Design & Optimization of Rehabilitation Exoskeleton device for Indian Amputees

A. Srinath, Komatipalli Umamaheswara Rao, Paladugu R P, Y. Kalyan Chakravarthy

Abstract*: *In the modern day scenario of medical robotics, one of the major problem where 16% of people suffering with problems is with the human gait. Replacement of lower limb is burdensome to the middle and lower class people as it includes huge amount of money. Especially the disorders caused to lower limbs might be a hectic challenge to cure the problem for the doctors as well as physiotherapists. Considering this issue as a challenge, this paper depicts a model exoskeleton for lower limb motion by imbibing the concepts of advanced Mechatronics. The created model supports the patient in all aspects of human gait effectively and efficiently. The dynamic analysis was performed by the software MS Adams and the Kinematic analysis was obtained with DH algorithm using MAT Lab. With rapid advancements in the field of engineering and technology, sensors like position, displacement and speed were employed for automating the exoskeleton model. This plays a vital role in supporting the patients to recover instantly from lower extremity disorders.

Index Terms*: *Exoskeleton, Lower-limb Exoskeleton, rehabili tation, walking, wearable, kinematic Analysis, dynamic Analysis.

I. INTRODUCTION

Severe health issues such as osteoporosis, muscle atrophy, pressure sore occur due to the unfortunate injuries or loss of lower-limbs in human beings. Because of these issues the humans can't do his/her daily jobs. The traditional rehabilitation can be completed by only the rehabilitation therapists and it is not possible to do the therapy because of high number of patients and shortage in the rehabilitation therapists [1,2]. Hence of these reasons the human beings life becomes very difficult and facing a lot of cardiac problems in these days. To rectify these urgency needs and to give a comfortable life to the human the robot machines are come into picture and these are named as a lower-limb exoskeletons or wearable exoskeletons. For these considerations, the most relevant concepts include mechanical, electrical and biomedical constraints while designing these types of human assistive devices [3]. It is observed that industrial revolution in the stream of biomechanical engineering gives a better and quality life to the human. The researchers have done a lot of research on these types of lower-limb exoskeleton robots, also some of the robots already came into market as domestic and commercial appliance products. Some of the researchers concentrated on the design and some on gait and some on DH notation of the lower-limb exoskeleton [4]. But the main motto of the whole research is to give a better and comfortable life to the patient. With the name "Hardiman" the first exoskeleton was developed by General Electric and United States Armed Forces in 1960s. It was a Hydraulic, electrical actuated and is too heavy and bulky of military use. But in the earliest by a Russian named Nicholas Yaginlater an exoskeleton-like device was developed for set of jumping, running and walking assisted apparatus in 1890. Consideration will be given to inventive steps should create what is more help to restore the elderly and physically tested subjects[5]. Through days gone by a couple of years, assistive gadgets have been processed that have the ability to provide support for the main body weight [6,7]. To process gadgets with more portability, wearable exoskeletons have gained ubiquity in the immediate future. For bio - mechanical engineering, the terms "Exoskeleton" use wearable robots that could also be viewed as robotic orthotics that will eventually be used for months to peruse the wearer [8,9]. In this paper we are going to design a model which is very useful to the aged persons or the persons having some lower limb disabilities and to assist persons while they are doing their daily tasks[10]. It can also be used for physiotherapy. A 6-DOF lower limb exoskeleton was designed and the Kinematic (Direct Kinematics and Inverse Kinematics) and Dynamic analysis was done by using DH notations, Euler-Lagrange methods. And the exoskeleton was controlled by means of EMG signals and interfacing of EEG, signal conditioning [11,12,16]. A new type of lower extremity exoskeleton robot with motor power driven at the hip joint, and the other joints without power driven is structured and the weight is diminished to a certain degree. The traditional uniaxial structure is replaced with 4-bar mechanism, to transfer power; an air-spring slide mechanism is designed here. To lock at standing, the knee joint and to unlock, the swing phase ankle mechanism is designed [13]. By using DH parameters the kinematic relation is established and the testing was done using MAT Lab and Solid-works. Here in this article the author described different type of lower-body exoskeletons which are widely employed in medical and non-medical applications.

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A. Srinath, Koneru Lakshmaiah Education Foundation, Vaddeswaram, INDIA.

Komatipalli Umamaheswara Rao, Koneru Lakshmaiah Education Foun dation, Vaddeswaram, INDIA.

