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Human Assistive Lower Limb Exoskeleton

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Abstract—**Exoskeletons have proven to be helpful in assisting humans in major fields such as rehabilitation, military, industries and more. However, even though these exoskeletons provide useful features,most of them fail to reach humans in need due to their high cost. In this paper, we present Human Assistive Lower Limb Exoskeleton (HALEX), a low-cost exoskeleton developed to provide human assistance during gait locomotion. HALEX is a hybrid lower limb exoskeleton which provides enough DOFs to users while locomotion. The paper discusses the development of HALEX, it uses electric motors coupled with self-developed gearbox at hip and knee and uses a passive element that is a tension spring at the ankle joint. Adjustable link lengths allow wearers of different heights and waist sizes to use this exoskeleton with ease. A load carrying structure allowsthe wearer to carry additional weights with reduced efforts. Tests were done to obtain the scale of assistance HALEX provides and the results of the same are discussed.**

Keywords—Exoskeleton,Hybrid,Gait locomotion, Rehabilitation, Gearbox, Adjustable

I. INTRODUCTION

Human exoskeleton research is an approach to understand and realize complex gait cycles of human locomotion and mimic the same in a developed human exoskeleton. Exoskeletons are broadly classified in two types (1) series limb exoskeleton and (2)parallel limb exoskeleton[1]. Exoskeletons can be active or passive[2]. Passive exoskeletons use passive methods such as springs for human assistance whereas active exoskeletons use active power source. Powered exoskeletons developed till recently use different types of sources of power for actuation. Hydraulics, pneumatics and electric motors being some of them. Hybrid exoskeletons also exist which use both passive and active methods for human assistance[3].

H. Kazerooni and R. Steger[4] developed Berkeley lower extremity exoskeleton (BLEEX), an anthropomorphic, powered exoskeletonfor human strength augmentation. They used hydraulic actuation system. An on-board internal combustion engine provided both electric and hydraulic power. Their joint angles, torque and power requirements were determined by human motion analysis of a 75 kg human walking on a flat ground roughly at a speed of 1.3 m/s. Also, average military male's reported joint limits were considered to derive joint ranges.

Sang-Ho Hyon et al [5] developed XoR [5] which is a light-weight lower-body exoskeleton prototype and uses hybrid pneumatic-electric drive.XoR was developed to achieve precise torque control, back-drivability and a desirable force/velocity profile as well as reduction in weight. This exoskeleton's design allows to augment operator's strength in rehabilitation applications and assist with postural control for disabled people.

Earlier exoskeletons have incorporated hydraulic and pneumatic drives as well as systems consisting a combination of both pneumatic and electric drive. These drives however require fluid storage and a pump ora compressor which contribute to the bulkiness of the exoskeleton system. These problems were overcome through complete electric drive exoskeleton systems.Yoshiyuki Sankai developed Hybrid Assistive Limb (HAL) [6] for human strength augmentation and as an assistive gait device in rehabilitation. The torque requirements in this system are achieved through DC motors coupled with harmonic drives. These harmonic drives facilitate compactness. HAL achieves human gait locomotion through predefined gait trajectories by controlling knee and hip joints.

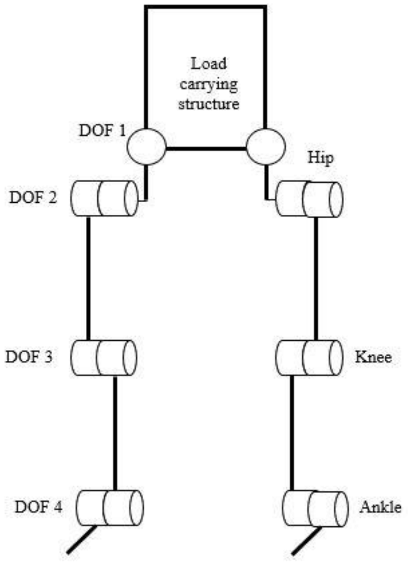

Fig. 1. Joint configuration of HALEX

The exoskeleton we have developed is also a hybrid exoskeleton which uses a combination of electric motors and passive elements like springs for functioning. Human Assistive Lower Limb Exoskeleton (HALEX) as the name suggests, is a lower limb exoskeleton developed for assisting humans in gait locomotion. HALEX can be used for rehabilitation as well as military purposes. The joint configuration and material selection of HALEX is discussed in section II. Section III presents discussions regarding actuator selection for active joints, design of gearboxes for torque enhancement of these actuators and design of ankle joint using passive element that is a spring. Further, the complete design and significant features are discussed in section IV. Section V presents the testing and results of HALEX. Section VI presents the conclusion and finally, section VII presents the future scope.

