Simulation and Control of Exoskeleton

Dissertation

Submitted by

Shivam Jaiswal

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Under the supervision of

Dr. Pooja Agarwal
Assistant Professor,
School of Robotics,
Defence Institute of Advance Technology

Dr. Subhashisha Sahoo
Scientist 'F'
Centre for Artificial Intelligence and Robotics,
DRDO, Bangalore, India

School of Robotics
Defence Institute of Advance Technology
Pune – 411024

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Abstract

Assistive exoskeleton in military has enormous uses, one of which is the load carrying activity (LCA), an important aspect of military during warfare as well in peace time. This study deal with the same LCA activities by troops. It's a collaborative project of various DRDO establishments working on different parts and technologies of exoskeleton for LCA. One of the key parts, simulation and control of upper body exoskeleton, is dealt by CAIR. It starts with collecting data from 100 soldiers at 59.8802 Hz during LCA activity at 17 joints and part of the body, which involves walking, bending, lifting, walking and dropping the weights, in same order. After data has been collected and proceeded, it was used to plot and simulate a line model of human to verify data and to study various segments of it, like bending and lifting. At first angular position values were used to simulate all joints, later torque profile of Elbow joint was used and its angular position, angular velocity was traced. And same was to be done with Waist part of the human model. For this purpose, we developed a human model in Solidworks, with various properties like body segment length, mass, its Centre of Mass (CoM) and other properties. Model was simulated and its results like angular position was compared with the experimental data. A CAD model of Waist-Assistive Powered Exoskeleton (WAP-Exo) is being for developed in Solidworks, to be used with the human model created above.

Keywords: Exoskeleton, Upper arm exoskeleton, Waist-Assistive Powered Exoskeleton, Load carrying activity,

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Abbreviation

LCA	Load Carrying Activity
CoM	Centre of Mass
CoG	Centre of Gravity
WAP-Exo	Waist-Assistive Powered Exoskeleton
ADL	Activities of Daily Life
DoF	Degree of Freedom
SEA	Series Elastic Actuator
EEG	Electroencephalography
EMG	Electromyography
sEMG	Surface Electromyography
F/T	Force and Torque
FSR	Force Sensing Resister
IRD	Intentional Reaching Direction
SCI	Spinal Cord Injuries
CAD	Computer Aided Design
RMS	Root Mean Square
NRMSE	mean Normalized Root Mean Square Deviation
SVR	Support Vector Regression
ANN	Artificial Neural Network
TDNN	Time Delay artificial Neural Network
GMM	Gaussian Mixture Model
RFECV	Recursive Feature Elimination with Cross Validation
LDA	Linear Discriminant Analysis
PI	Position and Integral
wrt	with respect to
IMU	Inertial Measurement Units
MEMS	Micro-Electromechanical Systems
GRF	Ground Reaction Force
FW	Fast Walk
NW	Normal Walk

Chapter 1

Introduction

In today's world of military aggression and confrontation on border, requirement of more and more advance system is becoming inevitable, for protection of troops, military, its establishments, more weather proof housings, all weather uniforms, advance weaponry, performance enhancement exosuits and exoskeletons, robust and autonomous vehicle system and many more. One of the key technologies available for military use is exoskeleton, which is becoming a more and more researched and developed area these days, Yang et al, 2008, Gull et al, 2020, Kapsalyanmov et al, 2020.

An exoskeleton (Exo meaning outer) is robotics device, which a living being can wear and this device provide the wearer with some assistance through a passive mechanism or provide power using actuators.

1.1 History and background

With the idea of exoskeleton laid around 1890 when a Russian engineer Nicholas Yagn designed an apparatus for facilitating walking, running and jumping as shown in Fig. 1.1, its roots go far into ancient times, when people used wood and iron to help differently abled people to do their daily activities. For an example, a walking stick, it can be said as an earliest form of exoskeleton, which assisted people in walking. Till 19th century most exoskeletons were a type of a passive exoskeleton. It is only in last 100 years that active exoskeletons are being developed and researched more.

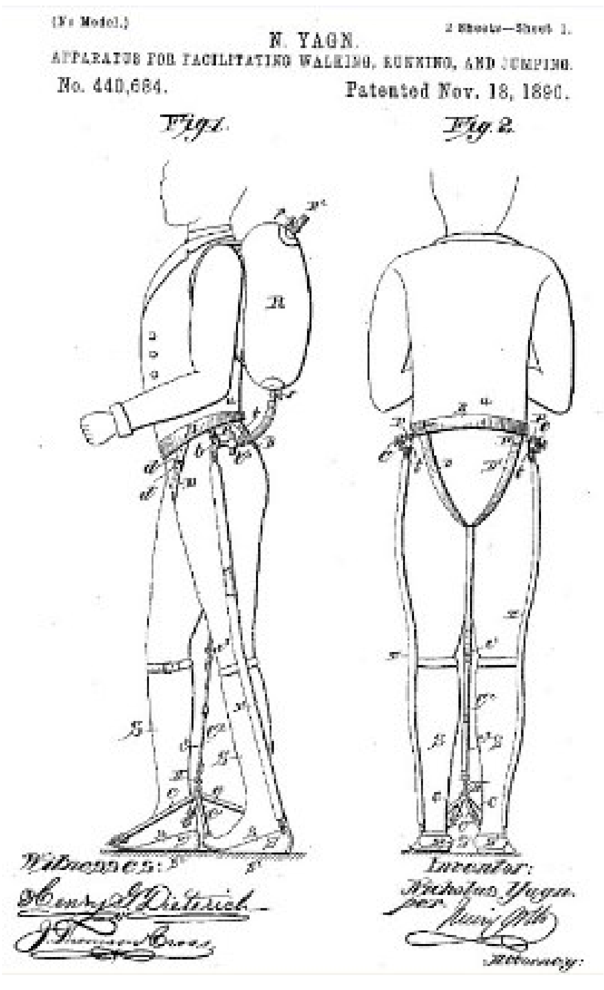


Fig. 1.1. Passive exoskeleton by N. Yagn, 1890

The first active exoskeleton was developed by General Electric Company, under the project Hardiman 1 between 1965-71, US, Mosher et al, 1967, as shown in Fig. 1.2. It was developed to enhance and augment human endurance and strength. Working on slave master configuration, a heavy machinery, was to be used for load carrying, stacking, moving cargo from place to place and similar application. It was designed for upper as well as lower body. Due to its heavy weight and bulky design its practice use was difficult and unsafe.

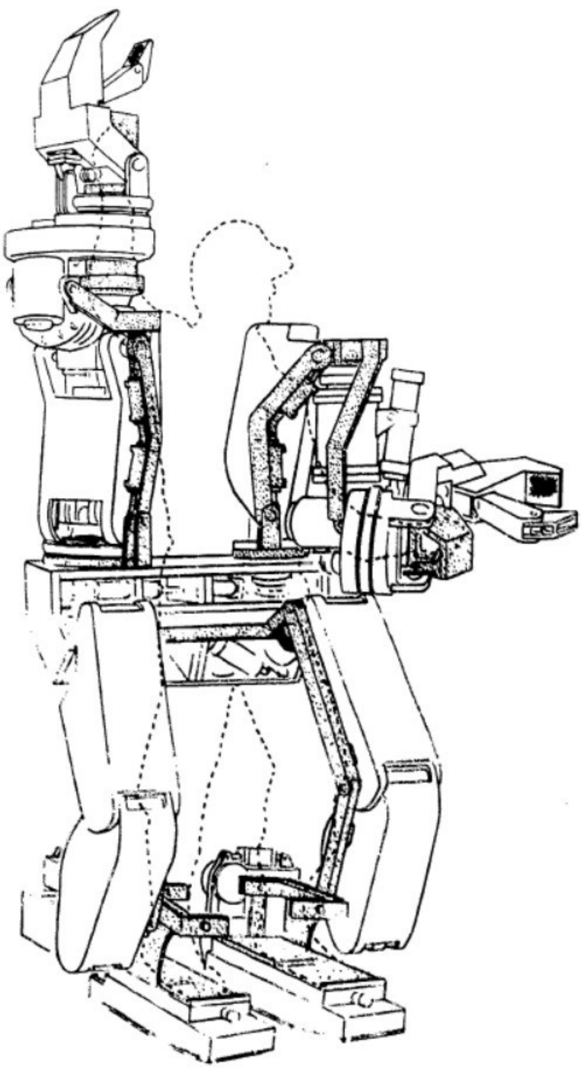


Fig. 1.2. Hardiman-1 diagram (Mosher et al., 1971)

With the advancement in technologies, size reduction of actuators, sensors and development of more efficient power source, size of exoskeleton started to reduce, Kumar et al., 2019. They became more and more task specific exoskeleton. This created a chance for engineers and scientist to research and develop exoskeletons.