Paladugu R P, Koneru Lakshmaiah Education Foundation, Vaddeswaram , INDIA.

Y. Kalyan Chakravarthy, Koneru Lakshmaiah Education Foundation, Vaddeswaram, INDIA.

In this the present existing exoskeleton in the market are compared in their design and functionality from Mechanical and Electrical perspective including key issues such as control strategy, actuators, powering methods, sensors, materials and mechanisms. In this the model is designed considering elderly people [14-15]. Here the control system is based on multi sensors and DSP was introduced in this work. By using DH parameter method the kinematic analysis is done. Using Newton-Euler method the dynamic modeling analysis and subsequently the required force at each to drive the lower extremity was obtained.

II. METHODOLOGY

A. Anthropometric Analysis:

Considering the dimensions obtained by anthropometric analysis, the mechanical structure of exoskeleton was modeled. Anthropometry provides the data used in the indirect appraisal of body composition. Considering skin folds and Girths as number of equations to estimate the total body fat, the body density and the overlying subcutaneous fat. Moreover, trunk and limb girths provide estimates of relative muscle mass.

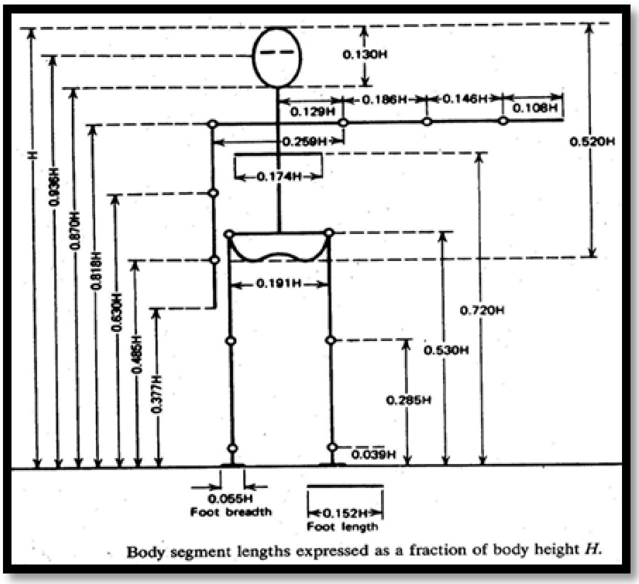

Fig.1: Body segment lengths expressed as a fraction of body height H

Here

A = H; B= 0.9243H; C = 0.870H; D = 0.818H; E = 0.630H; F = 0.468H; G = 0.3676H; H* = 0.122H; I = 0.5367H; J = 0.7384H; K = 0.5693H; L = 0.2252H; M = 0.039H; N = 0.1165H; O = 0.1569H; P = 0.1581H; Q = 0.1156H; R = 0.2495H; S = 0.04698H; T = 0.1479H.

B. Gait Cycle:

Analysis of gait is human locomotion study. It is necessar y to isolate the shortest, unique, repeatable task during gait in order to analyze and quantify how someone walks. This t ask is called the cycle of the gait.From any gait event to the same subsequent event on the same foot, a single gait cycle can be measured, but the conventional tacit model considers that the gait cycle is measured from one foot strike to the s ubsequent foot strike.

Quantifying aspects of the gait cycle, such as time and sp atial parameters, allow for gait symmetry, variability and qu ality analysis.

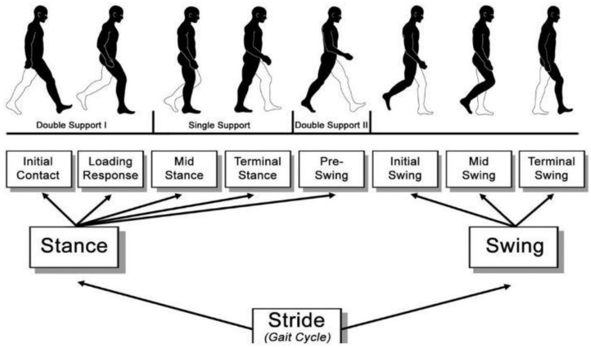

Fig.2: Gait Cycle

Primary Phases of the Gait Cycle:

The gait cycle can be broken down into two primary phases, the stance and swing phases, which alternate for each lower limb.

- Stance phase: Consists of the entire time that a foot is on the ground.
- Swing phase: Consists of the entire time that the foot is in the air.