II. BASIC DESIGN

Many well-developed exoskeleton systems like HAL[6] are parallel limb hybrid exoskeletons which provideenough DOFs, high functionalities and wide scope of applications. However, the main drawback of these systems is their high cost. Hence, after studying current trends and requirements in exoskeleton research, developing a low-cost parallel limb hybrid exoskeleton was the aim of this project.

The primary purpose of HALEX is to assist humans in their locomotion and amplify power. This was done by providing two 4 DOF in the system as shown in Fig. 1. The leg segments are connected by rotational joints including 2 DOF (1 actuated) at the hip, 1 DOF (actuated) at the knee, 1 DOF (passive) at the ankle. The joints are actuated using DC motors which are driven by electric DC power supply. External self-developed gearbox is coupled with DC motors for torque amplification as per the requirements. According to N. Latif A. Shaari et al [7], aluminium 7075 has high availability, sufficient yield strength and density. Hence, aluminium 7075 is used to manufacture complete exoskeleton.

III. JOINT MODULE DESIGN

As determined by N. Latif A. Shaari et al [7], the torque required at hip joint is 47.56 Nm, the torque required at knee joint is 21.68 Nm, and the torque required at ankle is 2.10 Nm. As the torque requirements at the hip and knee joints are high, using passive methods to provide the torque was difficult. Hence, actuation using DC motors coupled with self-developed gearbox were used at the hip and knee joint. The torque requirement at ankle joint is comparatively less, hence a passive method that is a spring of appropriate spring constant is used for human assistance in gait locomotion.

A. Actuator Selection

According to the torque requirements at the hip and knee joint, Banebot RS 550 – 12V high torque DC motor was selected. The no load rpm is 19300rpm and the stall torque is 0.488 Nm. At peak efficiency, the rpm is 17100 rpm and the torque is 0.055 Nm/A. The average operating current of the system is 5A resulting in the torque at the output shaft of motor to be 0.275 Nm. The motor is coupled with Banebot P60 gearbox, a planetary two stage gearbox providing a reduction ratio of 25.92:1.

Torque at the output shaft of= 0.275 Nm

Gearbox reduction ratio = 25.92:1

Therefore,

Torque at the output of motor with gearbox = 0.275×25.92
= 7.128 Nm

B. Gearbox Design

The torque at the output shaft of the selected motor gearbox unit is 7.128 Nm. This torque value needs to be multiplied by a factor enoughso that the required torque is obtained at the hip and knee. Hence, a compound gearbox was designed to meet the requirements. Most of the existing electrically powered exoskeletons use DC motors couple with harmonic gearbox which works on the strain wave gearing principle [9]. Although harmonic drive provides zero backlash, it is expensive which becomes an obstacle towards the aim of developing an exoskeleton system which is low cost.

Initially, a planetary gearbox as shown in Fig. 2was designed for the application as it provides high gear reduction ratio in compact size [10]. As the required torque at hip is 47.56 Nm [7] and the available torque was 7.128 Nm, a gear ratio of at least 6.672:1 is needed. The single stage planetary gearbox designed provided a gear reduction ratio of 9:1. The ring gear having 125 teeth was fixed and the output was taken at the carrier link. The planet gears were made of 56 teeth and the sun gear was made of 16 teeth. The module of each gear used in the gearbox was selected to be 1.25.

