scope and Future of the Exoskeleton

Since the concept of wearable robots is still very new, the scope to grow is very huge. Some of the recent advances made in the field are as follows:

- **Soft Exoskeletons -** Many exoskeleton companies are moving away from the rigid, metallic exoskeleton designs and are working on creating soft exoskeletons. The soft exoskeletons consist of fabric and flexible, artificial muscles. They can be very light and offer more range of motion (ROM) when compared to their metallic counterparts. Discovery of new soft materials like microlattice don’t have to sacrifice safety for mobility making the soft exoskeleton a viable tool for workplace protection. Due to their soft nature these exoskeletons look and feel like clothes and can be worn for long periods of time without causing any hindrances[4].
- **Passive and Pseudo-passive Exoskeletons -** Power consumption is a major problem when dealing with mobile robots. A proposed solution to this is the use of passive exoskeletons which don’t use any electricity at all, instead relying completely on mechanical energy to assist the wearer. A similar solution is the pseudo-passive design, which injects small amounts of power to bolster the otherwise passive exoskeleton. This alternative provides only when needed and can be designed with smaller rotors and run for longer thereby maximising energy efficiency[4].
- **Artificial Intelligence (AI) and Smart Sensors -** AI and connected sensor technology have also recently become a part of the exoskeleton design. In these designs, sensors throughout the exoskeleton gather data on the current state and the user’s physiological state. The AI then interprets this data and fine tunes the exoskeleton as necessary to deliver optimal performance. Some researchers have managed to create exoskeletons that adjust their torque to optimize the wearer’s running and walking economy based on the metabolic data[4].

1.4 Literature Review

In this section a brief discussion on existing exoskeleton designs and research being carried out in this domain is presented explaining the advantages, disadvantages and implementation.

The purpose of an exoskeleton is to replicate the kinematics and dynamics of human musculoskeletal structure and to thus support the limb's motion, which is challenging with the existing mechanisms and mode of actuation. Due to the complex anatomical structure, there is not a unanimous kinematic model available for the human upper limb in the biomechanics literature that could help us to design exoskeletons. Because of this it is very important to study human anatomy before developing the exoskeleton[5].

The complicated skeletal anatomy of the human upper limb includes the shoulder complex, elbow complex, wrist joint, and fingers. The shoulder is made up of four articulations that are formed by three bones: the clavicle, scapula, and humerus. The glenohumeral joint, which is created by the articulation of the humeral head and the glenoid cavity, is frequently referred to as a ball socket joint[6]. To simulate a three degrees of freedom (DOF) shoulder mechanism, most researchers have solely considered the glenohumeral joint. The glenohumeral joint, on the other hand, has an instantaneous centre of rotation (COR) that varies when the human upper limbs move. As a result, when modelling the exoskeleton shoulder mechanism, it is critical to account for the effect of the dynamic centre of rotation. Shoulder abduction/adduction, internal/external rotation, and shoulder flexion/extension are the main movements of the shoulder complex[7].

The humeroradial and humeroulnar joints make up the elbow joint, which is a synovial composite joint. The ball socket joint produced by the humerus in the upper arm and the radial in the forearm is known as the humeroradial joint. However, because of its strong resemblance to the humeroulnar joint and the proximal radioulnar articulation, the joint can only move in two directions. The elbow joint provides for forearm extension, flexion, and supination/pronation in general. Most of the exoskeletons found in the literature have modelled the elbow joint exclusively for 1-DOF flexion/extension[7].

Some of the latest exoskeletons designs used for motion assistance are as follows:

- **AAU Upper Body Exoskeleton -** This is a four DOF upper limb exoskeleton with a novel shoulder mechanism for assistive applications. The unobtrusive feature of this exoskeleton is the double parallelogram (DPL) spherical mechanism, which was designed to support 3-DOF shoulder glenohumeral movements. The exoskeleton structure with the DPL mechanism can actively support the shoulder extension/flexion and shoulder abduction/adduction, whereas the shoulder rotation was kept passive, which limits its use for several applications[2].

- **Compliant Robotic Upper-Extremity eXosuit (CRUX) -** The CRUX suit was a proposed design of a soft exosuit for upper limb rehabilitation. The study has identified the drawback of classical rigid body exoskeletons and their inability to comply with natural human body movements in a flexible way. Thus, it is highly required to design a flexible and compliant exoskeleton that can conform to the nonlinear musculoskeletal structure. Based on these requirements, a tensegrity design of upper-limb exoskeleton was proposed and a cable-driven mechanism was used to transmit the power mechanically. There is no comprehensive study measuring the effectiveness of CRUX for the active assistance and the design needs some additional degrees of freedom to adopt actual human biomechanics[2].
- **Stuttgart Exo-jacket -** The Stuttgart Exo-jacket was proposed for motion assistance in industrial applications by considering the ergonomic aspects. The exoskeleton was designed to actively support the extension and flexion of the shoulder and elbow joint. Based on these requirements, the human upper-body dynamics was analyzed from the mechanical design perspective. However, it was noted that the micro-misalignment caused by the non-coincident center of rotation between human arm joints and exoskeleton joints is a critical issue. The ill effect of this issue was minimized while directly installing the drives at joint locations[2].
- **CAREX -7 -** The CAREX-7 was a proposed 7 DOF cable-driven arm exoskeleton that can support the user in providing agile manipulations like translation and rotation. Based on the "assist-as-needed" paradigm, a novel wrench-field controller is designed to regulate a force or torque on the hand for assisting its agile manipulation. CAREX-7 is a cable-driven upper-limb exoskeleton where the actuators are used to remotely control the arm movements and helps to achieve a light weight and low inertia design properties. CAREX-7 makes use of the human skeletal structure as the underlying mechanical system, and lightweight cables are used to actuate cuffs attached to the human upper limbs. The cable-driven architecture can accommodate possible joint misalignment between the human upper limb and exoskeleton and reduces the chances of injuries to the human subject during robot-aided rehabilitation[2].
- **6-REXOS -** 6-REXOS is a 6 DOF upper-limb exoskeleton for supporting users with weak neuromuscular impairment. 6-REXOS is equipped with three motion generation units to supplement forearm and wrist movements with four active rotational DOFs and two passive translational movements. Two flexible couplings are attached to the elbow and wrist joint to support the translational movements

that help to enhance the kinematic redundancy and to preserve the axis alignment between both joints. It is observed that adding kinematic redundancy to the 6-REXOS through a flexible coupling improves the manipulation, which guarantees a comfort motion assistance[2].

- **NEURO-Exos -** NEURO-Exos is a proposed portable robotic elbow exoskeleton. It was designed for the rehabilitation of a typical type of the motor disorder spasticity. The initial design of NEURO-Exos was developed with the aim of solving two critical issues. These issues include the localization and distribution of interaction points between the exoskeleton and human arm. The localization issue was resolved by introducing an adaptive mechanism for the elbow joint. This adaptive mechanism consists of two major assemblies, that includes double-shell structured link-based assembly and a 4-DOF adjustable passive mechanism. NEUROExos was developed by carefully analyzing the neuro-scientific motion requirement, and later, it was used in several experimental studies to cure neurological disorders[2].
- **EAsoftM exoskeleton -** The design for this exoskeleton was that of one with soft modules. Integrating the 3D-printed exoskeleton with passive joints to compensate gravity and with active joints to rotate the shoulder and elbow joints resulted in an ultra-light system that could assist planar reaching motion by using visual servoing. The EAsoftM can support the reaching motion with compliance realized by the soft materials and pneumatic actuation[2].