It is possible to introduce complementary phases by obser ving both the spatial and temporal characteristics of the two lower limbs. When both members are in the stance phase si multaneously, we're talking about bipedal support or dual s upport (2 times 10 %); when only one is in the support phas e, we're talking about unipedal support or single support (4 0 percent), while the second is in the oscillating phase.

C. Structure of Lower Extremity Exoskeleton:

The dimensions of the thigh, shank and ankle are obtained from the anthropometric data, which is depicted above. The anthropometric data of a 5.85 feet healthy person was collected and according to it, the structure was designed. **Fig.3** shows the basic model of the lower extremity exoskeleton.

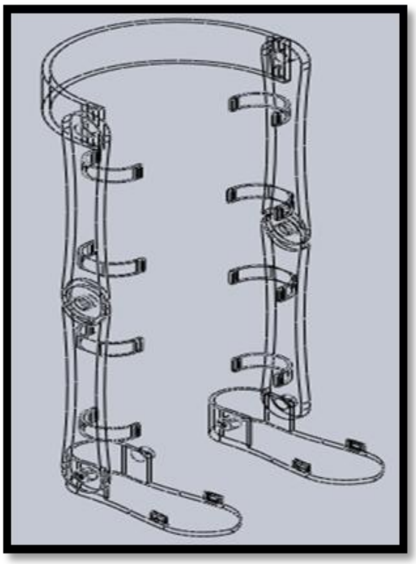

Fig.3: Basic Model of a Lower-Limb Exoskeleton modeled in Solid Works

D. Structural Analysis:

The structure was analyzed using ANSYS software and the static conditions were applied. The main aim of the static analysis is to test whether the designed model is sustainable to the applied load. For a 5.85 feet healthy person, the average weight was considered and applied on the model. As the model was designed for the aged people who are suffering with the lower-limb injury or unfortunate lower motor failure, the weight and other body segment conditions were also considered.

E. Multi Body Dynamic Analysis:

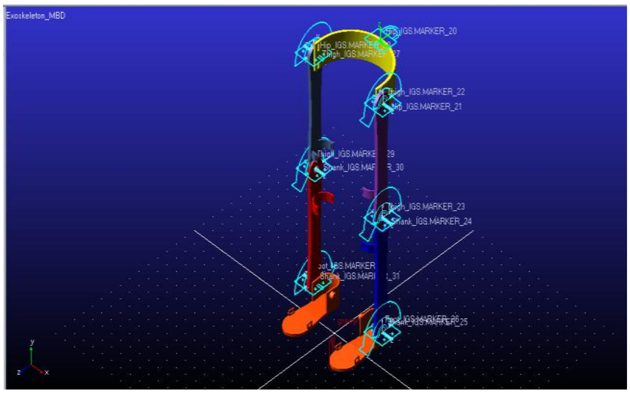

Fig.4: Applying motions to the imported model in MS Adams

Using Kinovea software Joint angles and linear velocity were measured for kinematic and dynamic analysis. The DH calculations were performed in MAT Lab.

F. Kinematic Analysis:

The relationship between end effector and articular space is given by Kinematics. To generate trajectories, and control joint actuators, this approach is very useful.

1) Direct Kinematics:

To find the position and orientation of the End-effector, the direct kinematics plays a vital role and the equations are defines as

Articular coordinates $(q_1, q_2, q_3, \ldots, q_n)$	⇄	Position & Orientation of the robot $(x, y, z, \alpha, \beta, \gamma)$

Fig.5: Kinematics of a Robot

$$x = f_x(q_1, q_2, q_3, \ldots\ldots\ldots\ldots, q_n)$$
$$y = f_y(q_1, q_2, q_3, \ldots\ldots\ldots\ldots, q_n)$$
$$z = f_z(q_1, q_2, q_3, \ldots\ldots\ldots\ldots, q_n)$$
$$\alpha = f_\alpha(q_1, q_2, q_3, \ldots\ldots\ldots\ldots, q_n)$$
$$\beta = f_\beta(q_1, q_2, q_3, \ldots\ldots\ldots\ldots, q_n)$$
$$\gamma = f_\gamma(q_1, q_2, q_3, \ldots\ldots\ldots\ldots, q_n)$$

III. MODELING

From the **Fig.1** the following calculations are done.

