Lower Body Passive Exoskeleton Using Control Enabled Two Way Ratchet

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***Abstract*—The field of bio-mechatronics has witnessed immense advancements recently and exoskeletons has emerged as a promising technology in that field. Exoskeletons can be used to restore lost limb functions, assist in mobility and enhance the users strength. The prevalent exoskeleton designs have some major drawbacks such as difficulty in movement, high energy requirement, high costs etc. In this paper, a servo controlled passive joint exoskeleton has been proposed. In the proposed mechanism, ratchets can be locked in desirable position for the load transfer and can be kept free for easy movement when not in operation. Moreover, the exoskeleton is designed to be modular and adaptive of the human body sizes which increases the utility of the system. The Design of Experiments analysis was done in ANSYS for identifying the key design parameters. Further, the structural analysis and topological optimization was done using these parameters. Payload is supported by the ratchets rather than the the actuators, this has made the system lightweight and economic and thus easily accessible and affordable to the masses.**

Keywords- **Passive exoskeleton, material handling and disaster management, Ratchet, ANSYS, Design of Experiments.**

I. INTRODUCTION

Exoskeleton is an artificial body suit that enables wearer with enhanced capabilities such as inhuman strength, work durability, functioning as armor and similar superior abilities that would be impossible to obtain otherwise. Similar to our skeleton, exoskeleton supports the body, albeit externally. However, instead of just supporting, it can also provide a positive assistance to its wearer. Thus, based upon functionality and architecture the exoskeleton can be classified as:

1) *Passive Exoskeleton:* Does not require power supply, requires human effort, harnesses body power, helps us in posture, Lightweight and easy to use.
2) *Powered Exoskeleton:* Requires power supply, does not require human effort, big and heavy, helps to do jobs which are not humanly possible.
3) *Haptic Exoskeleton:* Used in graphics, used to capture motions accurately, used in virtual reality.

The exoskeleton can also be used to assist (or augment) the function of a particular region or a joint of the body. Thus, the exoskeletons can be classified as Upper body, Lower body, full body, etc.

Lower Body Exoskeleton (LBE) can be active as well as passive. In this design of Lower body Passive Exoskeleton (LPE), four degrees of freedom (DOF) are provided at three locations viz. two at hip, one at knee and ankle on leg each. DOF of the knee, hip and one DOF of hip is arrested using a two way pawl and ratchet arrangement, controlled by a servo motor. One DOF of hip is kept free for easy movement. The detailed architecture is discussed in proceeding sections.

II. LITERATURE REVIEW

LBE have been extensively used to rehabilitate the people with paraplegia or to correct the walking gait pattern [1].LegX, ESKO and HAL are this type of exoskeleton robots. ESKO is a bionic exoskeleton that helps the individual with physical disability to walk again [2]. HAL is suited for helping the person who cannot utilizing his own muscle for doing everyday work [3]. These exoskeleton are essentially developed to assist the ailing adults, physically weak or incapacitated individuals. However, the LBE can also be used to assist able-bodied people to support their routine works or mitigate the stress on their bodies during strenuous jobs.

A noteworthy driving force for today's work in control of exoskeletons has evolved from a program supported by Defense Advanced Research Projects Agency (DARPA), an American research agency, called *the Exoskeleton for Human Performance enhancing*. The main objective of DARPA while developing the powered exoskeletons XOS 1, XOS 2 and HULC is offloading the weight carried by the army troopers [4].

The main limitation of these Powered exoskeletons is that, the actuated joints add to considerable amount of complexity, cost and weight. This takes a toll on battery, mobility and utility of the system. A remedy can be a Lower body quasi-passive or passive exoskeleton as it does not rely much on the power source and are relatively unconstrained.

Research is done in MIT by Conor James Walsh et al. [5] under DARPA to create a quasi-passive leg exoskeleton for load carrying. This exoskeleton uses springs and damper for its working. HEXAR 1 developed in South Korea [6] for carrying weight is also a quasi passive exoskeleton and uses gear transmitting loads across joints. The main limitation of these exoskeletons is, spring dampers and gears still have a considerable amount of inertia, and are difficult to maintain.

Many workers suffer from injuries and acute joint pain owing to heavy weight they carry. LPE be efficiently used for pick- place applications like airline baggage handling and construction sites, to reduce stress and injuries to the workers. LPE can relieve the stress in the sitting, standing and intermediate postures when locked. The LPE can also be used to assist the aging population, which is increasing day by day and will makeup greater than 30% population of China and European countries by 2050. The powered exoskeletons and quasi-passive exoskeleton are expensive and thus are not accessible to masses. Passive exoskeleton can however, achieve more market penetration owing to its economic costs and user friendly design. The design of our Lower body exoskeleton, EXoS is discussed in next section.