In the table below is a summary of the exoskeletons discussed above:

Table 1: Upper Limb Exoskeleton Designs

Exoskeleton Name	Supported Movements	Degrees of Freedom	Main Control Input	Type of Actuators
AAU Upper Body Exoskeleton	Shoulder (EF, AA, IE), Forearm (EF)	3-Active 1-Passive	FSR	Maxon DC Motor
CRUX	Shoulder Abduction, Forearm (EF, PS)	3-Active	Joystick	DC Motor
Stuttgart Exo Jacket	Shoulder (EF, AA), Elbow (EF)	3-Active 9-Passive	Force Sensors	EC Motor with Spring Mechanism

CAREX -7	Shoulder (EF, AA, rotation), Elbow (EF), Wrist (EF, AA, rotation)	7-Active	Joint Angle	Cables driven by Motor
6-REXOS	Elbow (EF, redundant), Forearm (PS), Wrist (EF, UR, redundant)	4-Active 2-Passive	pHRI	DC Motor
NEURO-Exos	Elbow (EF)	1-Active	Joint Angle	Maxon DC Motor
EAsoftM exoskeleton	Elbow (2-Passive DOF) Wrist (2-Active DOF)	2-Passive 2-Active	Visual Based Control	Pneumatic Actuator

Abbreviations: **AA**: Abduction & adduction, **EF**: Extension & flexion, **IE**: Internal & external rotation, **PS**: Pronation & supination, **RU**: Ulnar & radial movement/deviation, **EMG**: Electromyography, **sEMG**: Surface electromyography, **phRI**: Physical human robot interaction, **FSR**: Force sensitive resistors

1.5 Report Structure

The report is distributed into 4 chapters. Chapter 1 is an introduction to the problem statement of the exoskeleton. Chapter 2 is about the methodology involved in understanding and solving the problem. Chapter 3 describes the different control strategies used in exoskeletons and contains the implementation of one such control system. Chapter 4 is the conclusion along with the final results of the report.

Chapter 2-Methodology

Exoskeleton robots should ideally be an extension of a person's limbs, and their mobility must be mimicked in order to provide support and strength. The study of human joints allows researchers to have a better knowledge of which joints cause motion and how much they move when a job is completed. This data is critical for determining the DOF of the robotic linkages[8].

If a joint is given unnecessarily additional DOF, it will only complicate the design, add weight, and provide no benefit. If the DOF is smaller than what is needed, it may restrict motion, producing discomfort or extra exertion, which is counterintuitive, or it may not provide appropriate support for specific jobs. The study of joints allows for the selection of the appropriate DOF so that motion is not restricted and assistance is provided in the plane where it is most needed[9].

It's crucial to research joint velocities, acceleration, and moment after settling on the joint ROM and DOF for the exoskeleton. This knowledge aids in the choosing of actuators and gear ratios. If the actuator is chosen incorrectly, the exoskeleton may not be able to monitor the joint effectively and provide support. The actuator chosen should have capabilities that are well within the task requirements.

2.1 Human Anatomy

The study and movement of human joints are important for selection of DOF for the robotic exoskeleton. Human anatomy can be studied based on three factors: Planes, Joints and Centre of Mass and Moment of Inertia. These factors are discussed in further detail below:

1) Planes - The human body is segmented into 3 mutually perpendicular planes. This segmentation is done in order to differentiate between the movement across these planes. The 3 planes are as follows:

a) Coronal Plane - The coronal plane divides the body into the front (ventral) side and back (dorsal) side[10].

b) Transverse Plane - The transverse plane divides the body horizontally, i.e, the top half (superior section) and the bottom half (inferior section)[10].

c) Sagittal Plane - The sagittal plane divides the body into the left and right halves. This plane is important for forward motion[10].

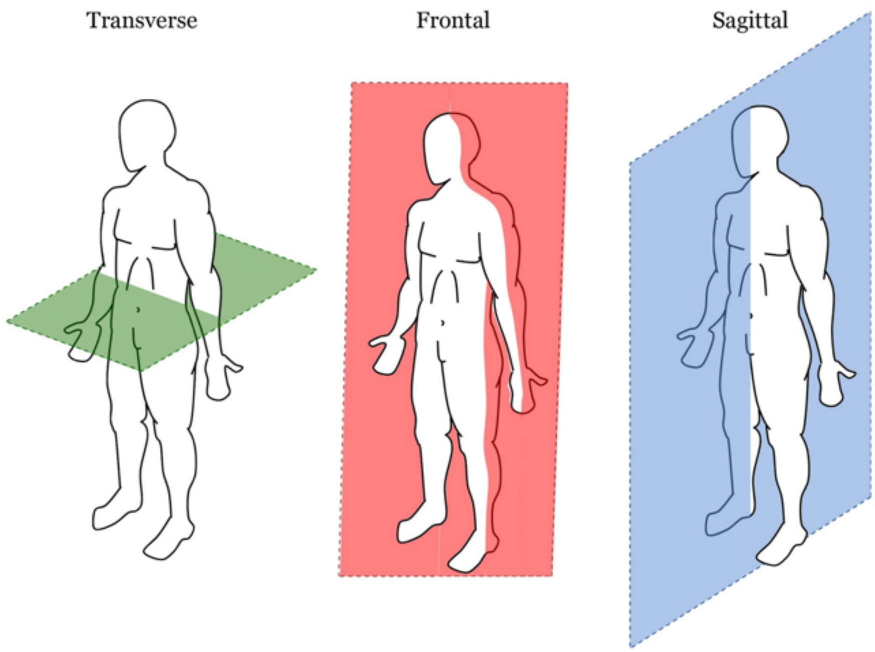

Fig 8. Planes of Anatomy of the Human Body[11]

2) Joints - The human body is made up of numerous simple and complex sets of joints that allow different kinds of movement. The joints can be classified based on the amount of movement they allow[12].

a) **Synovial -** These joints are freely movable.
b) **Amphiarthrosis -** These joints permit very little movement and are mostly cartilaginous joints.
c) **Synarthrosis -** These joints permit little to no movement and are mostly fibrous joints.

We will be mostly focused on synovial joints as they are the major contributors during movements. Since the exoskeleton design we are working on is going to be designed for the upper body, we will be focusing on the vertebrae joints, especially those associated with the hip joint[12].

Vertebrae - The adult human body has 24 vertebrae that are connected with the help of joints called facets. The vertebrae are divided into 5 segments[12]:

a) **Lumbar Spine -** 5 vertebrae from L1 to L5 in the lower back
b) **Thoracic Spine -** 12 vertebrae from T1 to T12 in the mid back
c) **Cervical Spine -** 7 vertebrae from C1 to C7 in the mid back
d) **Sacrum -** 5 fused vertebrae
e) **Causal -** 4 fused vertebrae

We are mainly concerned with the tasks of walking, bending and lifting. These tasks cause maximum motion at the lumbar spine segment.

Hip - The hip joint is a synovial ball and socket joint formed by the interaction of the pelvic acetabulum (socket) and the head of the femur (ball)[12]. This joint is designed for stability and bearing weight rather than for a large ROM. The movement of the joint is as follows:

a) **Flexion -** Movement of thigh towards trunk in sagittal plane
b) **Extension -** Movement of thigh away from trunk in sagittal plane
c) **Abduction -** Movement of the thigh toward and away from the midplane of the sagittal plane.