Here H is height of the person, take H = 5.85 feet = 174.3cm
Thigh = 0.53H - 0.285H = (0.53*174.3)-(0.285*174.3) = 92.379 – 49.6755 = 42.7035cm = 427.035**mm**
Shank = 0.285H-0.039H = (0.285*174.3)-(0.039*174.3) = 49.6755 – 6.7977 = 42.8778cm = 428.778**mm**
Knee = 0.039H = 0.039*174.3 = 6.7977cm = 67.977**mm**

By using the above dimensions the exoskeleton was modeled in Solid works.

Static analysis was made using ANASYS software. First the drawn model was examined whether it was capable of weighing the loads that were acting on it. In this analysis, an average load of 1000N applied (500N on each side of the lower limb extremity) by fixing the foot on ground and the weight was acting downwards.

It was performed several times for different load conditions. While doing some iterations the load was heavily acting on foot and it might get damaged. Hence it was observed that 1000N was feasible.

Thus, we conclude that the model is good with Aluminum material and can withstand a load of 1000N.

In Multi body Dynamic analysis, the forces acting on the model are considered and the torques at every joint has been obtained. The graphs for force Vs Displacement, Time Vs Displacement, Time Vs angle, Time Vs velocity graphs are obtained and they are depicted below.

The Kinematic analysis was performed considering Denavit Hartenberg rules. Thus Joint angle (θ), Joint Displacement/offset (d), Link length (a) and Link twist (α) were obtained, all these are tabulated below and the results are obtained by using MAT Lab.

Joint	Movement	α_{i-1}	a_i	d_i	θ_i
Hip	**Rotation**	0	0.427035	0	170

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Knee	**F/E**	0	0.428778	0	196
Ankle	**F/E**	0	0.067977	0	80

F/E – F – Flexion, E – Extension

Table.1: D-H parameters for Right Leg.

α – Link Twist;
a – Link Length;
d – Link offset;
θ – Joint Angle

The following is the DH transformation matrix

$$^{n-1}T_n = \begin{bmatrix} Cos\theta_n & -Sin\theta_n & 0 & a_{n-1} \\ Sin\theta_n Cos\alpha_{n-1} & Cos\theta_n Cos\alpha_{n-1} & -Sin\alpha_{n-1} & -d_n Sin\alpha_{n-1} \\ Sin\theta_n Sin\alpha_{n-1} & Cos\theta_n Sin\alpha_{n-1} & Cos\alpha_{n-1} & d_n Cos\alpha_{n-1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The following are the transformation matrices for right leg.

$$^{0}T_{1,R} = \begin{bmatrix} Cos(170) & -Sin(170) & 0 & 0.4270 \\ Sin(170)Cos(0) & Cos(170)Cos(0) & -Sin(0) & -(0)Sin(0) \\ Sin((170)Sin(0) & Cos(170)Sin(0) & Cos(0) & (0)Cos(0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 2$$

$$^{0}T_{1,R} = \begin{bmatrix} 0.938 & -0.346 & 0 & 0.4270 \\ 0.346 & 0.938 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 3$$

$$^{1}T_{2,R} = \begin{bmatrix} Cos196 & -Sin196 & 0 & 0.4287 \\ Sin196Cos0 & Cos196Cos0 & -Sin0 & -(0)Sin0 \\ Sin196Sin0 & Cos196Sin0 & Cos0 & (0)Cos0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 4$$

$$^{1}T_{2,R} = \begin{bmatrix} 0.342 & -0.939 & 0 & 0.4287 \\ 0.939 & 0.342 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 5$$

$$^{2}T_{3,R} = \begin{bmatrix} Cos(80) & -Sin(80) & 0 & 0.06797 \\ Sin(80)Cos(0) & Cos(80)Cos(0) & -Sin(0) & -(0)Sin(0) \\ Sin((80)Sin(0) & Cos(80)Sin(0) & Cos(0) & (0)Cos(0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 6$$

$$^{2}T_{3,R} = \begin{bmatrix} -0.110 & 0.993 & 0 & 0.06797 \\ -0.993 & -0.110 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 7$$

$$^{0}T_{3,R} = {}^{0}T_{1,R} * {}^{1}T_{2,R} * {}^{2}T_{3,R} = \begin{bmatrix} 0.992 & 0.1058 & 0 & 0.8288 \\ -0.1058 & 0.9926 & 0 & 0.2162 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 8$$

Joint	Movement	α_{i-1}	a_i	d_i	θ_i
Hip	**Rotation**	0	0.427035	0	190
Knee	**F/E**	0	0.428778	0	196
Ankle	**F/E**	0	0.067977	0	100

F/E – F – Flexion, E – Extension

Table.2: D-H parameters for Right Leg.