1.2 Applications and reach of exoskeleton

An exoskeleton has a wide range of application, ranging from military to medical and health, from heavy lifting and running for a longer time without getting tired, from performing maintenance in outer space to the bottom of the Ocean and many more. Some of the wide uses of exoskeleton are discussed below.

1.2.1 Rehabilitation

Use of mechanical devices in the rehabilitation of week human limb or spine has been there for ages, which were used as an assistive device for limbs and back exercise to regain muscle power. Today these devices have been replaced by exoskeleton and robotic devices for same task, such as, orthosis, neurorehabilitation, support device during spine injury, Abbruzzese et al., 2016, Parri et al., 2017, McDonald et al., 2020. Due to some accidents when a person loss its strength in a limb, a person can recover its strength using rehabilitation and exercises, for such exercises, it requires a specialized person who can hold his/her arm and lead it. But now with the development of wearable exoskeletons, these same exercises can be programmed and performed without the help and dependence on other people.

Such devices can also help elderly people to perform Activities of Daily Life (ADL), some of such device has been reviewed by Kapsalyamov et al., 2020. As people gets older their neuromuscular strength decreases due to which they require assistance even for simple task such as eating, walking and most ADL task. In such situation a wearable exoskeleton can act as an assistant providing strength to limbs, spine and waist, and reduce their dependence on other people.

1.2.2 Industrial work

Working in an industry or a factory for hours can have a huge impact on muscles and worker can become easily tired, which in turn can reduce efficiency of workers and reduce production. This can also cause a negative effect on the health of worker leading to pain in back, fatigue in muscles. To reduce such effects workers can use exoskeleton as an assistive device, Voilqué et al., 2019, Spada et al., 2018.

1.2.3 Military

As troops and military personnel has a lot of LCA activities, whether be a warfare situation or in peace time, they require to carry heavy loads such as weapons, ammunitions, foods and sometimes injured civilian or military personnel, and they have to complete such activities repeatably. Working so extensively can cause them to loss their strength, cause fatigue in muscles, which will reduce their efficiency. Reduced efficiency can be dangerous especially if they are deployed on border and have a very aggressive neighbour. To help them and reduce their fatigue and loss of strength and increase their efficiency they can utilize assistance from a robotic device, exoskeleton. A wearable exoskeleton can help them by providing some assistance in different parts of body and different activities. It will increase their efficiency, allow them to work for longer than they can work without it.

1.3 Some basic understanding regarding exoskeletons

1.3.1 Types of exoskeleton

There are numerous ways to classify an exoskeleton, two of the most common type of classifications are discussed below: -

On the basis of power

1. *Passive Exoskeleton: -* An exoskeleton which do not require any external power source like battery, pneumatic pressure to operate. These exoskeletons primarily use spring or damping to assist and depends solely on mechanism.
2. *Active Exoskeleton: -* These kind of exoskeleton needs an active source of power or energy to operate. They generally use electric motor, pneumatic or hydraulic system as a source of energy. These are more powerful then passive ones.

On the basis of assistance at body segment

1. *Upper limb exoskeleton: -* As name suggest these exoskeletons assists in the arm and forearm region. They are designed by keeping shoulder joint and elbow joint, especially shoulder joint which is a complex joint in human body.
2. *Lower limb exoskeleton: -* Lower limb exoskeleton assists while walking, running, sitting or jumping and to transfer and weight from human body to ground.
3. *Waist Assistive Exoskeleton: -* One of the crucial regions in human body while designing a upper or lower limb exoskeleton is waist region. It connects both the exoskeleton and also provides support to waist, especially while lifting any heavy object.

1.3.2 Power source in exoskeleton

Primarily there are 3 types of power source which can be provided to an exoskeleton, these are: -

1. *Electric* actuators*:* - Most common type of power source, these are compact and light weight compared with hydraulic power source and generates more torque then pneumatic source.
2. *Pneumatic actuators:* - These uses pressurized air to actuate component in exoskeleton, most of the pneumatic exoskeletons are made of flexible tubes, and applying different pressure at different parts of the tubes generates different motions.
3. *Hydraulic actuators:* - Most powerful of all other source, but hydraulic sources are heavy and unsafe to use. Because of these two reasons most exoskeleton uses electric or pneumatic actuators.

1.3.3 Sensors in exoskeleton

Almost all of the sensors are being used in exoskeleton, but some of them are almost in every design, some of them are listed below: -

For sensing human body signals

1. *EMG:* - One of the widely used sensors to detect actuation signal in human body, these sensors are used to detect whether a part of the body is being actuated or not and in some case by how much strength, by detecting electric signal coming to the specific muscles. EMG electrodes are directly placed over actuating muscles.
2. *EEG:* - EEG works same as an EMG except it is used to detect signals in brain, motion in different parts of body is generated by signals in different parts of brain.

An EEG electrode is placed in different section of the head, depending upon which signal we want to detect.

For sensing angular position of joints in body

1. *Encoders:* - Encoders detects angular position and angular velocity using rotary disk with cut section in it. There are various types of encodes, such as, rotary encoders, optical encoders, magnetic encoder.

For detecting force and torque

1. *F/T sensors:* - F/T sensor directly read force or torque applied on load cells and transfer its value to the controller after processing. A F/T sensor needs calibration before using it.
2. *FSR:* - When force is applied to a FSR sensor, resistance from sensor changes which is detected by processor and then converted to force value. Like F/T sensors, FSR also needs to be calibrated.

For detecting acceleration and orientation

1. *IMU:* - An IMU sensor uses MEMS technology to detect angular acceleration in all 3 directions and its orientations.

Chapter 2

Review of literature

In last few decades there has been an increment in research for the development of the exoskeleton. Some of the work and research conducted by different people in different countries has been discussed below.

2.1 Surveys on Exoskeleton

Lopez-Mendez et al., in 2020 developed a 3 DoF (but in the actual design they only used 2 DoF) armoured upper limb exoskeleton. One of the actuators was at shoulder and other at the elbow. They used Maxon Motors, EC90 for shoulder and EC45 for elbow. At shoulder, actuation was provided directly using DC motor keeping motor directly at shoulder (back side), while for elbow they attached motor at shoulder and gave actuation to elbow using belt and pulley system. They used PI (Position and Integral) position control using EPOS4 compact controller from Maxon Motors.

A portable active pelvis orthosis for ambulatory movement assistance exoskeleton was designed by Parri et al., 2017. This design was made to the support the hip during walking. They used two linear actuator and two curved plates made of carbon fibre, to attach on both sides of the hips and power was provided from a back pack. While walking the linear actuator provides more power and actuation to the thighs reducing torque at hips and assisting it in flexion and extension. They used Serial Elastic Actuator (SEA) and EC60 70W DC Maxon Motor coupled with 100:1 CPL-14A-100-2A Harmonic motor. And for control they used RT controller sbRI0-9632, National Instrument, and FPGA.

Designing a mechanism equivalent to shoulder is a complex task, as shoulder has 3 DoF. These 3 DoF are non-concurrent, which increase complexity, for this purpose Christensen et al., 2017 proposed a novel mechanism which provides 3 DoF at shoulder, which has a double parallelogram linkage. They used two motor and connected them using 4 links and 7 joints to form 2 parallelograms. This arrangement gave a remote centre of motion and a 3 DoF at it. They used 2 EC60 Maxon Motors and CSD 25 2A Harmonic Drive Gear. For elbow the attached motor directly over the elbow to actuate it.

A study was conducted by Macke et al., 2017 to compare a passive lower back support while lifting some load, between Counterweight and Spring. This was a study done to find a difference between counterweight and spring system as a passive lower back moment support and its effect on the erector spinae longissimus muscle. A counterweight was attached to the subjects at the back at some distance and for spring, it was attached between things and waist to generate a counter force against load held in hand. In this no major difference was detected and spring performed equally as for counterweight but participants preferred spring system as much better choice as it was not as bulky as the counterweight.

For neurorehabilitation of hand Abbruzzesse et al., 2017 did an assessment by integrating a 3 DoF haptic robot (Haptic master and FCS moog) with a 4 DoF exoskeleton which includes flexion/extension, abduction/adduction, pronation/supination at wrist and finger pinch. Admittance control was used, in a VR (Virtual Environment) environment to control exoskeleton. To test it, subjects has to pick and place virtual cube box in VR.