3) Centre of Mass and Moment of Inertia - Location of link length, mass and centre of mass are important parameters that are used to find the dynamics equation of the human body. The joint lengths and mass are found to vary proportionally with the height of the person, i.e, the limbs of a person who is taller tend to be longer and heavier which is also roughly in the same proportion to the length of the whole body. The average weight of the Indian man is 65 Kg and the average height is about 165 cm[34]. The waist exoskeleton carries the entire upper body whose mass is roughly 40 Kg and the location of centre of mass for the upper body in the sagittal plane is 31 cm for a perfectly straight posture from the lumbar joint.

2.2 PRTC Data

The experimental data was collected by DEBEL using the X-sense motion capture system along with 17 Inertial Measurement Unit (IMU) sensors placed on the body of the test subject to capture the angular position, velocity and acceleration at the various joints. The test was carried out on 100 troops weighing an average of 65 Kg.
The troops were given the task of lifting a box, walking a short distance with the box and placing it down under different walking conditions and with different loads. The different conditions are listed below:

1) Weight to be lifted = 17 Kg, Walking Type = Normal Walk
2) Weight to be lifted = 17 Kg, Walking Type = Fast Walk
3) Weight to be lifted = 22.6 Kg, Walking Type = Normal Walk
4) Weight to be lifted = 22.6 Kg, Walking Type = Fast Walk
5) Weight to be lifted = 29 Kg, Walking Type = Normal Walk

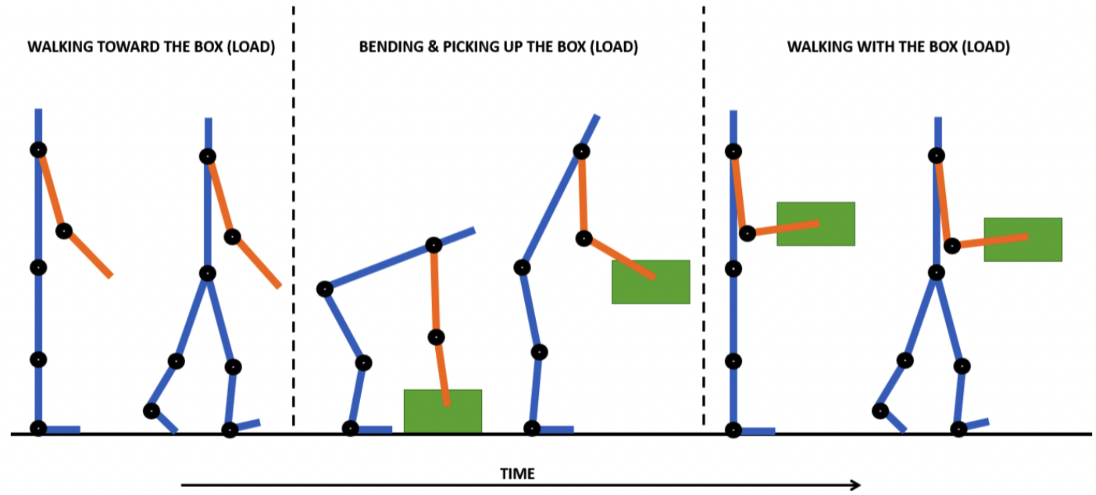

Fig 9. Visualization of the load carrying activity

The acquired data was then fed into the AnyBody software which was then able to find the joint reaction, muscle forces, muscle activation, power requirement, etc. using complex mathematical models.

The data generated from AnyBody software was then saved into an .h5 file. From the .h5 file the data pertaining to 11 joints of interest were extracted. The joints of importance were :

- Ankle flexion (both left and right leg)
- Knee flexion (both left and right leg)
- Hip flexion (both left and right leg)
- Pelvis
- Shoulder flexion (both left and right shoulder)
- Elbow flexion (both left and right elbow)

The values of angular position, velocity, acceleration and torque for the aforementioned joints were then plotted against time to gain a better understanding of the motions occurring at different parts of the load carrying activity.

Using the data, the ROM of the different joints were found. The ROM was important as this would help us in deciding which actuators to choose for the exoskeleton.

The data found has been presented in the tables below:

Table 2. Joint ROM in the sagittal plane[35]

Weight	Test Case	Shoulder (in degrees)	Elbow (in degrees)	Pelvis (in degrees)
17 Kg	NW_T1	-3.1 to 78.7	1.4 to 96.3	-47.6 to 4.6
	NW_T2	-7.4 to 78.7	1.4 to 102.1	-48 to 2.9
	FW_T3	-7.9 to 80.1	-0.2 to 110.6	-44.7 to 7.9
	FW_T4	-8.6 to 80.8	-0.7 to 111.7	-41.8 to 10.3
22.6 Kg	NW_T1	-13.2 to 76.5	1.1 to 114.3	-46.4 to 6.5
	NW_T2	-11.2 to 78.5	0.1 to 123.6	-47.6 to 5.2
	FW_T3	-19.9 to 77.9	-2.6 to 127.7	-42.2 to 2.9
	FW_T4	-15.5 to 79.8	-0.1 to 119.9	-44.3 to 5
29 Kg	NW_T1	-25.8 to 76.2	-0.7 to 123.8	-42.3 to 6
	NW_T2	-27.5 to 85.9	0.7 to 119.5	-43.8 to 3.2

Table 3. Maximum angular velocity of the joints in the sagittal plane[35]

Weight	Test Case	Shoulder (in degrees/second)	Elbow (in degrees/second)	Pelvis (in degrees/second)
17 Kg	NW_T1	157.8	219.4	92.7
	NW_T2	175.9	193.3	100.6
	FW_T3	217.7	222.9	103.7
	FW_T4	197.7	277.3	86.5
22.6 Kg	NW_T1	178.8	250.4	100.2
	NW_T2	219.9	266.4	96.8
	FW_T3	258.1	319.7	96.8
	FW_T4	227.2	226.3	92.1
29 Kg	NW_T1	204	219.4	96.8

	NW_T2	198.2	220	95.1

Table 4. Maximum angular acceleration of the joints in the sagittal plane[35]

Weight	Test Case	Shoulder (in degrees/second^2)	Elbow (in degrees/second^2)	Pelvis (in degrees/second^2)
17 Kg	**NW_T1**	1840.9	2704.5	499.6
	NW_T2	1428.4	2579.5	497.8
	FW_T3	2589.2	1663.9	740.8
	FW_T4	1497.7	1787.1	531.1
22.6 Kg	**NW_T1**	1303.8	2598.4	647.1
	NW_T2	2360	2516.4	559.8
	FW_T3	2997.7	4839.8	856.6
	FW_T4	2677.4	1994.5	791.5
29 Kg	**NW_T1**	1367.4	2715.9	794.1
	NW_T2	3606.8	2361.7	643.4

Table 5. Maximum joint torque in the sagittal plane[35]

Weight	Test Case	Shoulder (in Newton-meter)	Elbow (in Newton-meter)	Pelvis (in Newton-meter)
17 Kg	**NW_T1**	26.3	27.9	80.2
	NW_T2	27.9	27.6	84.3
	FW_T3	28.7	27.7	82.9
	FW_T4	27.5	27.8	76.5
22.6 Kg	**NW_T1**	36	34.8	80.8
	NW_T2	35.7	35.4	95.5
	FW_T3	34.4	34.1	136.8

	FW_T4	34.1	35.4	132.2
29 Kg	**NW_T1**	32.4	32.8	149.3
	NW_T2	37.9	32.2	185.8

Table 6. Maximum values of angular velocity, acceleration and torque for the different joints[35]

Joint	Angular Velocity (degrees/second)	Angular Acceleration (degrees/second^2)	Torque (Newton-meter)
Shoulder	258.1	3606.8	37.9
Elbow	319.7	4839.8	35.4
Pelvis	103.7	856.6	185.8

The information in the above table will be used to calculate the gear ratio, required torque, factor of safety (FOS), etc.

