Design and Kinematic Analysis of Lower Limb Humanoid Exoskeleton

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Abstract- *The lower limb humanoid exoskeleton is a smart external power unit combined with the mechanical energy, which can enhance human body function. The lower limb exoskeleton can be used to assist wearer with strength during walking, for carrying heavy loads or aiding the disabled people for walking. Depending upon the movement parameters of the human joints, kinematic analysis and modelling of the mechanical system of the lower limb humanoid exoskeleton is done. Design considerations of exoskeletons involves degree of freedom (DOF), range of motion (ROM), torque and velocity requirements for joints, actuation type, material selection of the links, weight and inertia kinematic considerations. The exoskeleton is designed as per Indian anthropometry 95th percentile data. The generalized kinematic model of the proposed exoskeleton is developed using Denavit and Hartenberg coordinate transforming matrix. Torque required for the actuators and the absolute forces acting at each joint are obtained by synthesizing the mechanism over the standard angular displacement of human joints as per the clinical gait analysis data (CGA). Simulations of the designed mechanical system in the CATIA's kinematics environment result in the motion trail in space structure. Comparing the simulated motion with the several points of a gait cycle validates the feasibility of the kinematic model established. This study paves the way for further optimization and the design of the control strategy of the exoskeleton.*

Keywords- Lower extremity exoskeleton, kinematic analysis, Workspace analysis, Virtual prototype, Simulation.

I. INTRODUCTION

Spinal cord injury cases admitted from January 2000 to 2008 is around 2716. In 2716 cases of spinal cord injury, 1400 were cervical and 1316 thoracolumbar with male to female ratio 4.2:1. [1] Most spinal cord injury patients suffer from walking impairment which seriously affected their quality of life. Further as they spend much time sitting in a wheel-chair, their lower limbs due to lack of exercise have trouble with blood circulation. To solve such problem, exoskeletons have been introduced to provide an effective method for lower limb rehabilitation. [2]

A lower extremity exoskeleton is a robotic device that can give a spinal cord injury patient increased mobility. Such a device has two legs connected by a torso structure, which is worn like backpack and houses electronics and batteries. The exoskeleton legs are coupled to the user's leg by straps that are designed to minimize pressure on the person's skin. [3]

The earliest study of exoskeleton system began in the 1960s. In 1962, the United States Air Force (USAF) required the Cornell Aeronautical Laboratory Inc. to conduct a feasibility research on the use of manpower amplifier system by using master-slave control mode. From 1960 to 1971, US General Electric Company began to develop an exoskeleton prototype based on master-slave control, called "Hardiman" which was mainly used to relieve fatigue of the soldiers caused by long distance marching load. In 2004, University of California, Berkeley, developed the machine clothing that could make people easily carry heavy loads for long distance or heavy objects to go upstairs and downstairs—Berkeley Lower Extremity Exoskeleton (referred to as the BLEEX), the objective of the project was to develop exoskeleton that could heavily armed soldiers increase the load and improve the marching speed. The main part of BLEEX is a pair of stainless steel mechanical legs, and a small engine is equipped in the buttocks of the carriers to offer the power required for walking. An exquisite small folding steel frame extends from the rearward of the buttocks to be easy for soldiers to carry the military backpack, weapons and other items on the back. There are several research institutes in Japan engaged in the study of wearable assisted robot, which is mainly for civilian areas, and aimed at improving the ability to live independently and weight-bearing capacity of the elderly and people with disabilities. University of Tsukuba in Japan developed the world's first commercial exoskeleton robot, namely the Hybrid Assistive Leg 3 (HAL3). This can help people to walk at a speed of 4 km per hour, and effortlessly climb the stairs. The domestic research on exoskeleton assistive robot has been started late and there's no mature product on the market. [4]

In this paper we have developed a spatial kinematic model for a lower limb humanoid exoskeleton. Further it was verified simulating a virtual prototype for the same function and finally synthesized it to obtain the torque and power profiles of each joint.

II. DATA ACQUISITION AND MECHANISM DESIGN

To design a powered lower limb exoskeleton which follows the anthropomorphic and ergonomic design, the kinematic design of the lower limb exoskeleton should be proper for human joints. Seen from a biological perspective, the lower extremity motion of the human body takes the joints as the fulcrum, the bones on both sides of joint is connected via ligaments, and then the skeletal motion around the articulation is driven by muscle contraction, thus to achieve walking and other movements. The angle curve of each articulation can be obtained by various methods like video capture, experimentation, or calculation. As shown in fig.*x*, the human body lower extremity when is within a walking cycle, the motion angular displacement of respective of the respective joints hip, knee and angle are continuous function of time. According to the CGA (Clinical Gait Analysis Data), hip flexion, knee flexion and ankle flexion has the maximum power consumption while walking, otherwise the other degrees of freedom are almost negligible comparatively. Hence, we control or actuate the hip flexion, knee flexion and ankle plantar-dorsi flexion in each of the two legs.