In the field of exoskeleton, exosuits are also being developed. An exosuit is a soft exoskeleton build mostly as textile-based materials. One of such exosuit was developed by Samper et al., 2020, a cable driven exosuit for upper limb flexion whose design is based on textile-wearable Exosuit, as a soft robotics. Actuation happens using .68mm Bowden steel cable which is being driven by DC motors at the back. Housing of the motors, power source and electronics is placed in a 3D printed case kept and attached in a bag pack on the back. Cable passes through shoulder pivot and pulls forearm and arm. Motor used was a 24V@0.5A geared Maxon motors with torque exertion up to 5Nm, for conditioning and processing used NVidia Nano. For feedback and inputs, they used sEMG, MyoWare. OptiTrack markers were used to track hand trajectory. They used sliding mode controller to design control system for the experiment phase. After completion of prototyping and experimenting with 4 subjects it was concluded that to some extent it was able to provide some assistance but it still needs to be improved.

As considered by Christensen et al., 2017 and discussed above, shoulder has 3 DoF, but there was one more actuation possible at shoulder, that is vertical movement of shoulder, i.e., pushing shoulder upward. While designing a shoulder mechanism, this movement will be restricted, to counter this problem Jung et al., 2015 proposed a mechanism. They also tried to remove They tried to remove singularity point from the workspace of the human arm while wearing exoskeleton by tilting exoskeleton at different angle at Shoulder joint. The vertical movement of shoulder which is restricted while wearing exoskeleton was countered by adding a vertical movement to the exoskeleton by making an external prismatic joint at shoulder. They used 6 axis F/T sensors, ATI Mini45 to measure force on shoulder. In the experiment it was observed that the proposed design was able to provide some assistance to shoulder for vertical translation motion.

Determining movement intention of the human arm or a limb can lead to a better control and low latency to exoskeleton. To determine the intention, Accogli et al., in 2017 used an EMG. They used TeleMyo 2400R form Noraxon Inc., to detect Myo signals of right shoulder in following muscles, Trapezius, Anterior and Posterior Deltoid, in following arm muscles, Biceps and Triceps Brachii and in following forearm muscles, Flexor and Extensor Carpi Ulnaris. And used Al algorithm, Gaussian Mixture Model (GMM) and Support Vector Machine to detect the intention of human for his upper limb movement. Experiment of screen touching shows a comparison between 3 test scenarios.

By Huang et al., 2015, an intention-guided control strategy was developed for an upper limb powered exoskeleton called Intentional Reaching Direction (IRD). To sense the direction of the motion of the forearm Force Sensing Resistors (FSR), Flexiforce A201 Sensor from Tekscan were used. 4 FSR were placed around wrist and above Elbow in a circular formation. To detect the direction of the motion the resultant of the 4 forces acting on the 4 FSR were calculated along with the direction. For actuation DC motor 250841 from Maxon company, attached with HEDL-A11 encoders from Agilent Technologies were used. The response time of the Flexiforce FSR is 5 microseconds and range of 0.454 kg 4 modes of Activities were used for the motion of the hand, Stop, Bending and Stretching on a single joint, Moving Straight and Moving along a smooth curve. Forward Kinematic and Dynamic model were made to detect the IRD. In later part Online IRD Estimation was used to detect IRD.

Jarrasse et al., 2010 tried to evaluate and quantify different parameter of Exoskeleton for performance measurement. They used an Exoskeleton called ABLE, which is a 4 DoF Upper Limb Exoskeleton and is designed by CEA-LIST. ABLE is composed of 3 DoF at shoulder joint as a spherical joint and 1 DoF at Elbow joint as revolute joint. Measurement or Performance Indices were based on two criteria, kinematic and force measurement. Total of 9 Performance Indices were divided into 3 groups, based on End-Point trajectory, based on Joint rotation and based on Interaction forces. Pls namely, Movement duration, Velocity profile symmetry, Trajectory curvature and Smoothness are based on End-Point trajectory while Performance Indices like, Final joint angle, Joint Range of Motion and Cyclogram of the shoulder angular velocity according to elbow angular velocity are based on Joint rotation and finally average Force and Moment at the fixation and mean of absolute value of force and moment from each sensor were based on Interaction of forces. For the experiment a setup was created with ABLE exoskeleton and 10 subjects were selected to perform a task of pointing toward a fixed point in space, with (for reference) and without exoskeleton. Data was sampled at 200 Hz.

Su and et al., 2020, worked on an algorithm to predict ankle joint torque using time delay artificial neural network (TDNN) model with help of signals from sEMG and angular velocity. To verify their work, they conduct an experiment using TDNN model, which was trained by 80% data and 20% data for the testing from 8 subjects. Data was collected from using Delsys Trigno Wireless System. Data from sEMG and position sensor was sampled at 2000 Hz and 418 Hz respectively, EMG data was filtered by a 10-500 Hz bandpass filter and RMS value was calculate for a small range at regular interval. TDNN contains 10 hidden layers and 1 output layer and backpropagation learning algorithm, which takes joint angular velocity and RMS value of the sEMG signal as input and produces joint torque as an output. Two criteria were chosen to compare performance of the model, Cross-correlation coefficient, mean normalized root mean square deviation (NRMSE) and was compared with some existing model for similar task but with ANN and Support Vector Regression (SVR) models. In the end it was analysed that TDNN predicted better then ANN and SVR model.

A myoelectric control interface to an exoskeleton for the elbow and wrist was evaluated on the 10 fit and 4 people with Cervical level Spinal Cord Injuries (SCI) by McDonald et al., 2020. They designed a classifier algorithm to detect single and multi DoF movement intention from EMG signals. It was designed for Elbow flexion/extension, supination/pronation, wrist flexion/extension and wrist radial/ulnar deviation. The following classifier was trained using Linear Discriminant Analysis (LDA) and Recursive Feature Elimination with Cross Validation (RFECV). Data was collected using Delsys Bagnoli EMG system, which was filtered using Analog bandpass filter of 20 Hz – 450 Hz then data was sampled at 1 kHz and again filtered using a digital bandpass filter of same bandwidth and same range. It was found, after test, that, on average, classification performed with accuracy between 100 % to 89.5 % for abled people and between 95.0 % to 61.3 % for people with SCI depending on level of injury.

Table 2.1 Tabulated work of some authors

Author	**DoF**	**Mechanism/Exoskeleton**	**Actuation**	**Sensors**
Lopez et al., 2020	3	Upper limb exoskeleton	Maxon motor EC90, EC45	-
Samper et al., 2020	-	SEA-Cable driven upper limb exoskeleton	Maxon motor 24V-0.5A	sEMG MyoWare
McDonald et al., 2020	5	MAHI-II Exoskeleton	-	Delsys Bagnoli EMG
Su et al., 2020	-	-	-	sEMG
Accogli et al., 2017	5	NESM Exoskeleton	-	EMG Tele-Myo 2400R-Noraxon
Parri et al., 2017	4	Hip actuated, SEA-based exoskeleton	Maxon motor EC 60 and 100:1 CPL-14 A 100-2A Harmonic Drive	17-bit Rotary Encoder (DS-37Netzer Precision Motion Sensors
Christensen et al., 2017	3	Double parallelogram linkage, upper limb exoskeleton	Maxon motor EC60 and CSD 25 2A Harmonic Drive	-
Macke et al., 2017	1	Counterweight and spring mechanism	Passive	EMG
Jung et al., 2015	5	Upper limb exoskeleton	-	6 axis F/Tsensor, ATI mini45
Huang et al., 2015	3	FSR based 3 DoF upper limb exoskeleton	250841- Maxon motor	HEDL-A11 Encoder, A201 FSR-FlexiForce sensor
Jarrasse et al., 2010	4	Modified ABLE Exoskeleton	-	F/T sensor

2.2 Surveys on human body

To simulate a human model wearing an exoskeleton, for determining its efficiency and workability, an accurate design of human model is a necessity. And to make an accurate human model, body segment length, their mass properties, stiffness, damping, CoM and other physical property was must be available and these properties were determined from the literatures discussed below.

Plagenhoff and et al., 1983 tried to determine different anatomical data for analysing human motion. His main focus was on the trunk of the human body. His most work was based on Dempster's work in 1955. He performed experiments with 135 athletes to find CoM, body segment lengths and weight percentage with special focus on trunk. He created a lead model of human trunk and dissected a cadaver to perform experiments, like water submersion, to detect all those value for 3 segments of the trunk, Thorax, Abdomen and Pelvis. All the data is given was in tabular form with an error of 10% to 15% from an actual living body.