The following are the transformation matrices for left leg.

$$^{0}T_{1,L} = \begin{bmatrix} Cos(190) & -Sin(190) & 0 & 0.4270 \\ Sin(190)Cos(0) & Cos(190)Cos(0) & -Sin(0) & -(0)Sin(0) \\ Sin(190)Sin(0) & Cos(190)Sin(0) & Cos(0) & (0)Cos(0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 9$$

$$^{0}T_{1,L} = \begin{bmatrix} 0.0663 & -0.997 & 0 & 0.4270 \\ 0.997 & 0.663 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 10$$

1

$$^{1}T_{2,L} = \begin{bmatrix} Cos(196) & -Sin(196) & 0 & 0.4287 \\ Sin(196)Cos(0) & Cos(196)Cos(0) & -Sin(0) & -(0)Sin(0) \\ Sin((196)Sin(0) & Cos(196)Sin(0) & Cos(0) & (0)Cos(0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 11$$

$$^{1}T_{2,L} = \begin{bmatrix} 0.342 & -0.939 & 0 & 0.4287 \\ 0.939 & 0.342 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 12$$

$$^{2}T_{3,L} = \begin{bmatrix} Cos(100) & -Sin(100) & 0 & 0.0697 \\ Sin(100)Cos(0) & Cos(100)Cos(0) & -Sin(0) & -(0)Sin(0) \\ Sin((100)Sin(0) & Cos(100)Sin(0) & Cos(0) & (0)Cos(0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 13$$

$$^{2}T_{3,L} = \begin{bmatrix} 0.862 & 0.506 & 0 & 0.0697 \\ -0.506 & 0.862 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 14$$

$$^{0}T_{3,L} = {}^{0}T_{1,L} * {}^{1}T_{2,L} * {}^{2}T_{3,L} = \begin{bmatrix} -0.5834 & -1.8098 & 0 & 0.3933 \\ 1.1895 & -0.1240 & 0 & 0.4929 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad 15$$

The above equations represent the kinematic analysis of the right and left legs. Here in the above **equation – 8** represents right leg final position and orientation matrix and **equation – 15** represents the left leg final position and orientation.

IV. Results

A. Static Analysis:

To the proposed model, we developed the static Analysis using Ansys Software and studied various analyses which were performed during the stimulated work. On observing various parametric results the equivalent von misses stresses and different types of deformations were observed predominantly.

Effectively positive results are developed within the stress limit were clearly observed as shown in the figures 6,7,8,9.