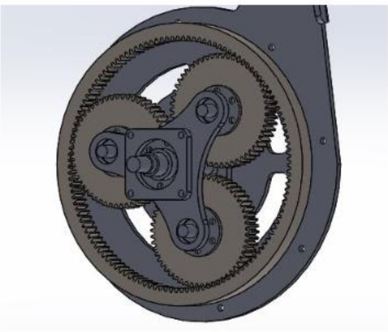

Fig. 2. Design of Planetary Gearbox

After studying the use of planetary gearbox designed for the application,for the rotational joint at hip, a two-stage compound gearbox as shown in Fig. 3 was developed. Each stage provided a gear ratio of 3:1. Hence, the gear ratio of the two-stage compound gearbox developed was 9:1.

Gearbox reduction ratio at hip = 9:1

As a result,

Torque at the output of compound gearbox = 9×7.128 = 64.152 Nm

Hence, using the two-stage compound gearbox with the available motor gearbox assembly provided a torque value of 64.152 Nm analytically.

To determine the actual torque obtained at the output of the assembly, efficiency needs to be considered. Theoretically, the angular velocity at the output of the assembly is calculated to be 73.3 rpm. But the actual angular velocity obtained by using a tachometer was 56 rpm. This resulted in an efficiency of 0.76.

Theoretical angular velocity = 73.3 rpm

Actual angular velocity = 56 rpm

$$\text{Efficiency} = \frac{Theoreticalangularvelocity}{Actualangularvelocity} = \frac{56}{73.3} = 0.76$$

As a result, the actual value of torque obtained at the output of the motor gearbox assembly after considering the efficiency of the system was 0.76 times the analytically obtained value.

Actual torque obtained at hip = 0.76 × 64.152
= 48.755 Nm

Hence, the actual torque obtained at the output of the motor gearbox assembly was 48.755 Nm. This torque value is greater than the torque required at the hip joint.

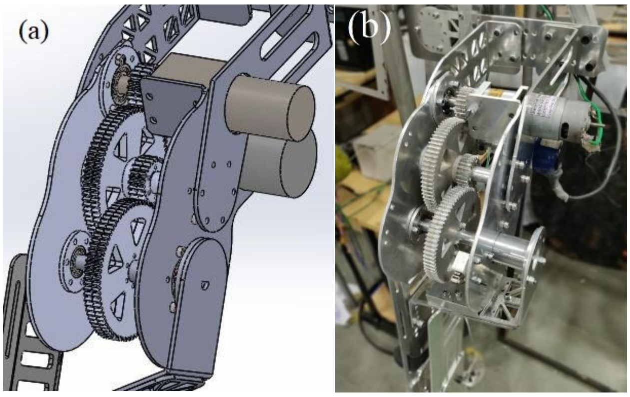

Fig. 3. (a) CAD model of compound gearbox for hip joint (b) Actual compound gearbox for hip joint

For the rotational joint at knee the required tor a simple gearbox with simple gear train as shown in Fig. 4 was developed. It was designed to provide a gear reduction ratio of 5:1. According to the dimensions required at the knee joint the pinion was designed with 25 teeth and the output gear was designed with 125 teeth. The module was selected to be 1.25.

Gearbox reduction ratio at hip = 5:1

As a result,

Torque at the output of compound gearbox = 5 × 7.128 = 35.64 Nm

Using this gearbox with the available motor gearbox assembly provided a torque value of 35.64 Nm theoretically. And the actual value of torque obtained at the output of the motor gearbox assembly after considering the efficiency of the system was 0.76 times the theoretically obtained value.

Actual torque obtained at knee = 0.76 × 35.64
= 27.09 Nm

Hence, the actual torque obtained at the output of the motor gearbox assembly was 27.09 Nm. This torque value is greater than the torque required at the knee joint.

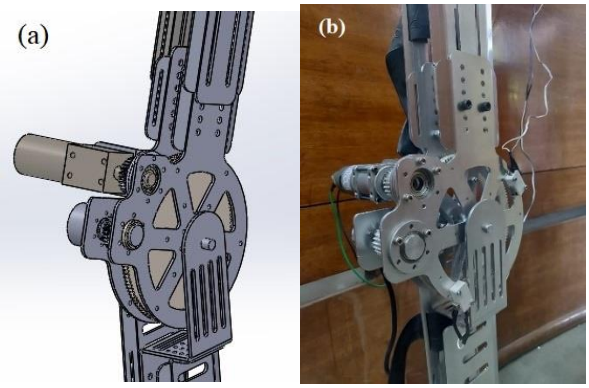

Fig. 4. (a) CAD model of gearbox for knee joint (b) Actualgearbox for knee joint

C. Ankle Design

As the ankle joint required very low torque[7] in comparison to the hip and knee joints, it was designed using a passive element that is a tension spring of appropriate stiffness constant as shown in Fig. 5. The placement of this spring was done such that it will assist the user during the push required to walk during a gait locomotion.