Nikolova et al., designed a CAD model of a male human body was designed in SolidWorks software using data from the reference used in it. Its Mass-Inertial characteristics were determined using SolidWorks media in two different position, Standing and siting. These values were compared with the previously available data, and its error was presented.

Krishnan et al., 2016, conducted a study of the human body's Moment of Inertia in bending position which can be used for a device. This device can be used by people with defect in legs and are using wheelchair and to help them when they are trying to shift from wheelchair to bed or chair. This self-transfer facility consists of a saddle attached from a turntable with the help of adjustable leg. By tilting and rotating a human can lay on the saddle and transfer himself to another chair. We require only the Moment of the Inertia of the human body found in this study along with the CoG point on different segments of the body.

N. Pan conducted a study on 86 males and 56 females in India to determine the length of the long bones and their proportion to the body heights for Femur, Tibia, Fibula, Humerus, Radius and Ulna bones. The average height of all subjects was 63.8 cm and 59 cm inches for male and female respectively. The average length and proportion of Femur, Tibia, Fibula, Humerus, Radius and Ulna bones, with respect full average human length are 16.7 cm and 26.2%, 14.2 cm and 22.3%, 14.3 cm and 22.4%, 12 cm and 18.8%, 9.4 cm and 15.1% and 10.5 cm and 16.4% respectively.

Table 2.2 list average length, mass and CoM for each segment of the body. It also shows proportion of these values with respect to length of whole body. The average height and weight of Indians as reported in ICMR short report of nutrient req. for Indians, is 177 cm, 65 kg for men and 162 cm and 55 kg for women. For current study we choose 177 cm as an average height of troops and 65 kg as their weight.

Table 2.2. Human model specification

Body part	Length (cm (%))	Weight (kg (%))	COM/COG wrt Proximal sagittal plane (cm) [15]
Full body	177 (100 %)	65 (100 %)	-
Head + Neck	27.656 (15.625 %)	5.092 (7.8 %)	(55 %) from Neck joint with Trunk
Torso (excluding Pelvis) Shoulder joint to Umbilicus plane	36.639 (20.7 %) Sagittal Plane (Shoulder joint to Umbilicus plane)	23.403 (36.006 %)	(63 %) From Shoulder including Pelvic
	43.365 (24.5 %) Frontal Plane (Shoulder to Shoulder)		
Pelvis	16.461 (9.3 %) Hip joint to Umbilicus plane	7.227 (11.118 %)	(5 %) form Umbilicus plane
	20.001 (11.3 %) Hip joint to Hip Joint		
Left Upper Arm	33.276(18.8 %) Humerus Bone	1.944 (2.992 %)	(43.6 %) from Shoulder Joint
Left Forearm (including Hand)	29.028(16.4 %) Ulna Bone	1.144 (1.76%)	(43 %) from Elbow Joint
	15.222 (8.6 %) Hand	0.474 (0.73 %)	(46.8 %) from Wrist
Left Thigh	46.374(26.2 %) Femur Bone	6.966 (10.717 %)	(43.3 %) from Hip Joint
Left Leg	39.471 (22.3 %) Tibia Bone	2.952 (4.542 %)	(43.4 %) from Knee joint
Left Foot	8.186 (4.625 %) Height	1.097 (1.688 %)	(50 %) from Ankle Joint Height
	22.125 (12.5 %) Length		

Chapter 3

Problem definition

Since exoskeleton is a new and rising technology, most of the exoskeleton being limited to medical and rehabilitation application and having a very less efficiency when it comes to the use in military or in industries and need for more extensive and broad research in this field is required. Even though passive and, to some extent, active exoskeletons are being utilized in the industries, an efficient and comfortable active exoskeleton is still in research phase. If we take a case of military use, it is even more less travelled and less achieved road. The one reason for such less achievement in military use is the gap between comfort of working without verse with exoskeleton, and since till today they are not able to provide enough assistance on regular basis, working without them can be more efficient.

3.1 Knowledge gaps in earlier investigations

Though research in the field of exoskeleton is growing rapidly, its use beyond rehabilitation is still a huge challenge. Exoskeleton which are build to provide assistance for task such as walking or lifting are not very efficient, due to latency from sensors, weight of exoskeleton, complexity of human body or many other factors. Since every human body differ in structure, weight and strength, designing a universal exoskeleton is a very complex task, even for a single part of body, such as upper arm. Due to a complex and semi-flexible musculoskeletal structure of human body, designing a simple outer joint to assist human joint is a difficult task. Most of these designs restricts one or more natural motion in human body causing discomfort and prolong use of such devices can lead to pain and injury in body. Most of the exoskeleton designed by scientist and engineers around the world have this problem, some restrict motion, some can be bigger in size and can only be operated with the help of external support for an example Jung et al., 2015's, design for vertical motion at shoulder needed an external support, while Christensen et al., 2017 design doesn't consider issue of vertical movement of shoulder joint.

3.2 Scope and objective

Purpose of project by DRDO is to develop a full body exoskeleton, which can help a soldier to lift heavy materials, lift them for longer time and be able to walk for a long distance without having much fatigue in muscle and prevent troops from having pain from lifting and walking heavy loads. In this project we restrict ourselves to the upper body exoskeleton, which will assist in lifting load and transfer it to the lower body exoskeleton. To be more specific, this project will deal with WAP-Exo, providing torque at pelvis when soldier is trying lift heavy object.

3.3 Problem statement

In the field, whether it be a warzone or peace time, a solider need to carry loads from one place to other, it can be in form of loading-unloading or transferring it from one place to another. In such situation and repeated tasking muscle will get tired due to fatigue and will reduce person's ability to perform other task such as border patrolling. To reduce fatigue and provide some assistance to soldiers, a WAP-Exo can be developed which can provide additional torque at pelvis and reduce fatigue in soldier's back, prevent him from injury and increase their efficiency.

For the above purpose, a weight limit has been specified on load while lifting task which is 30 kg. The designed exoskeleton must be able to support troops if they are trying pick weight under the specified limit. This support is only provided in sagittal plane, i.e., for flexion and extension of each joint.

Chapter 4

Methodology for solution of problem

To solve problem stated in section 3.3 work flow is shown in flow chart in Fig. 4.1. At first data from the experiment conducted in Parachute Regiment Training Centre (PRTC), Bangalore, was extracted, pre-processed and analysed with the help of graphs plotted in MATLAB. Secondly, to verify data that we posses correct data, simulation analysis was also conducted using Simulink's multibody block and MATLAB and to do so an approximated human model was designed with required joints. Thirdly, second part was repeated in OpenSim and in Adams. Third step was processed so that in later stage of this project it will be easy to migrate from one software to another, as these software has their own benefits and limitations. And also, they provide more confidence in data, as they are verified over different platforms. To have an accurate simulation wrt to real world PRTC experiment, an accurate design of human model is needed, so in next stage an accurate human model was designed with the help of data presented in Table 2.2. And in later stages, deep analysis and simulation was conducted on Elbow joint and to some extent on Shoulder joint.

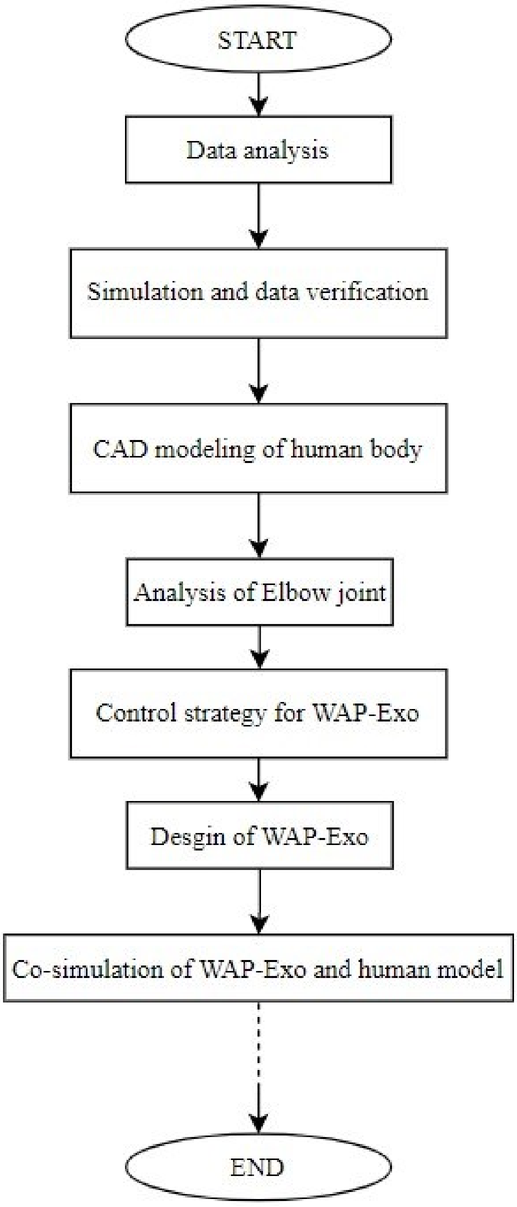


Fig. 4.1. Flow chart representing workflow

4.1 Stages of the work flow

The stages discussed above are detailed in following subsections: -

4.1.1 Stage 1: Data analysis

PRTC data contains angular position, angular velocity, angular acceleration and moment at different segments and joint of the troops. Along with this it contained time information as well, i.e., at what instant all those parameters were captured. To capture these data, they used Xsens's sensors placed on most joints, 17 to be exact and was pre-processed and stored in .H5 format.