2.3 OpenSim

OpenSim is an open source software system for biomechanical modeling, simulation and analysis. OpenSim allows users to conduct analysis on walking dynamics, studies of sport performances, simulations of surgical procedures, analysis of joint loads, design of medical devices and animation of human and animal movement. OpenSim was developed by Simbios, a NIH Center for Biomedical Computation at Stanford University[13].

For our project we wanted to verify the PRTC data values by simulating the experiment in OpenSim. The problem we faced was that to generate the torque values at the muscle joints we needed the ground reaction forces (GRF) to input into OpenSim's Computed Muscle Control (CMC) tool. At present there is no framework to reverse engineer the GRF values of the human body without the use of force plates. Due to this we weren't able to run the simulation successfully in OpenSim.

2.4 Sensor Selection

The next task was shortlisting sensors to measure different parameters required to build the control system.

The different types of sensors required for the exoskeleton along with their use are as follows:

1) **EMG sensor** - Electromyography sensors or more commonly known as EMG sensors detect electrical signals being generated by the muscles upon movement. The mechanical movement of the muscles causes depolarization, i.e change in the electromechanical gradient which is then detected by the EMG sensor. There are two types of EMG sensors[14]:
    a) **sEMG sensors (Surface electrodes)** - These sensors are non invasive in nature and take readings with the help of electrodes placed on the skin surface. They are commonly used in clinics and by sports teams to monitor the athlete's performance. One major drawback of these sensors is that they are restricted to superficial muscles and are dependent on the weight of the wearer and the amount of adipose tissue as well[14].
    b) **Intramuscular EMG** - These sensors take measurements by inserting a monopolar needle electrode into the muscle tissue. These are less commonly used when compared to the sEMG sensors and can cause muscle soreness as well[14].
2) **Encoders** - They are a type of mechanical motion sensor that creates a digital signal from motion. It is an electro-mechanical device that provides the user with information on position, velocity and direction[15]. There are two types of of encoder sensors:
    a) **Linear Encoders** - In linear encoders, there is a magnetic sensor passing over a magnetic scale. As the sensor moves along this scale, it detects changes in the magnetic field which are proportional to the measuring speed and the displacement of the sensor. Since linear sensors only detect changes in the magnetic field, external factors such as light, debris or oil have no effect on the sensing capabilities, and as a result they are often used in harsher environments. Optical linear encoders are not as widely used, but use parallel beams of light on a glass scale to generate sinusoidal wave outputs that are detected using a photodetector[15].
    b) **Rotary Encoders** - Rotary encoders can be magnetic or non-magnetic in nature. In a magnetic rotary sensor, the sensor is passed over a rotating disc of alternating magnetic regions. The sensor detects the small changes in the magnetic field either via the Hall effect or the magneto resistive effect. Electronic rotary encoder sensors are a little more complex and are typically controlled via the rotation of a shaft which is connected to the circuitry of the encoder. The shaft is connected to the encoder via a part

known as the hub. When the shaft rotates, it causes the disc to rotate across the circuitry of the encoder. The circuitry contains LEDs that can be spotted using a photodiode. The speed of the rotation is dependent upon the speed of the shaft attached to the encoder. Each concentric ring in the rotary encoder has its own light source to identify each line in the rotating disc. The signal from the detectors is then converted into an output that provides feedback on the position or velocity of the sensor[15].

3) **Force/Torque Sensors** - These sensors are designed to monitor, detect, record and regulate linear and rotational forces exerted upon them. They can be compared with the micro-receptors humans have giving us the sense of touch. Depending on the model and intended function, a force torque sensor is able to send digital or analog signals, and measure static or dynamic forces. The most popular type of force torque sensor is the six-axis sensor. This particular FT sensor is capable of measuring forces in every direction. A six-axis FT sensor generally utilizes strain gauge technology; when pressure is applied, the resistance within the gauge increases or decreases proportionally to the force it receives[16].
4) **IMU Sensors** - An Inertial Measurement Unit (IMU) is a specific type of sensor that measures angular rate, force and sometimes magnetic field. IMUs are composed of a 3-axis accelerometer and a 3-axis gyroscope, which would be considered a 6-axis IMU. They can also include an additional 3-axis magnetometer, which would be considered a 9-axis IMU. Technically, the term "IMU" refers to just the sensor, but IMUs are often paired with sensor fusion software which combines data from multiple sensors to provide measures of orientation and heading. In common usage, the term "IMU" may be used to refer to the combination of the sensor and sensor fusion software; this combination is also referred to as an AHRS (Attitude Heading Reference System)[17].

Table 7. List of sensors

Sensor	Company	Sensor Type	Specifications
MyoWare™ Muscle Sensor (AT-04-001)[18]	Advancer Technologies, LLC	EMG Sensor	Dimensions: 0.82" x 2.06" Supply Voltage: +3.1V - +6.3V Input Impedance: 110GΩ Max Supply Current: 14mA Input Bias: 1 pA
BTS FreeEMG 1000[19]	BTS Bioengineering	EMG Sensor	Resolution: 16 bit Acquisition Frequency: 1 kHz Weight: 13 grams

			Dimensions: 41.5x24.8x14mm
Ultium EMG[20]	Noraxon USA	EMG Sensor	Sampling Rate: up to 4000 Hz Baseline Noise: < 1μV Input Impedance: > 100MΩ Accelerometer Sample Rate: Up to 500 Hz Full IMU Sample Rate: Up to 400Hz
Trigno Galileo[21]	Delsys	EMG Sensor	Dimensions(Body): 27x46x13mm Dimensions(Head): 23x30x7mm Mass: 19 grams Bandwidths: 10-850Hz,20-450Hz Contact Material: 99.9% Silver Sampling Rate: 2222 samples/sec
A2 Absolute Optical Shaft Encoder[22]	US Digital	Optical Encoder	Operating Temperature: -25 to 70℃ Max. Acceleration: 100000 rad/sec^2 Weight: 2.9 ounces Supply Voltage: 7.5V - 16V Supply Current: 18.5 mA Angle Tracking Speed: Single turn mode: 3600 RPM Multi turn mode: 1800 RPM
AS5048A[23]	AMS	Rotary Encoder	Resolution: 14 bit Supply Voltage: 3.3 or 5.0 V Temperature Range: -40 to +150℃ Supply Current: 15 mA Magnetic Input Field: 30 - 70 mT Sampling Rate: 10.2 - 12.4 kHz
Mini 43 LP[24]	ATI Industrial Automation	Force/Torque Sensor	Weight: 0.0499kg Height: 7.9mm Diameter: 43mm Stiffness(Kx, Ky): 3.3x10^7 N/m Stiffness(Kz): 2.1x10^7 N/m Single Axis Overload(Fxy, Fz): 1200N Single Axis Overload(Txy):

			15Nm Single Axis Overload(Tz): 25 Nm
QLA414[25]	Futek	Force/Torque Sensor	Capacity: 22.2 N Bridge Resistance: 250Ω Rated Output: 0.5 mV Height: 5.5 mm Diameter: 3 mm
3DMCX5-AR[26]	LORD Sensing MicroStrain	Inertial Measurement Unit(IMU)	Sampling Rate: Up to 1000Hz Operating Temperature: -40 to +85℃ Weight: 12 grams Dimensions: 38x24x10.7mm Standard measurement range: Accelerometer: 8g Gyroscope: 300°/sec

2.5 Actuator Selection

An actuator is a part that initiates movements by receiving feedback from a control signal. Once it has power, the actuator creates specific motions depending on the purpose of the machine[27].