Fig. 5. Tension spring used at ankle joint

Spring is made up of hard drawn steel ASTM A227 having a spring constant of 5.112 N/mm. The normal length of the spring is 80 mm, the outer diameter is 12 mm, wire thickness is 2 mm. The joint connects the tibia link and the foot using radial ball bearings, aluminium shafts and a C shaped structure as shown in Fig. 6. The C shaped structure is provided with bearings on the opposite ends. The lower end of the tibia link is also provided with a radial ball bearing. The foot is mounted between the bearings on the C shaped structurewith the help of aluminium shafts. The aluminium shaft mounted on one side of the foot goes through the bearings on the C shaped structure and the tibia link. Further to avoid cantilever condition, another aluminium shaft is mounted on the other side of the foot which goes through the bearing of the C shaped structure.

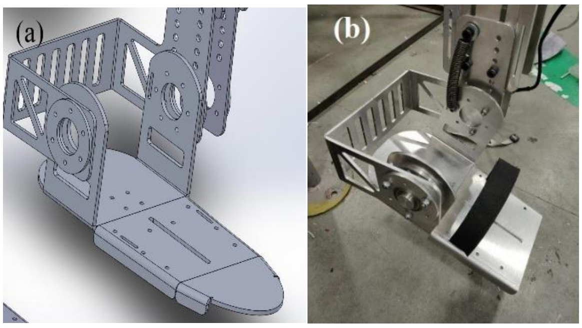

Fig. 6. (a) CAD model of ankle joint (b) Actual ankle joint

Table I provides the comparison between the required torques and obtained torques at respective rotational joints. The obtained torque values are sufficiently greater than the required torque values. Hence, the designed rotational joints are capable to mimic human gait cycle during locomotion.

TABLE I. COMPARISON OF TORQUE VALUES

	Torque Values		
	Hip	*Knee*	*Ankle*
Required	47.56 Nm	21.68 Nm	2.10 Nm
Obtained	48.76 Nm	27.09 Nm	Passive

IV. COMPLETE DESIGN

The motor and gearbox assemblies are responsible in facilitating the required torque to respective joints. Further, linkages and a support structure are designed using aluminium 7075 material to complete the exoskeleton system. The linkages are the connecting members between two joints. The support structure is designed in such a way that it balances the exoskeleton assembly and also provides mounting for electronic circuits and space for backpack which can carry any added load. The linkages and support structure are discussed in detail in further section. Fig. 7 presents the HALEX worn by a user.

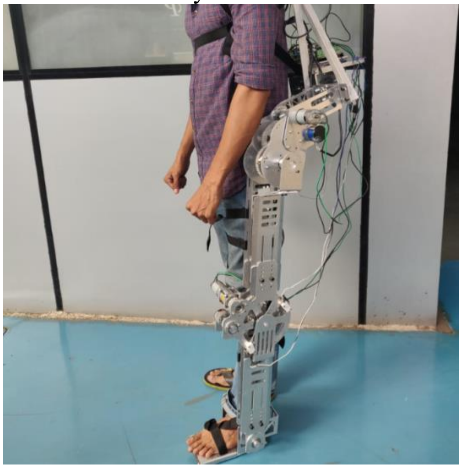

Fig. 7. User wearing HALEX

A. Adjustable Links

As shown in Fig. 8, the hip and knee joints are connected to each other through linkages. The link connecting the fixed side of the knee gearbox module is mounted on the output shaft of the hip gearbox. Further, another link is used to connect the knee joint with the ankle joint. Here, also the link connecting the fixed part of the ankle joint is connected to the output shaft of the knee gearbox.