We extract data only for Elbows, Shoulders, Pelvis joint to simulate and control upper limb exoskeleton and Hips, Knee and Ankle joint to simulate and verification of data and analysis in later stages. The extracted data includes only flexion and extension of each joint, since assistance is to be provided in Sagittal plane only and they include angular position, velocity, acceleration and torque for each joint.

PRTC experiment was conduct with 3 different loads with 2 different speed and for 2 test cases each. A data sets is the combinations of loads, speed and test cases, and these combinations are shown in Table 4.1.

Table 4.1. Possible combinations of test

Weights (kg)	Speeds (m/s)	Test case
17	NW - 1.5	T1
		T2
	FW - 1.75	T3
		T4
22.5	NW – 1.5	T1
		T2
	FW – 1.75	T3
		T4
29	NW – 1.5	T1
		T2

Extracted data was plotted in MATLAB using an interactive program, which gives options to the user to select which data they want to see, based on the combination from Table 4.1. One of the plots, trimmed for this thesis is shown in Fig. 4.2. Fig. 4.2, shows experimental angular position of the left Elbow joint wrt time.

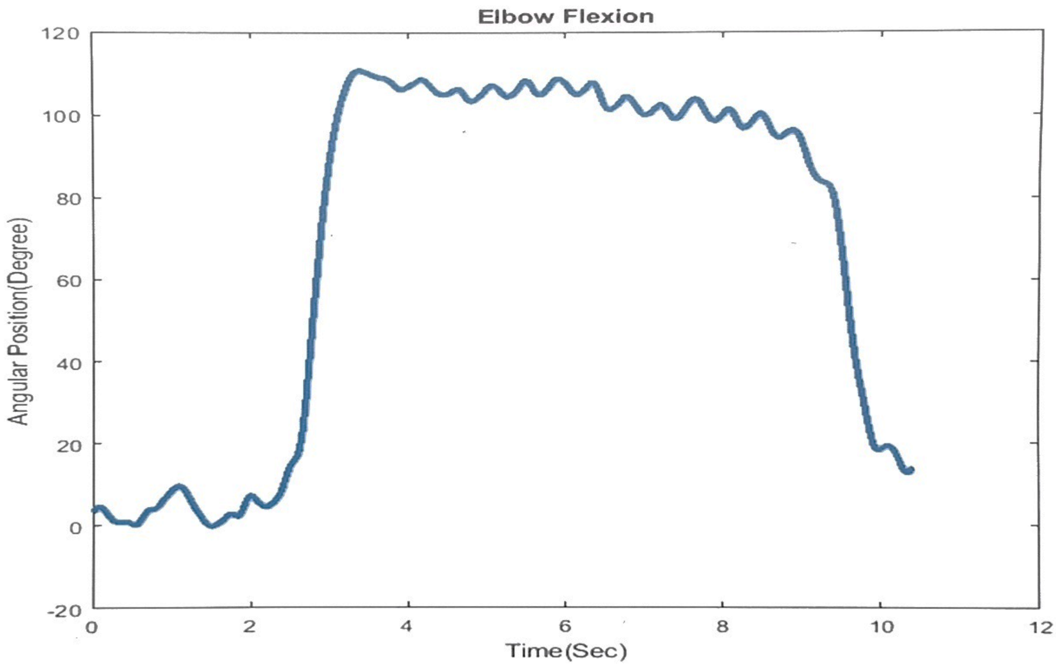


Fig. 4.2. Experimental angular position profile of left Elbow joint flexion

Test used for the plot in Fig. 4.2 is 17 kg – FW and T3 as indicated in Table 4.1.

Next, by superimposing data from all test cases for different kinematic parameters, such as angular velocity, for flexion and extension in Elbow, Shoulder and Pelvis joints, we determined the limit of kinematic parameters and listed them in Table 4.2. Based on this limits sensors and actuators will be selected for prototyping.

Table 4.2. Limits of each joint based on PRTC experiment

	Elbow	**Shoulder**	**Pelvis**
Velocity (degree/sec)	350	300	150
Acceleration (degree/sec^2)	5000	2500	1000
Torque (Nm)	40	40	160

4.1.2 Stage 2: Data verification through simulation

Data extracted in subsection 4.1.2 was used to simulate an approximated human model using Simulink' Multibody block and MATLAB, then stick figure of human model in MSC Adams and then in OpenSim using an open source musculoskeletal model. For this stage we only provided angular position to each joint. All simulation and analysis presented in this thesis uses only one set of data, 17 kg, Fast Walk and T3 data.

For simulation in MATLAB-Simulink, an CAD model of human body was designed in Solidworks with all required joints. Two instances of the simulation are shown in **Fig. 4.3**, position when picking up weight from ground and in **Fig. 4.4**, when model is walking with load in hand.

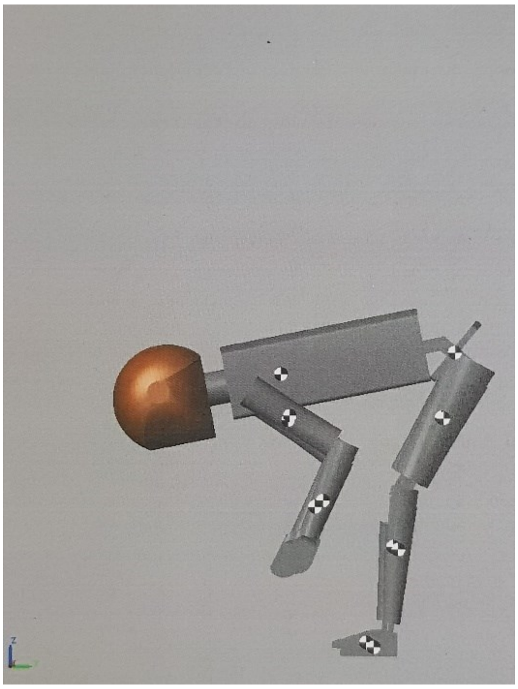


Fig. 4.3 Bending for lifting weight

Fig. 4.4 Walking & holding weight in hand

Parts of whole multibody Simscape model is shown in Fig. 4.5, Fig. 4.6, Fig. 4.7 with block description given in Table 4.3. The data provided to Simscape model was in form of an array, 1 array at each joint and 1 array for time values. Also, the time (T) values were shifted to origin, i.e., zero value, so that simulation always begin from T=0, to avoid any garbage value send to simulating model between zero and the starting time.