III. DESIGN

In the lieu of development of exoskeleton, not much work seems to be done in the area of passive exoskeleton, which rather than augmenting and enhancing the capabilities of the user, will just assist him in his routine work. The exoskeleton which will not consume an enormous energy and hence will not be limited by the operation cycle. In this section we will discuss about the design and architecture of our system.

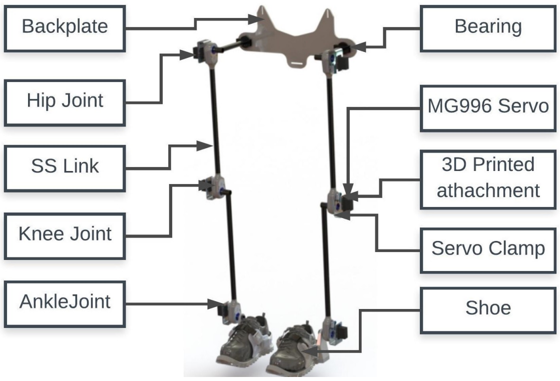


Fig. 1. Lower Body Exoskeleton Architecture

The Lower body exoskeleton has 4 degrees of freedom in each leg .Two at the hip joint and one at the knee joint and one at ankle joint. Being passive, exoskeleton does not provide force input to wearer to assist in lifting the load i.e. it does not require a continuous power input for its operation. Rather, the power is only required when the locking state of Ratchet needs to be toggled. Lower body exoskeleton transmits all the forces, exerted by the payload to the ground and virtually no forces are exerted on the wearers hips, knees and ankles.

Our Lower body exoskeleton consist of two way ratchet for locking and unlocking of each joint. These ratchets are bidirectional i.e. they can allow and restrict motion in either direction. The direction of ratcheting or in other words direction of locking and unlocking of joint is controlled by a toggle knob.The knob position is controlled by a servo motor. Each joint is connected to the next joint with help of a stainless steel pipe. These pipes are welded to the two ratchets with the TIG welding. Last link is connected to the shoes where it transfers all the loads to the ground.

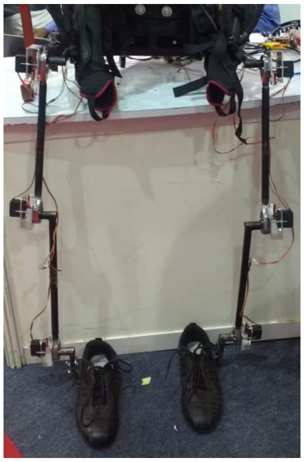


Fig. 2. Lower Body Exoskeleton Actual Model

A. Linkages

The links connecting two joint are made of stainless steel of grade AISI 304 [8]. The links are of circular cross section hollow pipes.the diameter of circular is 19mm outer diameter with thickness 2mm. There are three links in each leg supporting the joint assemblies. The analysis of linkage is done in ANSYS and is discussed in the proceeding section.

B. Belts and Straps

Strap and belts are used to attach the exoskeleton to user quickly. Straps and belts gives advantage that they can be used to strap same exoskeleton to different sizes of wearer.They save lot of fatigue of customizing the sizes of exoskeleton according to size of wearer. Straps used are Velcro and harness types for easy equipping and unequipping of exoskeleton that will save a lot of time.

C. Two way Ratchets

Passive joint consists of a two way ratchet controlled by MG996R servo motor. MG996R servo motor gives 180 degree rotation and a torque of 12 kg-cm. The direction of ratcheting is controlled by a servo which is housed above the face of the ratchet with help custom mounting made of 3 mm aluminum sheet metal. The mounting is manufactured by CNC laser cutting and CNC bending machine.

Motion is transferred to the pawl of ratchet which controls the direction of ratcheting. The shaft of servo has splines. A metal horn is attached to the shaft that has the same module of splines. A 3D printed Bracket is used to transmit motion of servo to the pawl. A metal horn is connected to the servo and the Bracket is attached to the metal horn. At the central position of pawl, the ratchet allows bidirectional motion freely but, after rotating the pawl to the either side its motion is constrained to the opposite side and allowing free motion in only one direction. So there are three position of this ratchet which gives the 3 types of direction of rotation.