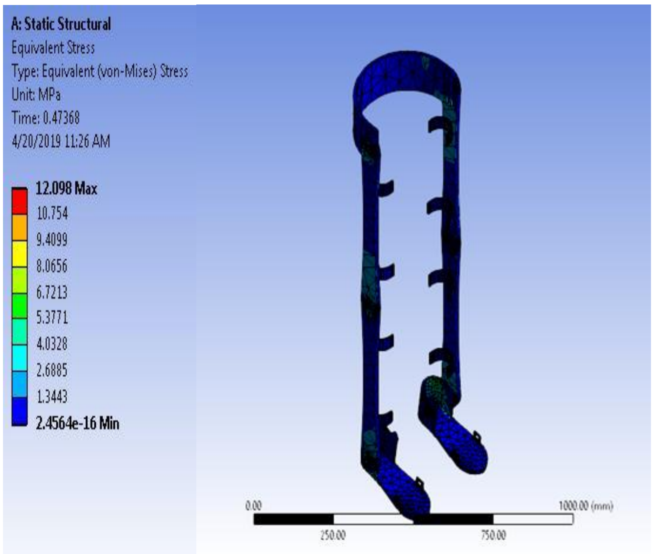

Fig.6: Equivalent (VON-MISES) stress analysis done in ANSYS

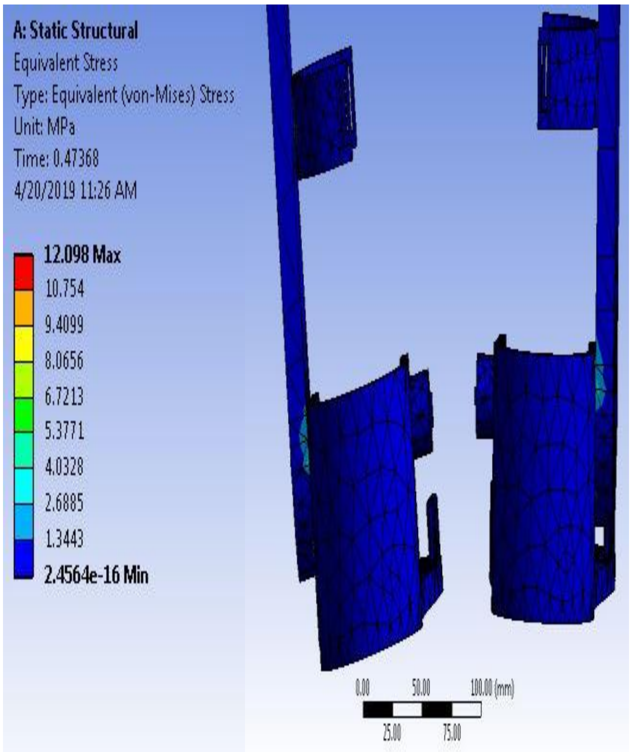

Fig.7: Equivalent (VON-MISES) stress analysis done in ANSYS

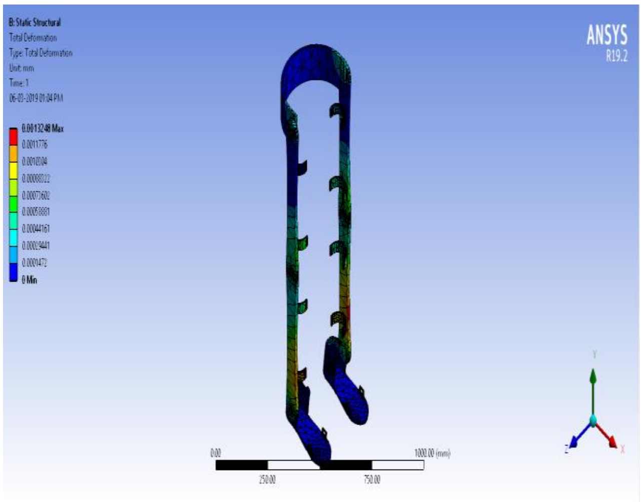

Fig.8: Total Deformation analysis done in ANSYS

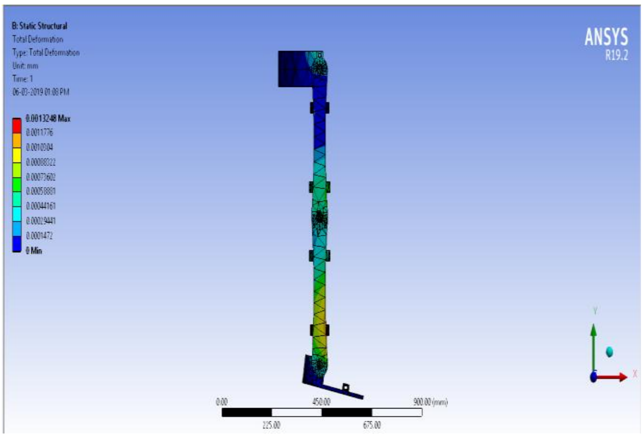

Fig.9: Total Deformation analysis done in ANSYS

B. Dynamic Analysis:

Dynamic analysis of the proposed model has been done in Adams software by taking count of various links with various movements and momentums in the scenario, also calculated time vs force analysis for each individual link of the lower limb exoskeleton. Here maximum force acting on the exoskeleton is 300N and the minimum force the same situation is about 10N. Concluding that even though various exoskeletons were modeled to various persons the force would be in the same premises.