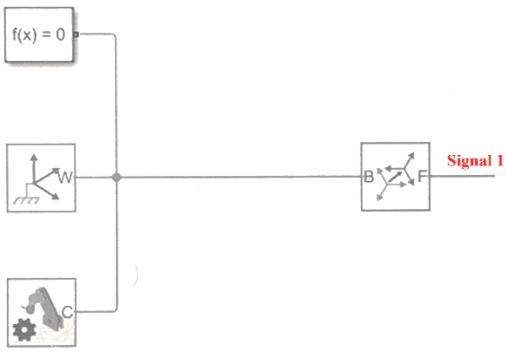


Fig. 4.5 Part-1 of the Simscape model for simulation

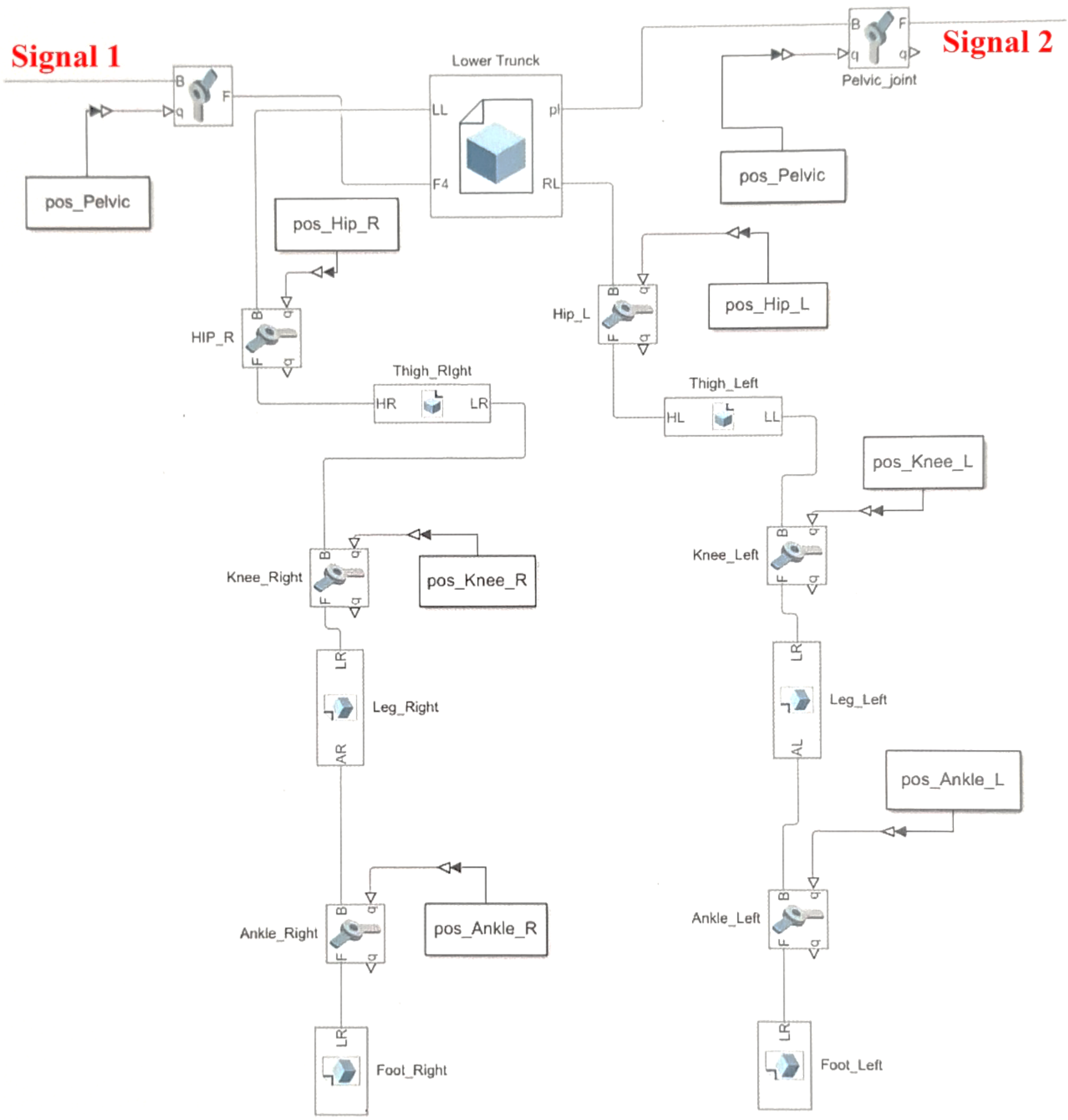


Fig. 4.6. Part-2 of the Simscape model for simulation

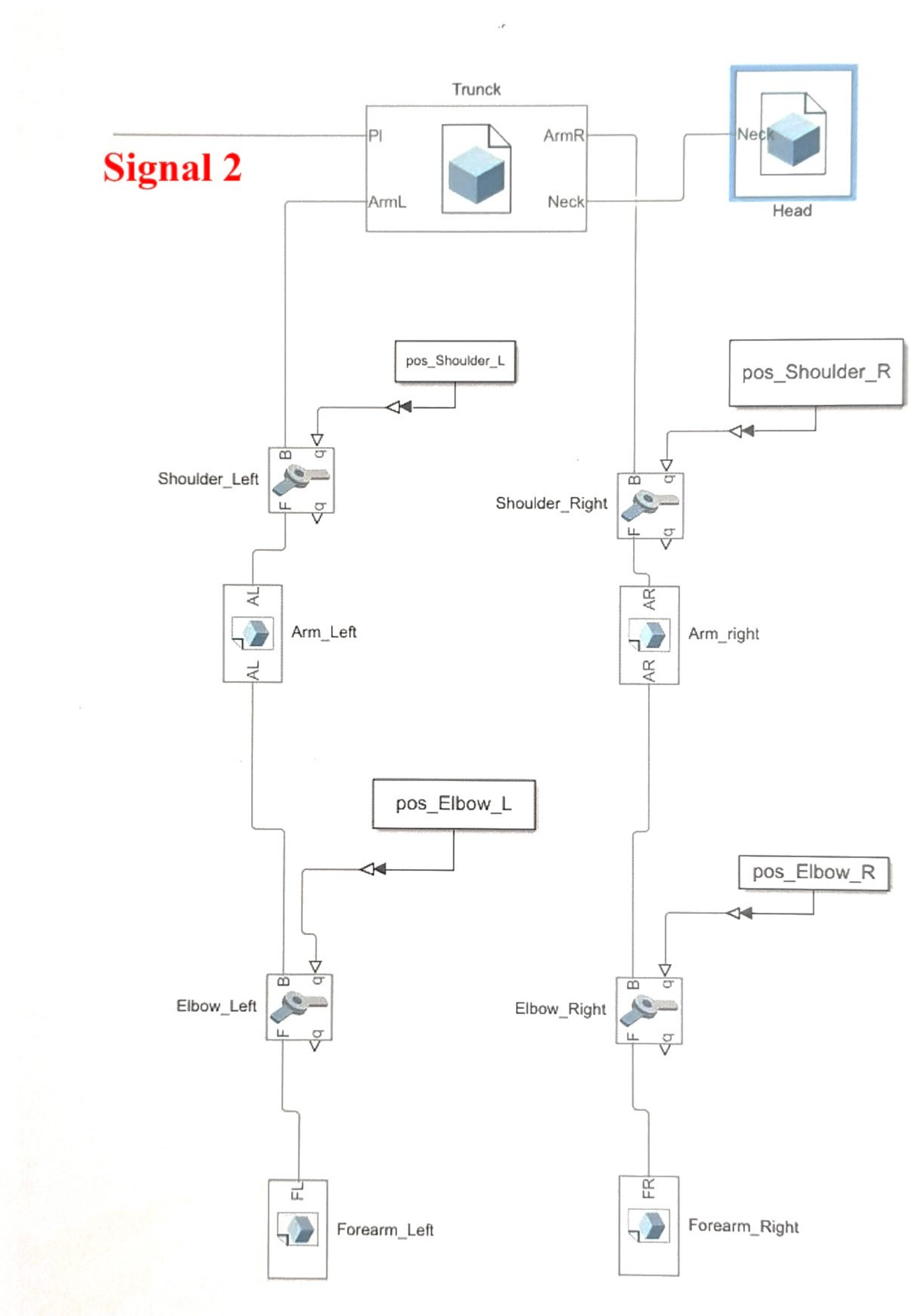
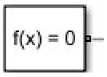
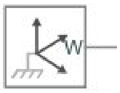
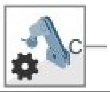
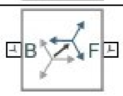
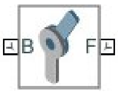


Fig. 4.7. Part-3 of the Simscape model for simulation

Table 4.3. Description of blocks used in Simscape model

Block	Name	Description
	Solver Configuration	Settings for simulation
	World Frame	World reference
	Mechanism Configuration	Mechanical and simulation parameters, like Gravity
	Rigid Transform	Rotational and translational transformation
	File Solid	To imports solid file, CAD models
	Revolute Joint	To provide revolute joint between two file Solids
	From Workspace	To read data from workspace of MATLAB
	Simulink-PS Converter	Converts Simulink/MATLAB values to physical values

For conducting simulation in Adams, we used a full-scale stick figure model, made in Adams its self, using links and joints. Angular position was provided using Spline in at each joint. Spline is way to provide 2D or 3D data set to Adams and one of the dimensions was set to time dimension. Simulation was conducted in a gravity free state, as we didn't have GRF and Joint properties to support the model under gravity. A platform was created as visible in Fig 4.8, Fig. 4.9, and contacts were provided between ankle and platform along with friction. For smooth forward motion a horizontal prismatic joint was applied on the pelvis, so that model is restricted to move forward only and data like segment length and mass were kept as approximated value.