The actuators will be the main component in the active exoskeleton, providing assistance to the limbs, hence making their selection very important.

Since each limb has different ranges of motion and varying ranges of torque required during the weight carrying activity it is important to choose the actuator for each limb very carefully[27].

Actuators can be classified based on various different criteria as listed below:

1) **Motion**
    a) **Linear** - These actuators, as the name suggests, produce motion in a straight path. They are mostly electric or mechanical and are commonly found in pneumatic and hydraulic devices[27].
    b) **Rotary** - These actuators produce circular motion and are used to complete a turning movement. Most of them are electrically powered, but some are powered using a hydraulic or pneumatic system[27].
2) **Source of Energy**
    a) **Hydraulic** - These actuators operate by the use of a fluid filled cylinder with a piston suspended at the center[27].

b) **Pneumatic** - These actuators use pressurized gases to create mechanical movement. They are one of the most reliable options for machine motion[27].

c) **Electric** - They are further divided into two more categories:

   i) **Electromechanical** - They convert electric signals into rotary or linear movements and may even be capable of both[27].

   ii) **Electrohydraulic** - They are powered by electricity but provide movement to a hydraulic accumulator, which in turn provides the force for the required movement[27].

d) **Thermal and Magnetic** - These consist of shape memory alloys which can be heated to produce movement. The motion produced by these actuators is based on the Joule Effect, but can also occur when a coil is placed in a static magnetic field[27].

e) **Mechanical** - These produce motion with the help of purely mechanical structures such as pulleys or rack and pinion systems. They rely on some mechanical force being applied to produce the desired motion[27].

f) **Supercoiled Polymer** - These are a relatively new type of actuator and can replicate the motion of the human muscle via a coil that contracts and expands when heated or cooled[27].

Table 8. List of Actuators

Actuator	Company	Type	Specifications
ILM-E85x13[28]	TQ-group	Frameless motor	Power: 409 W Rated Torque: 1.39 Nm Peak Torque: 4.47 Nm Rated Voltage: 48 V Maximum rotation speed: 2810 rpm Rated Current: 9.9 A Weight 356 gms
Quantum Nema Brushless Servo Motors (QB017)[29]	Allied Motion	Brushless Servo Motor	Rotor Length: 54-92 mm Motor Voltage: 24,40,130V Rated Load Torque: 0.1-0.23Nm Rated Speed: 3850-13800 RPM Rated Current: 1.4-8.5A Rated Power Output: 68-213
BLDC ES030A[30]	Haydon Kerk	Brushless DC	Diameter: 35mm Continuous Torque:

	Pittman	Motor	0.029-0.041 Nm Rated Power: 11-22 Watts Max. Speed: 8000 RPM Voltage: 0-60 V
Direct Drive KBM Series 10[31]	Kollmorgen	Frameless Motor	Outside Diameter: 59.96mm Through Bore: 16.01mm Continuous Stall Torque: 0.49-1.45 Nm Peak Stall Torque: 1.17-4.91 Nm Continuous Output: 0.9-3 kW
EC 90[32]	Maxon Motors	Brushless DC Motor with Hall sensors	Weight: 600 grams Max. Speed: 5000 RPM Ambient Temperature: -40 to +100℃ Nominal Voltage: 24V Stall Torque: 4940 mNm Stall Current: 70 A Nominal Torque: 444 mNm Nominal Current: 6.06 A Terminal Resistance: 0.343Ω

2.6 Determining Motor Specifications

We will try to determine the specifications for the motor which could be used for our exoskeleton. To find the motor's minimum requirements we will have to assume either speed or torque. The formulas used are as follows:

Gear Ratio, $GR = \boldsymbol{\tau}_o/\boldsymbol{\tau}_i = N_i/N_o$ (1)

Power, $P = 2\pi\boldsymbol{\tau}_i N_i/60 = 2\pi\boldsymbol{\tau}_o N_o/60$ (2)

Here, $\boldsymbol{\tau}_o$ = Output torque in N-m

$\boldsymbol{\tau}_i$ = Input torque of the motor in N-m

N_o = Output speed in rpm

N_i = Input speed of motor in rpm

Since the latest design of the exoskeleton is going to be powered only by the pelvis we will be making the calculations only for the pelvis. From **Table 6** we have the:

$\boldsymbol{\tau}_o = 185.8$ N-m and $N_o = 103.7/60 = 1.73$ rpm

$\boldsymbol{\tau}_o * N_o = 185.8 * 1.73 = 321.434 = \boldsymbol{\tau}_i * N_i$

Now we will assume the input speeds and find the required input torques and the gear ratio. Taking increments of 500 rpm to the assumed input speed the table below shows the required values of the input torque and gear ratio.

Table 9. Requirement of motor torque and gear ratio

S. No.	Input Speed (rpm)	Input Torque (N-m)	Gear Ratio
1	500	0.64	289
2	1000	0.32	578
3	1500	0.21	867
4	2000	0.16	1156
5	2500	0.13	1445
6	3000	0.11	1734
7	3500	0.09	2023
8	4000	0.08	2312
9	4500	0.07	2601
10	5000	0.06	2890
11	5500	0.06	3179
12	6000	0.05	3468

Power requirement from the motor for the pelvis region,

$$P = 2\pi \boldsymbol{\tau}_o N_o/60 = 2*\pi*185.8*1.73/60 = 33.66 \text{ W}$$

Keeping in mind FOS, we multiply the required power by FOS 1.5,

$$P` = 33.66 * 1.5 \sim 50.5 \text{ W}$$

Therefore to lift a load of upto 29 Kg a motor providing power of 50 W will be required.

2.7 Derivation of Transfer Function

In this section we will derive the transfer function for the motor. The below figure is the representation of a motor.