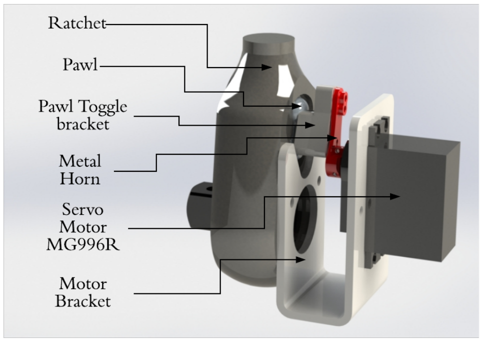


Fig. 3. Two way ratchet assembly

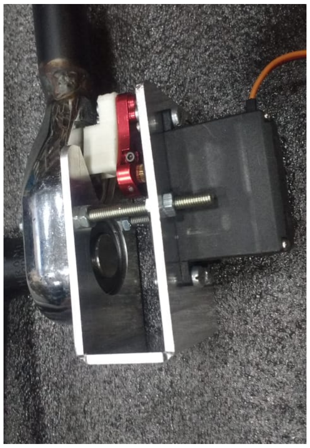
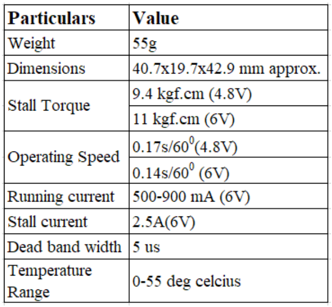


Fig. 4. Two way ratchet assembly actual model

D. *Servo Motor*

The servos used for actuation are MG996R. It gives 180 degree rotation. Specification of MG996 servo are shown in Fig. 5.



Particulars	Value
Weight	55g
Dimensions	40.7x19.7x42.9 mm approx.
Stall Torque	9.4 kgf.cm (4.8V)
	11 kgf.cm (6V)
Operating Speed	0.17s/60^{0}(4.8V)
	0.14s/60^{0} (6V)
Running current	500-900 mA (6V)
Stall current	2.5A(6V)
Dead band width	5 us
Temperature Range	0-55 deg celcius

Fig. 5. Servo Motor MG996 specifications. [9]

E. *Electronic system*

We are using Arduino Open Source Platform to operate the Exoskeleton in Autonomous mode. Controller is taking the feedback from the force sensor to control the joint ratchet locking state.

Lithium polymer battery pack 12-volt 3 cell 5200 mAh is used as a power source. It will power up all the electronics and Servo motors. Servo motors require 5v supply. A Buck converter is used to step down the voltage. It also steps down the voltage for the micro-controller. There are total 6 servo motors which require maximum current of 1 ampere each and buck converter can supply only maximum 3 A. So two buck converters are used to operate 6 servo. Architecture of the system is shown in Fig.6.

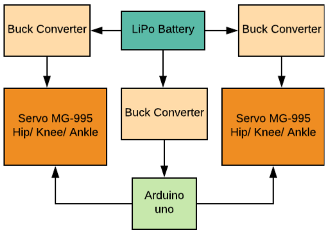


Fig. 6. Electronics System

The weight of the entire system is 6 kg and is expected to work for about 8 hours and can be used to lift a weight of additional 30 kg comfortably without straining the joints or muscles. The analysis of the system for the same is done in the proceeding sections.

IV. MODELING AND SIMULATION

For structural analysis of the exoskeleton we used ANSYS 18.0 release software. The exoskeleton was modeled simplistically initially for the purpose of finding out the key design parameters. Based upon the outcomes, the structural design and optimization was done thereafter.

A. *Design of Experiment*

A Parameter Correlation simulation was carried out to find out the sensitivity of stress induced, joint reaction force and moment and total resultant deformation with various design variables. For this, two experiments were simulated:

1) By varying the joint angles for simulating the bending postures.
2) By varying the height from the ground, for sitting, standing and intermediate postures.