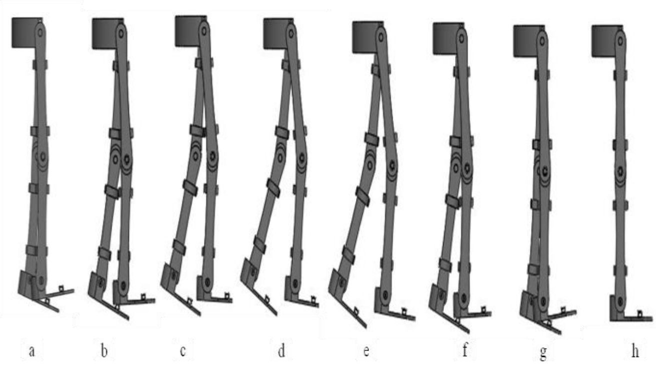

Fig.10: Gait Cycle

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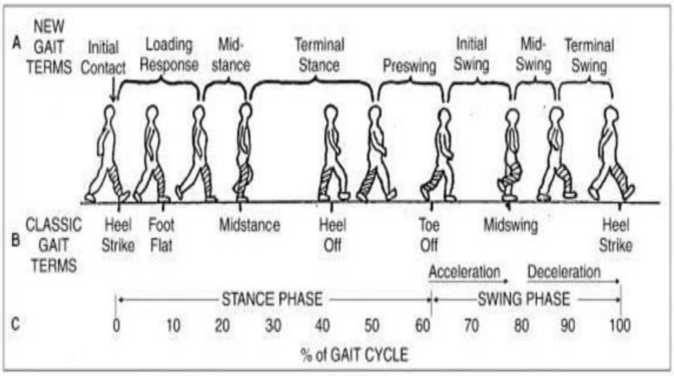

Fig.11: Gait Analysis

From the kinematic analysis we can get the position and orientation of the end-effector (i.e. the foot).