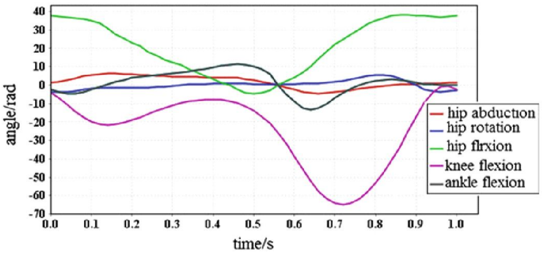

Fig.1 Angular displacements of human body joints within walking cycle.

Fig.2 3-D model of exoskeleton

The Figure 2 above shows the developed virtual model in CATIA V5 R20. The model was even checked in the CATIA anthropometry toolbox for selected dimensions of 95th percentile of Indian anthropometry data.

III. SPATIAL KINEMATIC MODELLING

In robotics, kinematics mainly includes the study of mapping relationship between workspace and joint space. Of which forward kinematics indicates the spatial space determined by the end actuator of the joint parameters, the trajectory planning of the end actuator can be conducted by changing the motion parameters of the joints, or the determined joint parameters can conduct the trajectory analysis of the end actuator. In the proposed design we have considered two degrees of freedom for hip, one for knee and one for ankle.

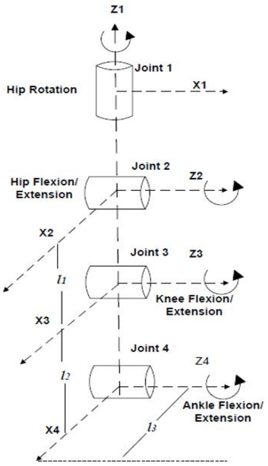

Fig.3 Free Body Diagram

Link parameters of the proposed exoskeleton is found in Table.1. where α_{i-1}, a_i, d_i, θ_i represents link twist, link length, link offset and joint angle respectively.

No.	Joint	Movement	α_{i-1}	α_i	d_i	θ_i
1	Hip	Rotation	0	0	0	θ_1
2	Hip	F/E	-90	0	0	θ_2
3	Knee	F/E	0	L_1	0	θ_3
4	Ankle	F/E	0	L_2	0	θ_4

Table1 Link Parameter as per the DH Parameter

*F/E= Flexion/Extension

* range of θ will be restricted as per human joint

Homogenous transformation of link parameters as per DH notation can be calculated as per following relation

$$T_i^{i-1} = \begin{bmatrix} \cos\theta 1 & -\sin\theta 1 & 0 & \alpha i-1 \\ \sin\theta 1\cos\alpha i-1 & \cos\theta i\sin\alpha i-1 & \sin\alpha i-1 & -\sin\alpha i-1.di \\ \sin\theta i\sin\alpha i-1 & \cos\theta i\cos\alpha i-1 & \cos\alpha i-1 & \cos\alpha i-1.di \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Now transformations from hip to foot as per the above equation will be given as

$$T_1^0 = \begin{bmatrix} \cos\theta 1 & -\sin\theta 1 & 0 & 0 \\ \sin\theta 1 & \cos\theta 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad T_2^1 = \begin{bmatrix} \cos\theta 2 & -\sin\theta 2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta 2 & -\cos\theta 2 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2 = \begin{bmatrix} \cos\theta 3 & -\sin\theta 3 & 0 & l1 \\ \sin\theta 3 & \cos\theta 3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad T_3^4 = \begin{bmatrix} \cos\theta 4 & -\sin\theta 4 & 0 & l2 \\ \sin\theta 4 & \cos\theta 4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{foot}^4 = \begin{bmatrix} 1 & 0 & 0 & l3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Transformation matrix from hip to foot will be calculated as,

$$\mathbf{T_{foot}^0 = T_1^0 * T_2^1 * T_3^2 * T_3^4 * T_{foot}^4}$$

$$\mathbf{T_{foot}^0} = \begin{bmatrix} c1c123 & -c1c123 & -s1 & c1c123l3 + c1c12l2 + c1c2l1 \\ s1c123 & -s1c123 & -c1 & s1c123l3 + s1c12l2 + s1c2l1 \\ -c123 & c*234 & 0 & -s123l3 - s12l2 - s2l1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where,