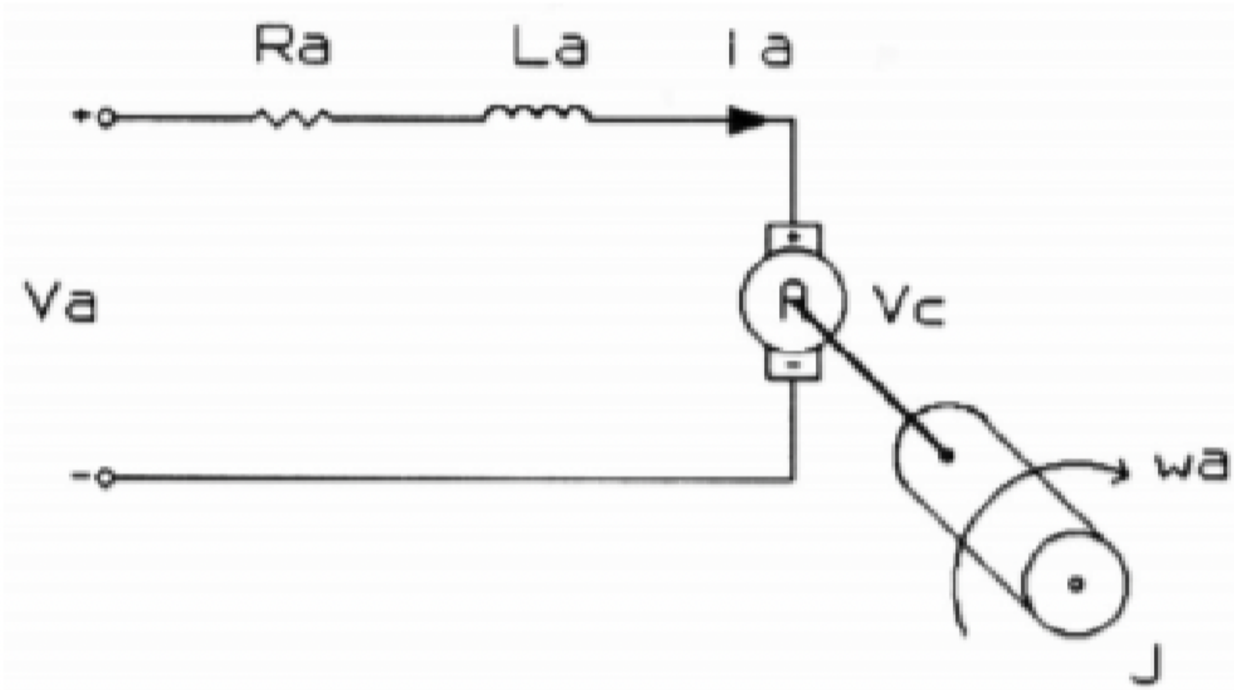

Fig 10. Representation of motor

1) **Electrical Characteristics**

Applying Kirchhoff's law to balance the voltages across the circuit,

$V_a - V_{Ra} - V_{La} - V_c = 0$ (3)

$V_{Ra} = I_a R_a$ (4)

$V_{La} = L_a (di_a/dt)$ (5)

$V_c = K_v \omega_a$ (6)

Substituting eqn. (4) to eqn. (6) into eqn. (3),

$V_a - i_a R_a - L_a (di_a/dt) - K_v \omega_a = 0$ (7)

2) **Mechanical Characteristics**

Balancing torques,

$T_e - T_{\omega 1} - T_\omega - T_L = 0$ (8)

$T_e = K_t i_a$ (9)

$T_{\omega 1} = J (d\omega_a/dt)$ (10)

$T_\omega = B\omega_a$ (11)

Substituting eqn. (9) to eqn. (11) into eqn. (8),

$K_t i_a - J (d\omega_a/dt) - B\omega_a - T_L = 0$ (12)

3) **Transfer Function**

Taking the Laplace transformation of eqn. (7)

$sI_a(s) - i_a(0) = -(R_a/L_a) I_a(s) - (K_v/L_a) \Omega_a(s) + (1/L_a)V_a(s)$ (13)

Taking the Laplace transformation of eqn. (12)

$s\Omega_a(s) - \omega_a(0) = (K_t/J) I_a(s) - (B/J) \Omega_a(s) - (1/J) T_L(s)$ (14)

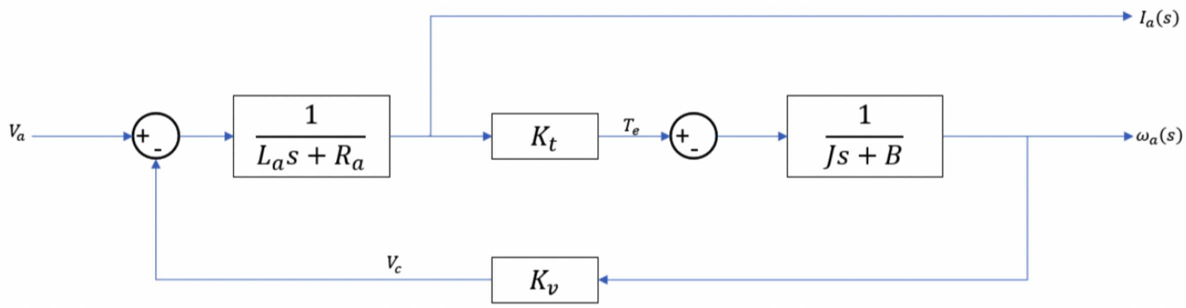

Fig 11. Flow diagram representation of the transfer function

The motor is connected to the exoskeleton joint through a gear reducer. The gear ratio is the ratio of input speed to output speed or input torque to output torque. From this relation the motor's output torque and speed can be found which is the exoskeletons input torque thus the equation is modified only in the mass matrix as,

$$[(I_1/GR^2) + M_1L^2_{1C} + J]\ (d^2\theta_1/dt^2) \qquad (15)$$

In addition to this an additional term B is added to the entire expression. Thus, the complete dynamics equation for 1 DOF exoskeleton with motor and gear ratio is represented as,

$$\tau_1 = [(I_1/GR^2) + M_1L^2_{1c} + J]\ (d^2\theta_1/dt^2) - M_1gL_{1c}\cos(\theta_1) + B \qquad (16)$$

Chapter 3-Control Strategies

In this chapter we discuss the various control strategies and implementation for the application in the exoskeleton, particularly for the pelvis joint.
The simulation of the control system will allow us to check how the actuator chosen will behave when a load is applied. Based on the actuator behavior we can modify the parameters to obtain the optimized performance.

3.1 Types of Control Strategies

The various strategies used for controlling an exoskeleton are as follows in the figure below:

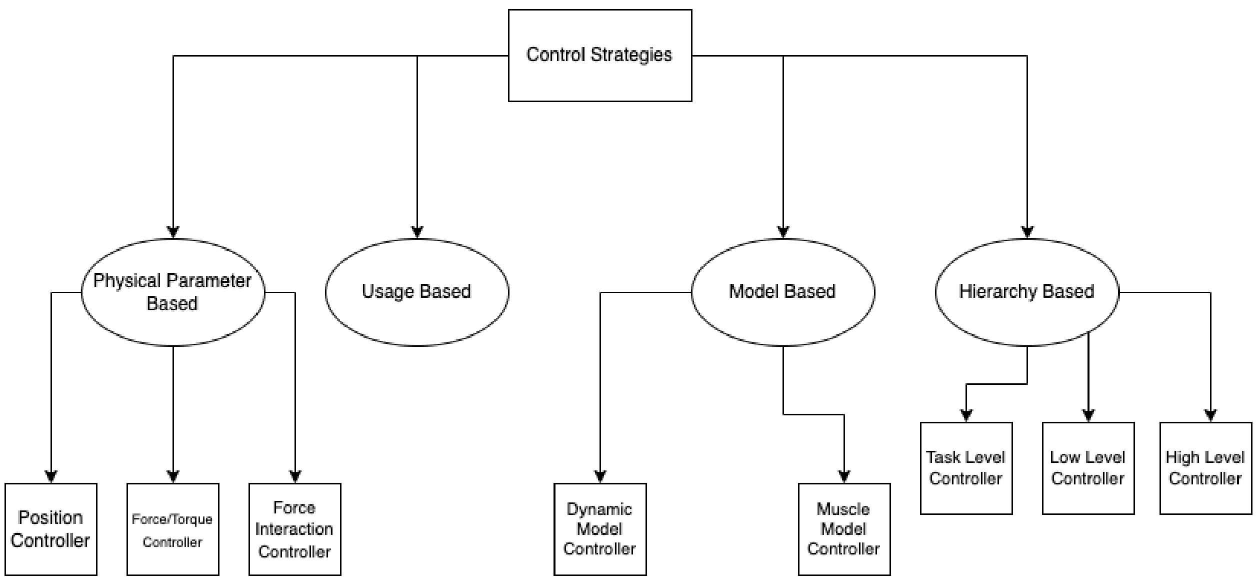

Fig 12. Different Control Strategies

A more elaborate description of the control strategies is given below.