C. Multi Body Dynamic Analyses:

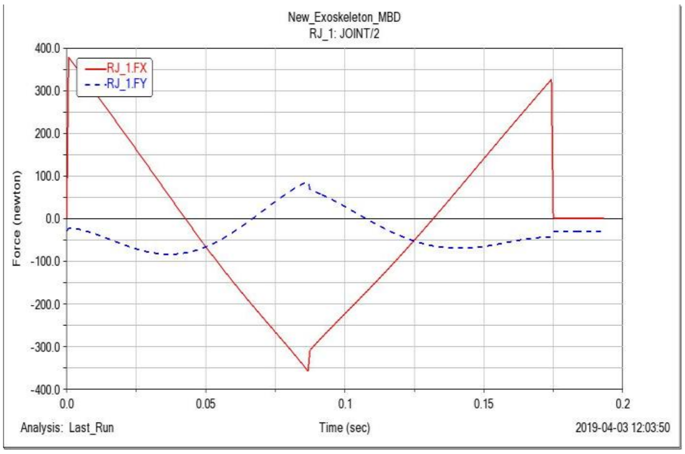

Fig.12: Time vs Foce Graph at Right Joint of HIP position

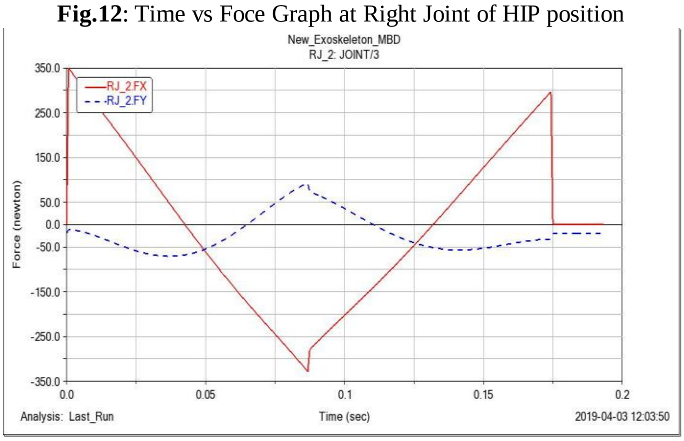

Fig.13: Time vs Force Graph at Right Joint of Knee position

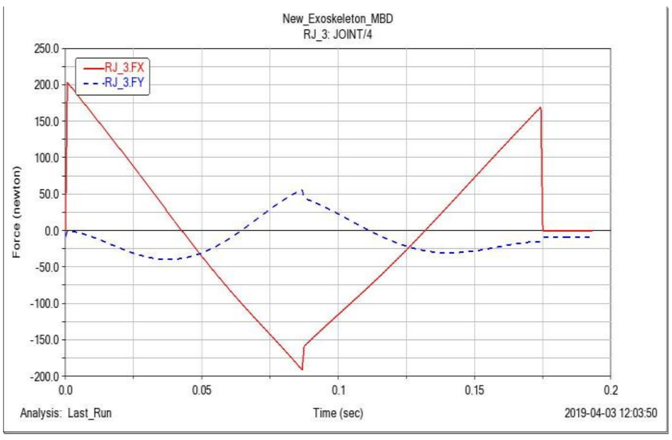

Fig.14: Time vs Force Graph at Right Joint of Ankle position

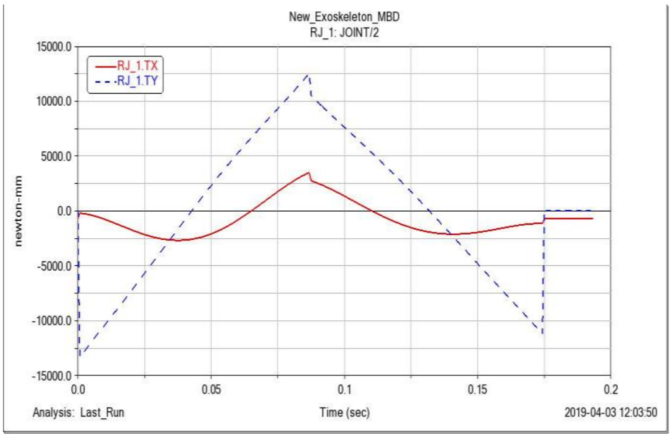

Fig.15: Time vs Torque Graph at Right Joint of HIP position

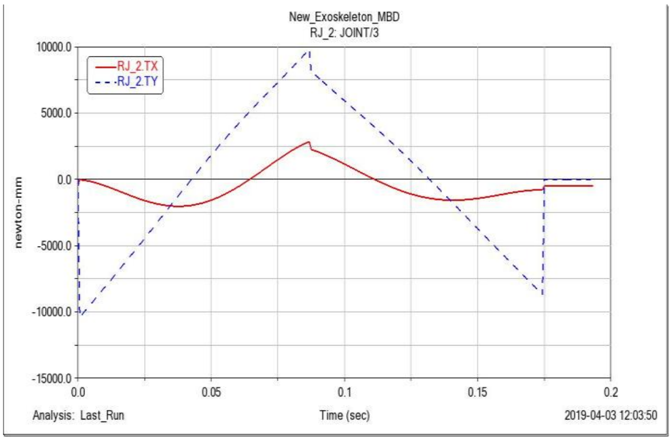

Fig.16: Time vs Torque Graph at Right Joint of Knee position

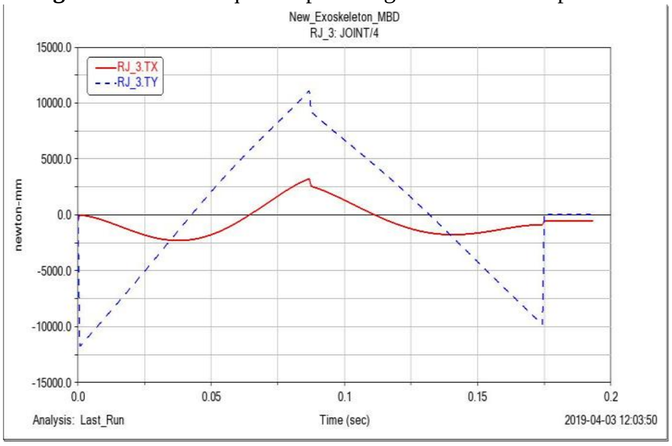

Fig.17: Time vs Torque Graph at Right Joint of Ankle position

Here in the above Time vs Force and Torque graphs are obtained and the same are depicted. Based on the joint moment and the torque required we can select the motors at the hip, knee and ankle positions. Most of the cases the position at the ankle is not taken into consideration and a spring type system is considered at that position. Because of the unfair moment of the ankle and the sagital plane with which we have to take as reference it may so difficult and hence ankle position is neglected. The maximum torque was obtained at hip position.

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V. CONCLUSION

In this article, for paraplegic patients or the persons who are having lower extremity disability, a lower extremity exoskeleton was modeled in solid works software by considering the anthropometric calculations. The model was examined in ANSYS for stress and total deformation analysis considering material as Aluminum. For the given conditions the results obtained shows that the model is feasible. Considering joint angles obtained by Kinovea software and parameters of DH notation, kinematic analysis was performed. The dynamic analysis was performed using MS ADAMS software and the results obtained are depicted above as Time vs Force, Time vs Torque graphs are obtained. According to the human gait and the torque obtained we select the motors at the joints.

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