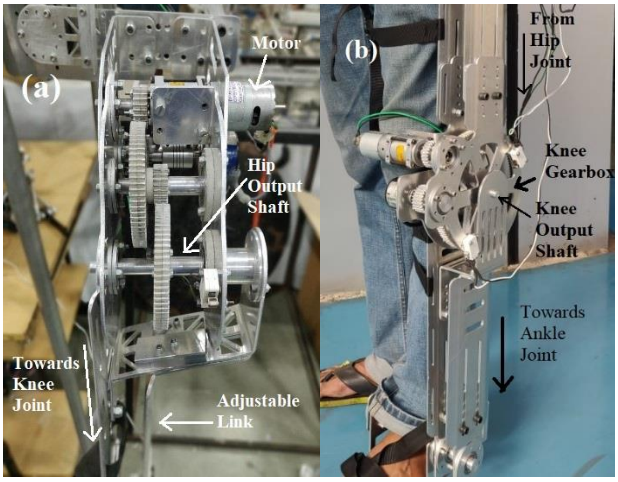

Fig. 8. Link joining hip and knee joint

Arrangements have been made for adjusting the length of the links of exoskeleton by providing slots on the links. Hence, the lengths of the links can be adjusted by tightening the nut and bolt at a suitable length in the slot according to the height of the user. The width of the exoskeleton at the waist can also be adjusted according to the waist size of the user with the help of slots provided on the link between the load carrying structure and the motor gearbox assembly on the hip joint. These arrangements can be seen in the Fig. 9.Fig. 11, Fig. 12 and Fig. 13 show the simulation results of the structure and links between hip and knee module as well as knee and ankle respectively. These results are obtained through applying appropriate forces and torques at required points and the simulation data is obtained from SolidWorks software.The stresses developed in hip and knee module links can be seen in Fig. 12 and Fig. 13 respectively and it can be concluded that the stresses are in permissible limits as the complete area of link is in blue zone.

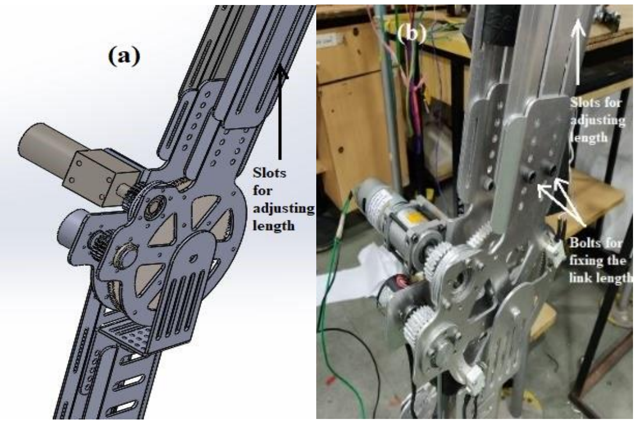

Fig. 9. (a) CAD model of slots for adjusting link lengths (b) Actual slots for adjusting link lengths

B. Structure

A structure is designed to balance the exoskeleton system and carry loads while walking. It is designed such that the weights of the loads carried on the back will be transferred to the ground through the exoskeleton. The structure rests on radial ball bearings as shown in Fig. 10.

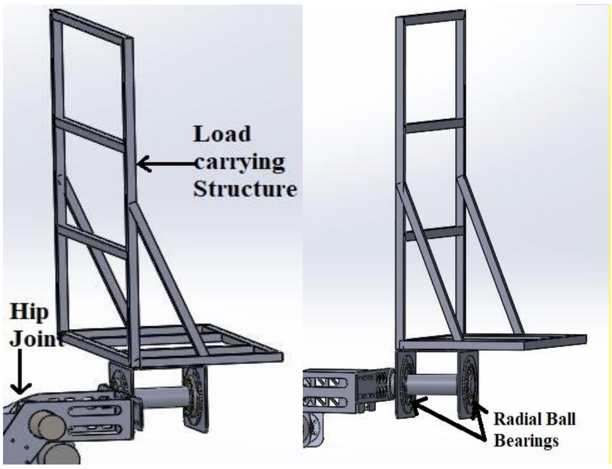

Fig. 10. Load carrying structure resting on radial ball bearings

The load carrying structure is basically the torso of the exoskeleton. The two limbs of exoskeleton are mounted on this structure. The structure is designed using aluminium material depending on the maximum loads it has to withstand. The structure provides space for backpack which can carry any added load. It also supports the electronic boards and the battery pack used for powering the exoskeleton. The stresses developed in back structure can be seen in Fig. 11 and it can be concluded that the stresses are in permissible limits as no red zone is obtained.