1) **Physical Parameter Based Control:**
   a) **Position Controller:**
      - It is a low-level controller.
      - It is used to ensure that the exoskeleton's joint angle is the same as the human limb's joint angle by using the IMU sensor[33].
      - The position controller has been used by the HAL exoskeleton.

   b) **Torque/Force Controller:**
      - This is also a low level controller.
      - It is used to ensure that the exoskeleton's joint torque is controlled to produce the desired interaction force between the wearer and the exoskeleton[33].

- The ARMIN III exoskeleton used this type of controller for medical rehabilitation[2].

c) **Force Interaction Controller:**
   - This is a high level controller. Its aim is to provide assistance during a task.
   - The interaction force can be controlled either by using impedance (input is position and the output is force/torque) or admittance control (input is force/torque and the output is position)[33].
   - Impedance controller receives error in joint position to give force/torque that acts as a reference for the force/torque controller[33].
   - Admittance controller receives error in force/torque to give joint positions that acts as a reference for the position controller[33].

2) **Usage Based Control:** The usage based control is based on the usage of the exoskeleton. For example master-slave control or gait based control[33].
3) **Model Based Control:** The model-based control is further sub-divided into 2 categories, i.e., the dynamic model and the muscle model. The muscle model establishes relation between input joint angles and muscle activation to output forces[33].
4) **Hierarchy Based Control:**
   a) **Task Level Controller:** This is the highest level controller and is used to assign various controllers based on the types of tasks performed.
   b) **Low Level Controller:** This controller is used for controlling the joint position or torque/force of the exoskeleton.
   c) **High Level Controller:** This controller receives information from the task level controller and is used to control the human-exoskeleton interaction forces.

3.2 PID Tuning Method

The main objective of tuning PID parameters is to ensure that the plant is able to maintain set-point value and reach it as fast as possible all while ensuring minimum accepted level of error which ideally should be zero. The PID is widely accepted for use in exoskeletons where the aim is to track the joint and provide assistance. The tuning of PID is of extreme importance in exoskeletons as it requires tracking human motion and for it to be effective it should have a very low response time and very low error. The error percentage that is acceptable for exoskeletons is also very low as high errors can be detrimental to the health of the wearer. There are various methods of tuning a PID, however in this section we will limit our scope to the Genetic algorithm for nonlinear systems, particularly for the waist exoskeleton.

Genetic Algorithm: It is a search-based optimization technique based on the concepts of natural selection and genetics. It is one of the most popular and widely used methods to find optimal solutions to problems such as tuning a PID. The algorithm works by initializing a random population at first whose fitness value is evaluated based on an objective function. The simulation terminates if the fitness function is within a predefined set criterion else, a set of parents are selected at random to produce offspring which are generated using single point or multi point criteria. The offspring are then randomly mutated (i.e., 1 change to 0 and vice versa for a 2-bit type approach to the problem). The new mutated population now becomes the initial population and the entire process repeats until the solution terminates or the set number of iterations are completed.

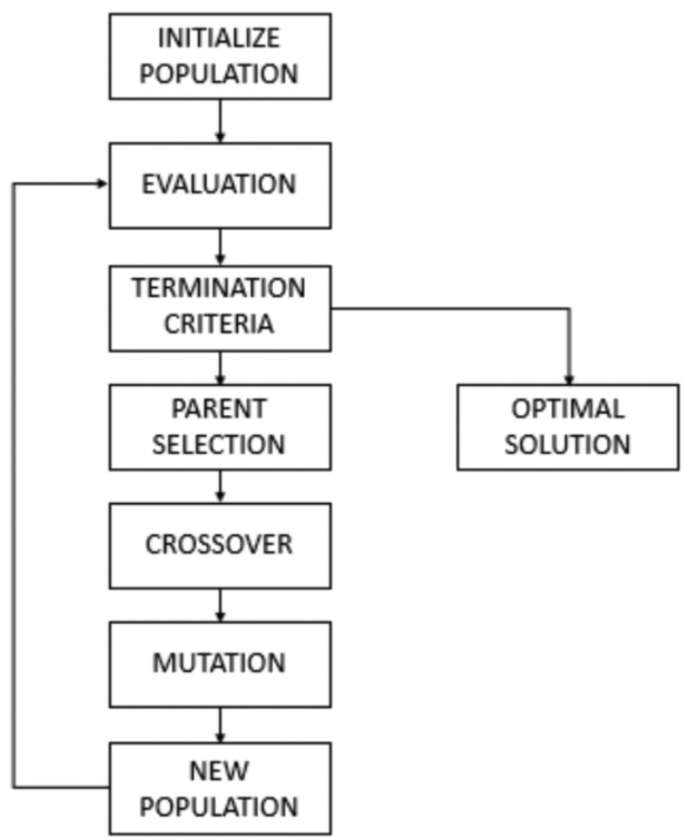

Fig 13. Work flow of the genetic algorithm

3.3 Implementation of Control System

In this section the implementation of the control system in the exoskeleton for tracking and assistance is evaluated and compared. The below figure of the Simulink model has 3 PI controllers: force controller, voltage controller and current controller. In this model the entire load is carried by the exoskeleton with no effort from the human. The pressure sensor and voltage relation is taken as linear and directly proportional to voltage, however any other value can also be used without affecting the controller performance as it is essentially a proportional gain.