- $c1 = \cos(\theta 1)$
- $s1 = \sin(\theta 1)$
- $c123 = \cos(\theta 1 + \theta 2 + \theta 3)$
- $s123 = \sin(\theta 1 + \theta 2 + \theta 3)$
- $c12 = \cos(\theta 1 + \theta 2)$
- $s12 = \sin(\theta 1 + \theta 2)$
- $c*234 = \cos(\theta 4 - \theta 2 - \theta 3)$

For kinematics simplicity we can write T_{foot}^0 as

$$T_{foot}^4 = \begin{bmatrix} r11 & r12 & r13 & p1 \\ r21 & r22 & r23 & p2 \\ r31 & r32 & r33 & p3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The last column of the above matrix represents the position and orientation of the exoskeleton in x and y coordinates respectively.

p1(x)=c1c123l3+c1c12l2+c1c2l1
p2(y)=s1c123l3+s1c12l2+s1c2l1

First and second derivative of the above equations will give the velocity and acceleration of the proposed exoskeleton.

IV. SIMULATION AND SYNTHESIS

In order to verify the proposed spatial kinematics analysis, a virtual prototype of the lower limb exoskeleton was created in

CATIA V5 R12. Then the model was imported in the DMU Kinematics Environment of the software. A law function for the developed equation for each link was assigned and simulated. The virtual exoskeleton was found to be walking stably by the used controlling variables and reasonable control constants. Based on the developed function assuming a normal cubic spline input with respect to the clinical gait analysis angular motion data, the developed prototype was synthesized for the same.

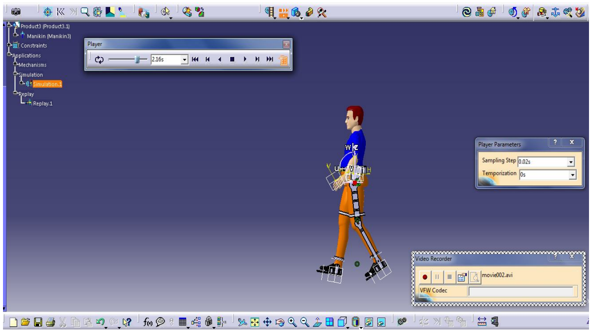

Fig.4 Simulation in CATIA

Synthesizing the mechanism for the respective angular data and assuming a considerate inertia in each joint result in the following power and torque profile for each joint actuator.