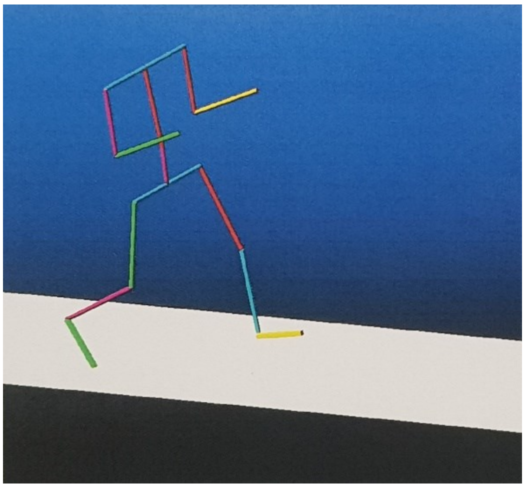


Fig. 4.8. Holding weight and walking

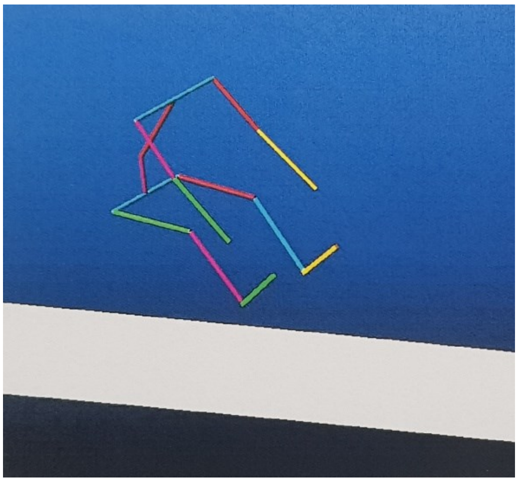


Fig. 4.9. Lifting weight

As visible in **Fig**. 4.9, during bending and lifting period model lifted its hips rather going down. It happens as bending at hip and lifting lower body at hip generates same results and because of the Pelvis region is made as prismatic joint in forward direction. To counter this problem, we can use time based joint appointment, till it walks, prismatic joint will be active and when it starts to bend it can be deactivated. And another solution would be to provide data for up and down movement of CoM. As a third alternative, we can fix foots while bending and fix Pelvis while walking.

And lastly it was simulated in OpenSim as well, by providing data through motion (.mot) file to a musculoskeletal model, and it was observed to be behaving as expected.

During simulation and based on observation from the behaviour some data were corrected, like Ankle joint was not behaving as is should be, its data was again extracted from PRTC experimental data, and its behaviour in simulation was observed and it came as expected.

4.1.3 Stage 3: Design of an accurate human model

An accurate human model was developed in Solidworks with the help of value presented in **Table** 2.2. Whole body was divided into following segments: -

1. *Torso:* - this segment includes portion from Shoulder joint to Umbilicus plane, i.e., pelvis is excluded from trunk.

2. *Pelvic:* - pelvic is the region between Hip joint and Umbilicus plane.
3. *Upper arm:* - as name suggest it's the region between Shoulder joint and Elbow joint, i.e., whole length Humerus bone.
4. *Forearm:* - forearm includes two bone, Radius and Ulna bone, and designing its model accurate was complex, so for simplicity we choose Ulna bone. Since wrist and hand motion is not included for the design of exoskeleton, hand and wrist are taken as single portion with forearm.
5. *Thigh:* - thigh lies between Hip and Knee joint and Femur bone has been taken as base design for the thigh.
6. *Leg:* - also known as Shank, includes two bones, namely Tibia and Fabula bone. Since Tibia is larger than Fabula, we choose Tibia as our base bone for the design of leg.
7. *Foot:* - lower most part of the body, which generate friction to walk and provide platform for the rest of the body. Height in foot varies nonlinearly, so approximated the height and curve, to generate, required dimension, weight and mass distribution.
8. *Head and Neck:* - since head and neck does not have much part to play in mechanism expect for changing CoM and weight of the human model, we fixed them with torso.

Designing a very accurate CAD model of a human is very complex task, because joints in human body are not as a point joint or an axis joint. Each joint has its own complexity. To reduce such complexity and make a simple CAD model, which is accurate enough for simulating exoskeleton, following consideration has been taken: -

- Only flexion and extension motion of each joint has been considered
- Motion is restricted to Sagittal plane only
- Each joint in human body will be considered as revolute joint, with axis of rotation pointing towards Z axis, and perpendicular to Sagittal plane.
- Each limb is considered as near cylindrical shape, but some shaping is done to make them look and behave more accurate to real human limbs.
- Torso is a highly complex structure as studied by Plagenhoff et al., 1983. The joint is not a fixed joint as in Elbow or any other joint. Joints in torso can be visualized as if each differential portion of lower torso has one revolute joint. So, to simplify it we considered upper portion and lower portion (Pelvis) of torso as a solid body and a single revolute joint exist between them, which provides rotation in Sagittal plane.

Based above discussion, consideration and Table 2.2, we designed an accurate CAD model of a human and is presented in Fig. 4.10. Head and Neck portion is still to design and to add in the following model.

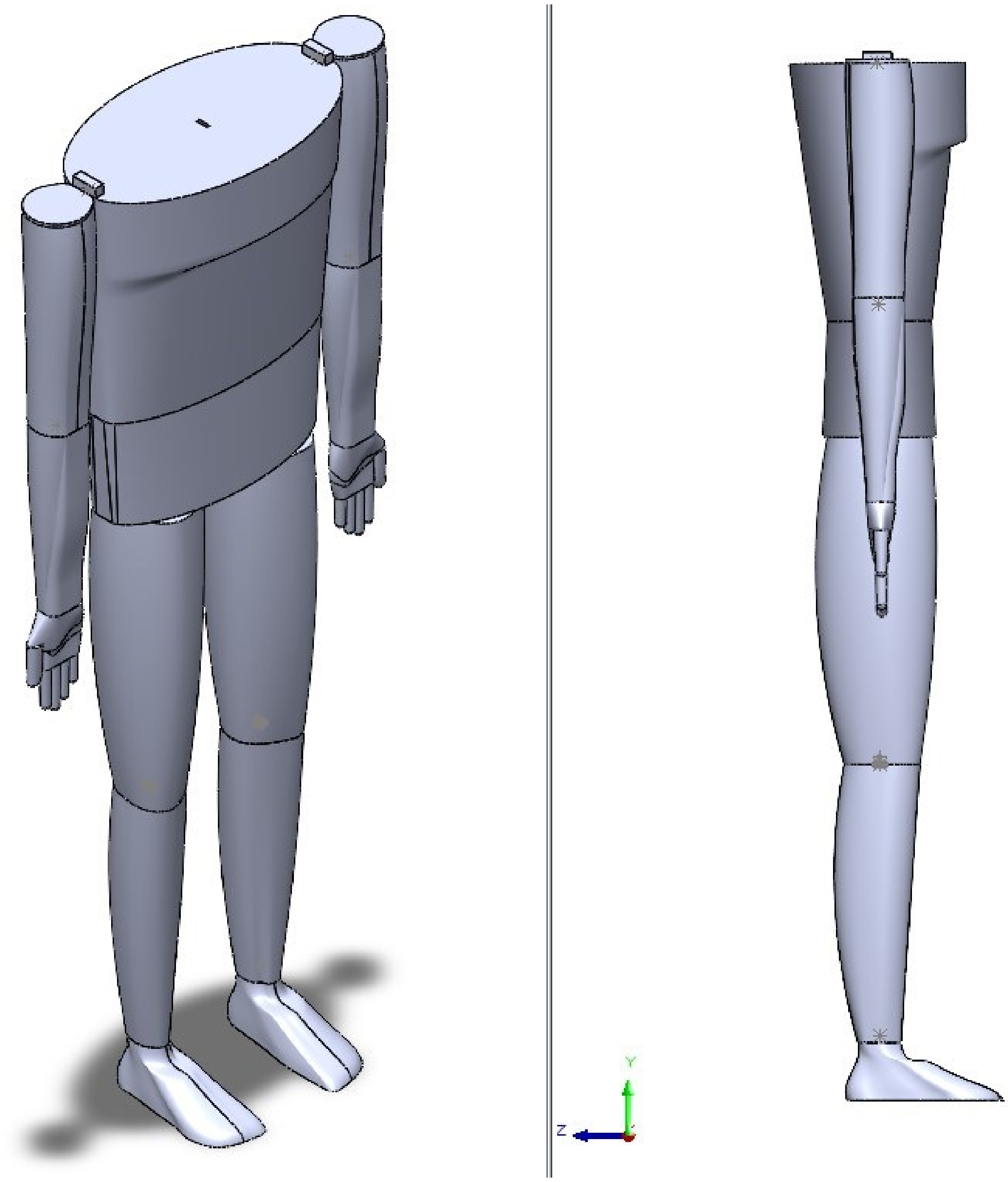


Fig. 4.10. CAD model of human, left, isometric view and right, right side view

4.1.4 Stage 4: Analysis of Elbow joint

Analysis of all 9 joints in human model is a complex, and since we are supposed to simulate and control an upper limb exoskeleton our primary focus is on Elbow, Shoulder and Pelvis joints. With this focus in mind, we first analysed elbow flexion and extension using torque data provided in PRTC data. For this purpose, a 3 link, 2 revolute joint model was created in Adams as shown in Fig. 4.11, with its component specified in the figure.