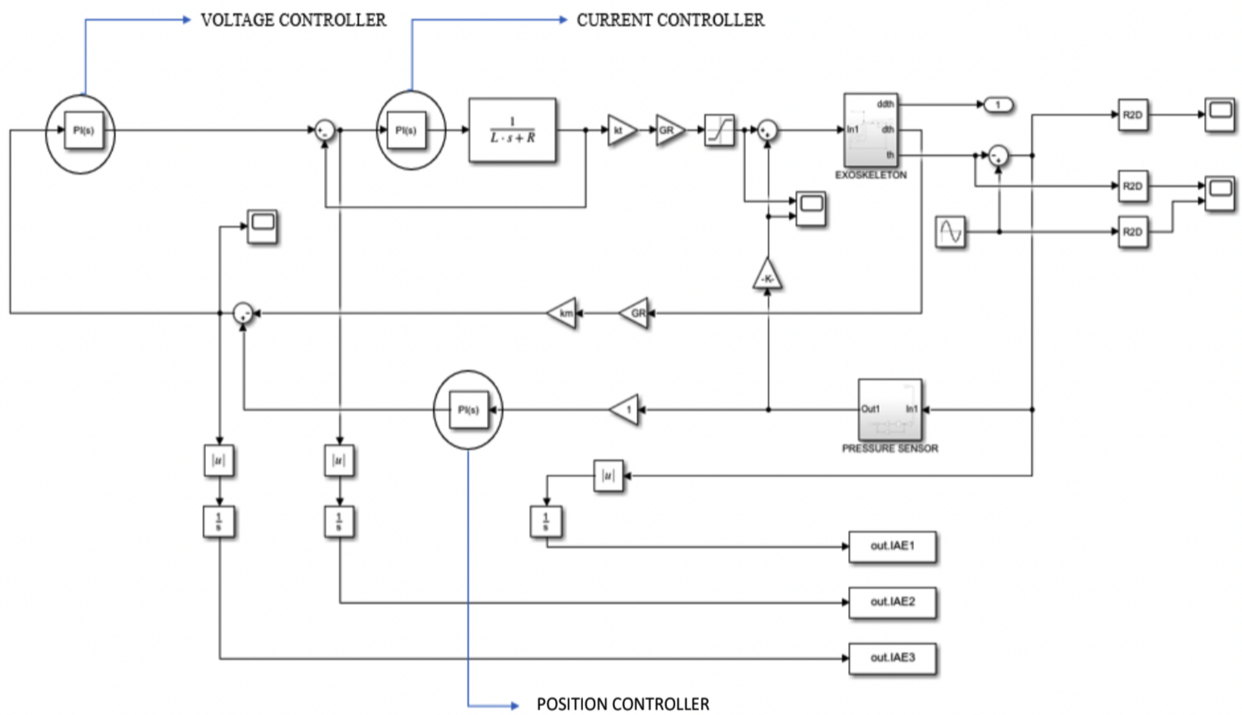

Fig 14. Control architecture of waist exoskeleton

The control structure has a total of 3 PID controllers thus making it a multi-objective problem in which 3 objective functions need to be reduced in order to give the best fitness value. This is achieved by passing the objective function as a vector which in this case is taken as integral absolute error (IAE). The stopping criteria was set as 50 generation (stall generation) and the simulation was run for a maximum of 100 generations with a population size of 200.

The desired input tracking trajectory input is given as a sinusoidal wave of 0.4 rad (22.92 degrees) amplitude and 2 rad/s (114.59 degrees/s) frequency.

The plot of the exoskeleton compared to the expected angle is shown below.

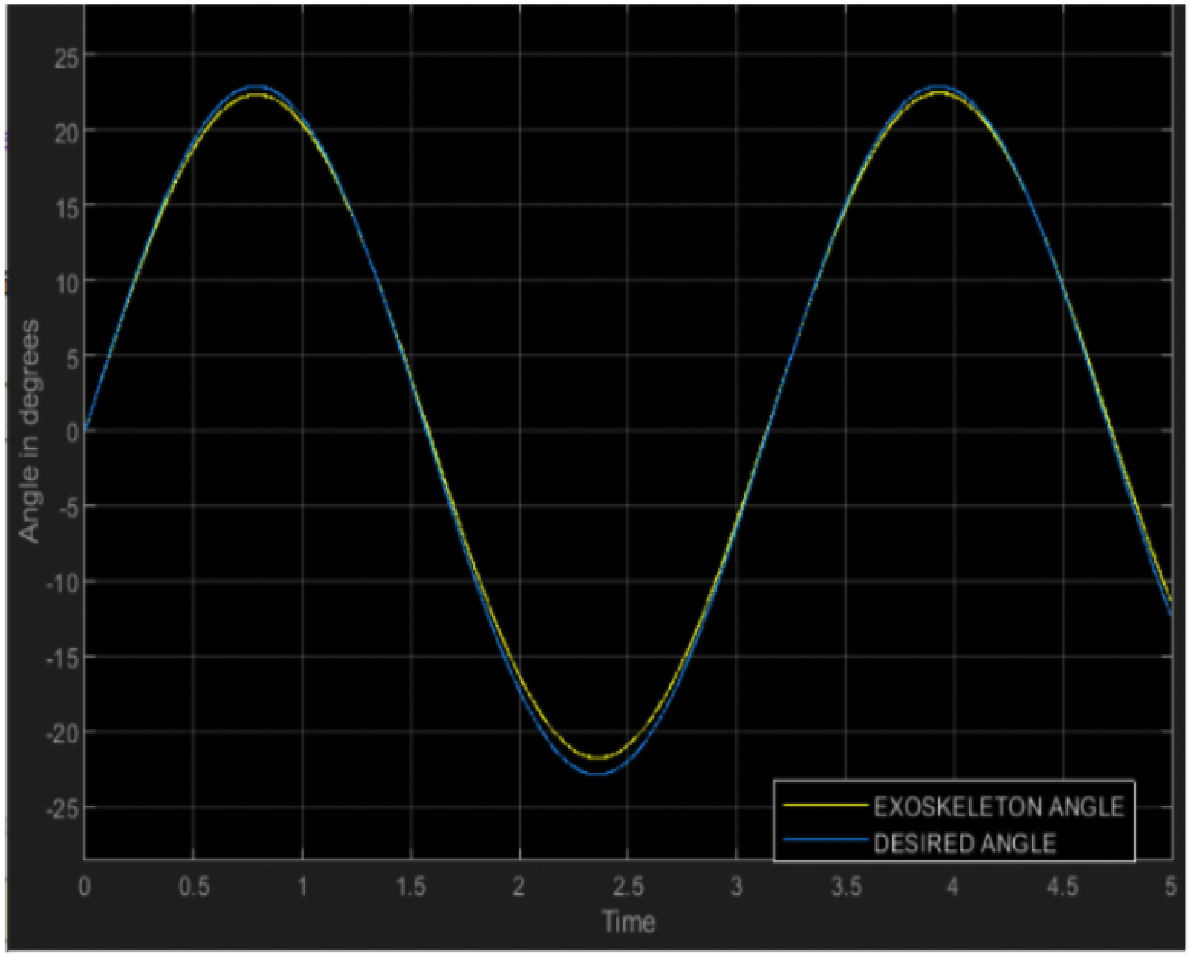

Fig 15. Tracking Response for no load condition

The maximum error in angle occurs during the second cycle of the sine wave at a time of roughly 2.5 seconds. The error for the first cycle is significantly smaller, lying under 1 degree. This scenario will not occur in practical cases usually, however the error is still within acceptable limits.

Chapter 4-Conclusion

In our study using some assumptions and using data gathered experimentally we were able to determine the values of torque and power which would be needed for a waist powered exoskeleton. The required power was found to be roughly 50.5 W taking into account a factor of safety of 1.5.

We were also able to create a control system which was based on parameter tuning using the genetic algorithm. The controller was able to generate fairly accurate values and had only marginal errors.

The work on exoskeleton can be further extended to incorporate other control schemes such as sliding mode-PID, fuzzy logic controller, also neural network self-adaptive PID controller can also be explored and which has the potential to produce excellent controller response but comes at the expense of computation. The physical design of the exoskeleton can also be studied to make the design more flexible such as using a scissor mechanism or flexible link in the lower portion of a waist exoskeleton, etc.

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