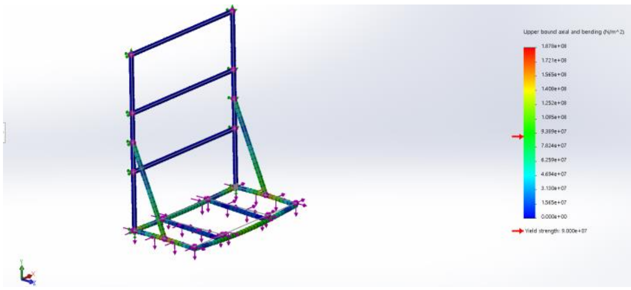

Fig. 11. Stresses developed in back structure

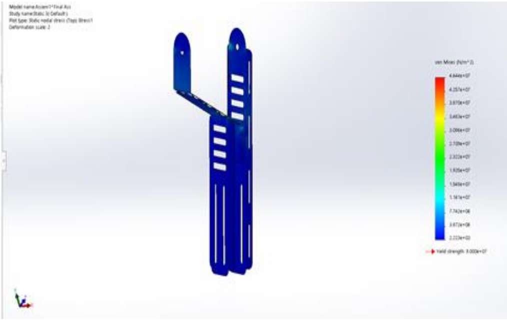

Fig. 12. Stresses developed in hip module links

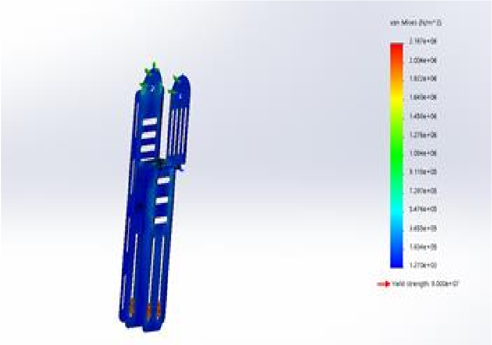

Fig. 13. Stresses developed in knee module links

C. *Working and Implementation*

The variation of joint angles of 20 subjects (age 20-25) walking on a treadmill were recorded using a video camera. These videos were analyzed for joint angles on Dartfish Pro, a video analysis software.The average combined results of all the subjects considering all three angles i.e. hip, knee and ankle are shown in Fig. 14. These angles are used as reference for pre-defining gait trajectories for walking motion through closed loop control.

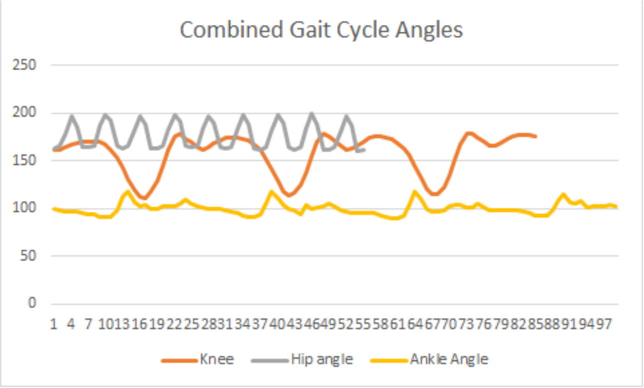

Fig. 14. Combined Gait Cycle Angles

Fig. 15 depicts the architecture of the electronic system that achieves the working and implementation of walking gait locomotion. As shown in Fig. 15 the master microcontroller is like the brain of the total circuit. Its main function is to send commands (signals) to other components according to the program. Initially, according to our application and process algorithm, code logic is developed. This code is then uploaded in this main controller. Now, according to the program the main controller sends commands (signals) to the motor controller using the protocol involving high and low values.On receiving commands from the main controller, the motor driver controls the motor's speed and direction according to the user program.