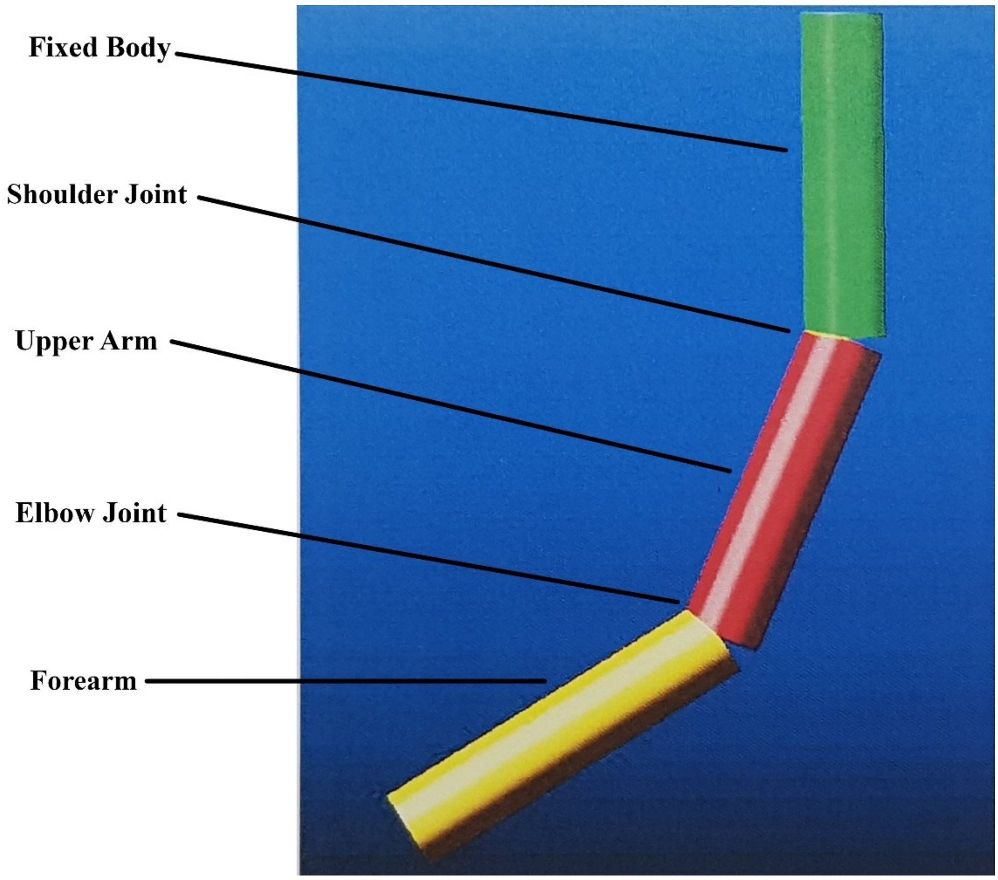


Fig. 4.11. Snap during simulation of the Elbow and Shoulder joint flexion

Before simulation, each of the two joints were provided with a random stiffness and damping coefficient, and torque profile for Elbow and Shoulder joint was applied. During simulation its behaviour was observed, its angular position and angular velocity profiles were generated. Fig 4.11 shows an instance during simulation.

Ones simulation shows an expected result, we moved to simulating Elbow and Shoulder joint of the CAD model. Same procedure was followed, and during this simulation all other parts of human body were kept fixed, except for the Shoulder and Elbow joint of left side of the model. Angular position of the Elbow, as an output is shown in Fig. 4.12.

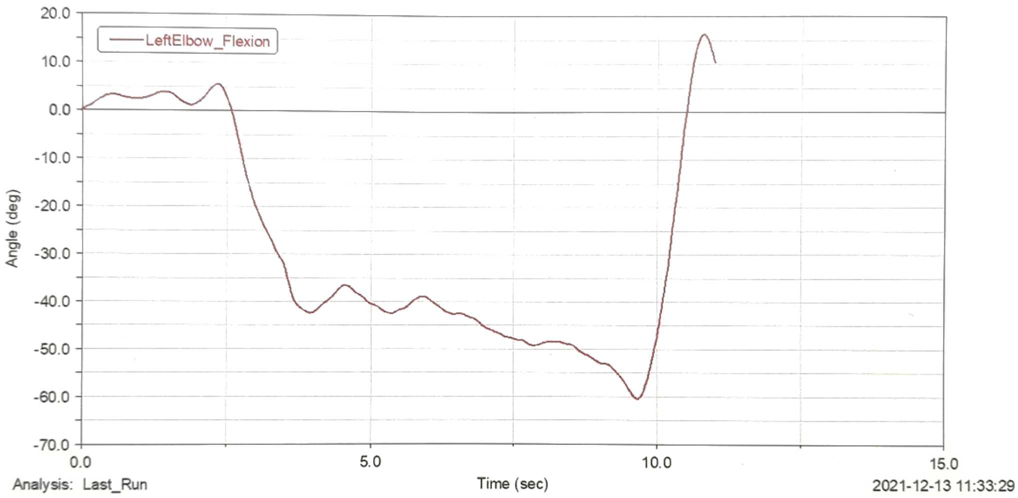


Fig 4.12. Simulated angular position of left Elbow joint flexion

Fig 4.12 is inverted as compared due to change in the direction of the axis of rotation in Adams software.

4.2 WAP-Exo for Pelvic region

To design and control a WAP-Exo for lifting and walking, we first designed a flow chart of the flow of action. Using which one can design control system and its algorithm for control of WAP-Exo. Stated flow chart is presented below.

Chapter 5

Results, discussion and future work

In stage 1 in subsection 4.1.1, it was calculated frequency of data sampling during experiment was 59.8802 Hz, i.e., time interval between two samples were 0.0167. In same stage, subset of data of different parameters can be utilize to determine action of the troop, which can be used to study transient and steady state response separately.

Data presented in Table 4.2 was used to sort available actuators and sensors for prototyping of the model. For each joint, Elbow, Shoulder and Pelvis, one specific actuator and sensors will be selected.

Fig. 5.1 shows a comparison between experimental and simulated results. Maximum value of simulated result reached 60 while actual or experimental value reached 110. This difference occurs due to the fact that, Stiffness and Damping coefficient of

Elbow joint is unknown, and values were chosen based on hit and trail method. Simulation with CAD model of human was conducted repeatedly, with various values of both coefficients. For each case maximum value of simulated graph was different than that of experimental value. One of such case is presented in Fig. 5.1.

Next stage of this project is to design a control system, using space state model of a simple WAP-Exo exoskeleton, for specifically lifting task, as explained in Section 4.2. The model will be simulated in numerically in MATLAB, and in Adams, a simple cable and pulley mechanism operated with a motor, for lifting weight, will simulated and control will be tested. Simultaneously, one model for upper limb exoskeleton and a WAP-Exo will be designed in Solidworks for prototyping and testing control and algorithm in real world environment.

Chapter 6

Conclusion

So, far seen in the above discussions in various chapters, data analysis, superimposition of data to find out requirement for building a prototype, simulation to verify and move one step towards simulation with exoskeleton, modelling of an accurate CAD model of human will lead to more accurate results. We performed torque analysis using simulation in Adams for one joint, Elbow, which can be extended to Elbow and Shoulder working together for development of upper limb exoskeleton. While designing a control for single joint for WAP-Exo in next stage, can be utilize to control Elbow and Shoulder actuators and provide some assistance to them. In next stage we might not even need full body CAD model of human, its one or two parts can be separated to co-simulate upper-limb, arm and forearm, with an upper limb exoskeleton. Same can performed for WAP-Exo.

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