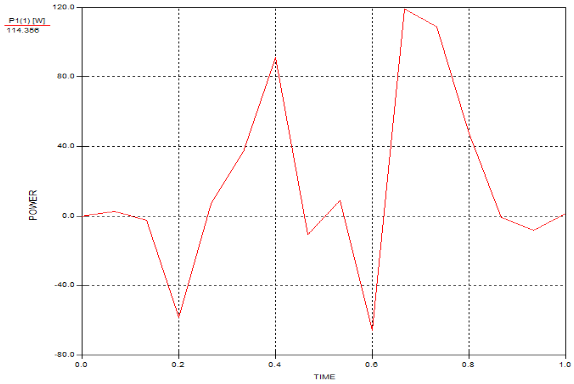

Fig.5 Power profile for hip actuator

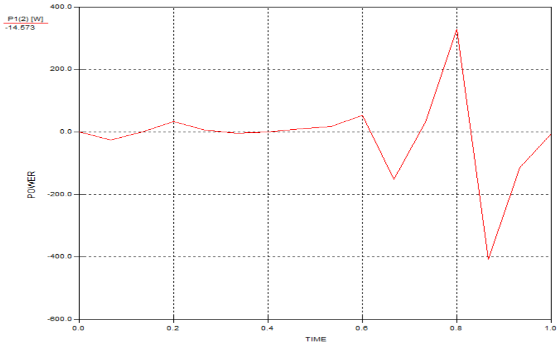

Fig.6 Power profile for knee actuator

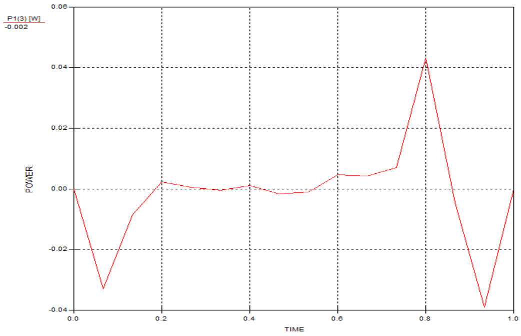

Fig.7 Power profile for ankle actuator

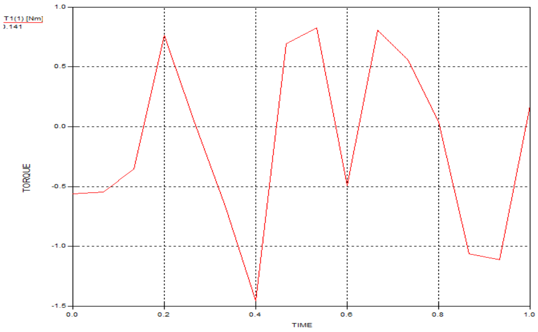

Fig.8 Torque profile for hip actuator

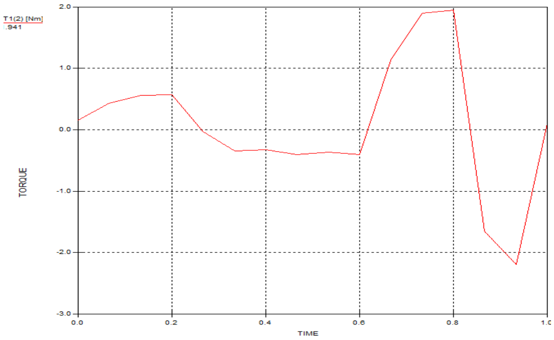

Fig.9 Torque profile for knee actuator

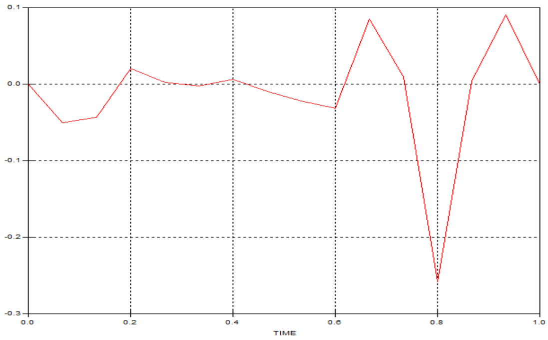

Fig.10 Torque profile for ankle actuator

Fig.11. A series of phase of the exoskeleton walking gait cycle

V. WORKSPACE ANALYSIS

Robot workspace refers to the range of activities with the coordinate origin of the end actuator reaching the maximum, and it is an important kinematics indicator used to measure the work capacity of the robot. The relationship between position coordinate of point M, parameters of joints and link rod parameters can be obtained from Equation, since the motion of each articulation angular displacement hi and length of the link rod a_i are known, the workspace of coordinate system origin M of the end actuator. The robot workspace is mainly determined by the robot configuration and structural parameters of the link rods, but also affected and restricted by their articulation motion range. It can be known from the analysis of Fig.12. that the workspace of the structure is with the presence of empty and cavities. Therefore, this institution should avoid corresponding region during operation, thus to be placed within flexible workspace as far as possible.

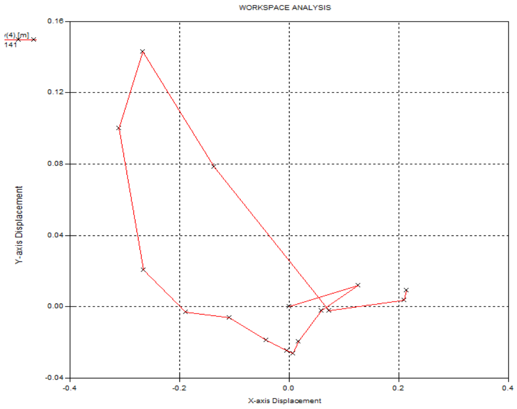

Fig.12 Workspace Analysis

VI. CONCLUSION

The work presented a power assisted leg of lower extremity exoskeleton developed for increasing strength, speed & endurance of the operator. The kinematic model for exoskeleton is established and formulation of kinematics is explained in detail. The exoskeleton was designed in keeping in mind anthropomorphic and ergonomic consideration. The results of synthesis of the model given the mapping between workspace and joint space. It was found that the path comprises of a cavity hence institution should avoid corresponding region during operation, thus to be placed within flexible workspace as far as possible. The respective torque and power profile obtained from the synthesis can be used for actuator selection in future work.

The synthesis also resulted with the absolute forces acting on each joint considering inertia forces, man of the wearer and gravity. This can be used for further analysing the designs for optimization. The simulation of the designed exoskeleton in the DMU kinematic toolbox of CATIA depending upon the angular displacement inputs on the developed model and the respective DH parameters considered in the spatial kinematic modelling verifies the kinematic equation developed.

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