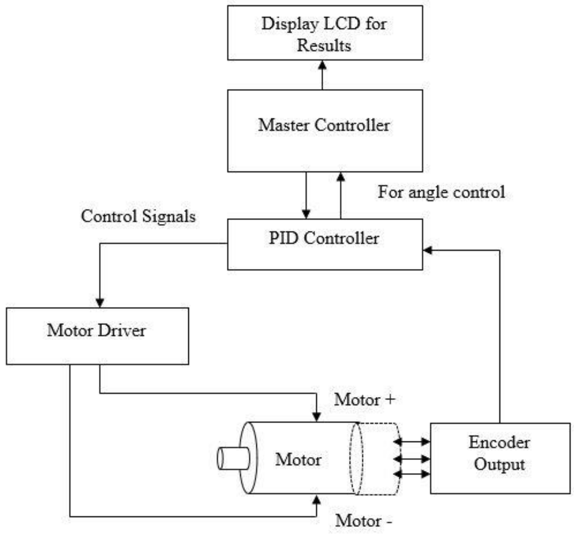

Fig. 15. Electronics System Architecture

The motor driver reads the commands and rotates the motor until a limit switch is pressed which stops the motor. This limit switch defines the home position of the hip and knee module depending on the position of initial limit switch. After the home position is defined the motor driver inputs the angular input received from the commands through PID control. This angular input varies for the hip and the knee module. The desired movement for hip module is achieved through a limit switch and position control mode (i.e. angular input). On the other hand, the desired motion for knee module is crucial and is achieved through two limit switches mounted at angles derived from human gait cycle and velocity mode control (i.e. the link only moves between the two limit switches).

V. TESTING AND RESULTS

The weight carrying capacity of the one leg of the exoskeleton was tested by performing a simple experiment. First, the wearer was made to keep one leg with exoskeleton on a weighing scale. The weight shown on the scale was set to zero. Then, metal rods weighing 2kg, 4kg and 8kg were attached to this exoskeleton leg one at a time and weight measurements were taken. The readings of weight indicated by the weighing scale against each attached weight were recorded. These readings were significantly less than the added weights indicating that the exoskeleton provided assist to carry the weight.

Table II provides the comparative results of assist obtained from the exoskeleton when metal rods of varying weights are attached. We can conclude from these comparative results that an assist of 80% to 90% is achieved. These results can also be seen in Fig. 16 as difference in measurements on the weighing scale.

Fig. 16. (a) Weight of metal rod (b) Weight of exoskeleton after attaching metal rod

TABLE II. QUANTIFIED RESULT DATA

Sr. No.	*Weights*	*Weight without exoskeleton*	*Weight with exoskeleton*	*Percent enhancement in power*
1.	2 kg	2 kg	0.19 kg	90.56%
2.	4.2 kg	4.2 kg	0.45 kg	89.21%
3.	8 kg	8 kg	1.17 kg	85.42%

VI. CONCLUSION

The torque values obtained at the output of the joints developed for the functioning of HALEX are sufficiently greater than the required torque values. Hence, these joints provide enough torque for operation of the exoskeleton. The joints of HALEX provide enough torque so that it can assist humans weighing up to 100Kg and height up to 1.85m during gait locomotion. The results also indicate that HALEX allows wearers to carry extra weights with reduced efforts. It suggests that HALEX can assist humans effectively with increased load carrying capacity.

VII. FUTURE SCOPE

The torque provided by the joints of HALEX is enough for human gait locomotion. Still, there is a huge scope for improvement in torque supply. The hip and knee joints of HALEX are actuated by electric motors whereas the ankle joint is passive which uses a tension spring. This selection of components is effective as indicated in the results. But, there also lie some disadvantages. The gearboxes developed for hip and knee joints consist of spur gears which may result in backlash. To avoid this, helical gears can be used. The actuator specifications can be selected to make even better motor gearbox configuration. Actuators of smaller dimensions and higher torque values can be selected to make the exoskeleton even more compact and powerful. With time the tension spring used in ankle joint can face changes in the properties, hence an alternative such as a damper can be used. Aluminium is used in complete manufacturing of the exoskeleton. Some different materials such as composites and fibers having less weight and high strength can be used as an alternative.

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