1) Joint Angle: The key input variables were Joint Angles at Ankle, Knee and Hip joints. The output parameters were Total maximum deformation, Maximum equivalent Von-Mises stress and all three reaction components at each joint developed due to loading. The Ratcheted joints were modeled as plain revolute joints with same joint offset as that of ratchets, for simplicity in simulation. the Simulation setup for Design Point 12 is shown in Fig. 7. The load of 300 N in negative Y direction was applied at the point (0,1200,350) remotely to the points of harness mounting.The gravity is -9.81 m/s2 in -Y direction. The solution converged after 126 iterations:

The correlation and sensitivity matrix suggests that:

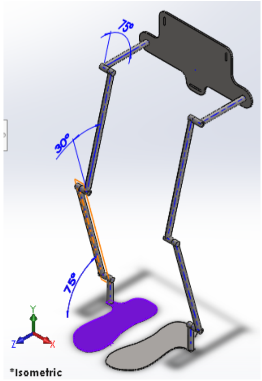
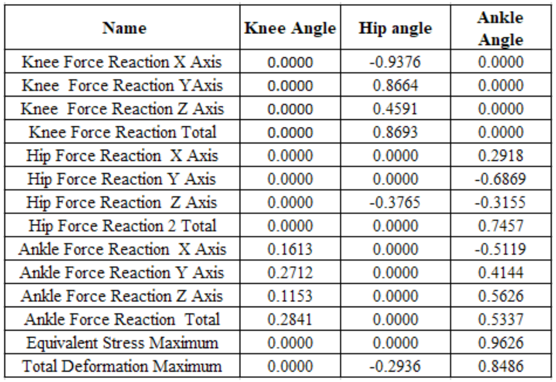


Fig. 7. Simulation setup for Joint DoE

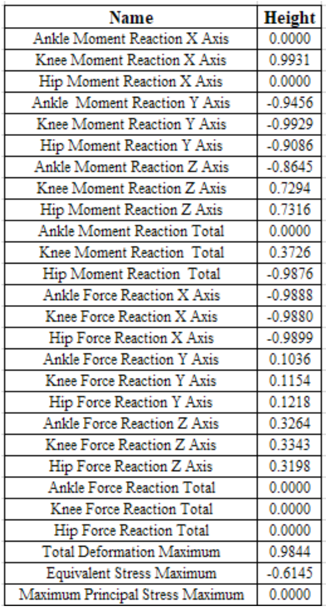


Name	Knee Angle	Hip angle	Ankle Angle
Knee Force Reaction X Axis	0.0000	-0.9376	0.0000
Knee Force Reaction YAxis	0.0000	0.8664	0.0000
Knee Force Reaction Z Axis	0.0000	0.4591	0.0000
Knee Force Reaction Total	0.0000	0.8693	0.0000
Hip Force Reaction X Axis	0.0000	0.0000	0.2918
Hip Force Reaction Y Axis	0.0000	0.0000	-0.6869
Hip Force Reaction Z Axis	0.0000	-0.3765	-0.3155
Hip Force Reaction 2 Total	0.0000	0.0000	0.7457
Ankle Force Reaction X Axis	0.1613	0.0000	-0.5119
Ankle Force Reaction Y Axis	0.2712	0.0000	0.4144
Ankle Force Reaction Z Axis	0.1153	0.0000	0.5626
Ankle Force Reaction Total	0.2841	0.0000	0.5337
Equivalent Stress Maximum	0.0000	0.0000	0.9626
Total Deformation Maximum	0.0000	-0.2936	0.8486

Fig. 8. Sensitivity and Correlation Matrix,Bending DoE

- The total deformation and maximum equivalent stress show a strong positive coupling of outcomes with the ankle joint. This concludes that the ankle joint should have a higher rigidity and a robust design than the other two joint to counter the deformation and stress.
- The hip angle shows a strong negative coupling with the X reaction in Knee joint, while a strong positive coupling with the Y component and total reaction force in knee joint. There is a slight negative coupling between hip angle and Z component of reaction in Hip joint
- The ankle angle shows a weak negative coupling with the Y reaction of Hip joint and weaker correlation Z reaction of Hip joint. However the coupling with total reaction force is relatively stronger and positive.
- The Knee joint angle only shows a slight positive coupling on the ankle joint reactions and thus is not an essential criteria.

2) Height: Similar to bending; sitting and standing are also important load cases that we need to consider in designing the exoskeleton. The height from the ground at which we lock the mechanism, is expected to show correlation with the joint reaction forces and moments. The same are investigated in this DoE. The key input variable is the Height from the ground, while the output variables are the joint reaction forces and moment components along with the maximum deformation and equivalent Von-mises stress and maximum Principal Stress. The Simulation setup was same as that shown in Fig. 7.



Name	Height
Ankle Moment Reaction X Axis	0.0000
Knee Moment Reaction X Axis	0.9931
Hip Moment Reaction X Axis	0.0000
Ankle Moment Reaction Y Axis	-0.9456
Knee Moment Reaction Y Axis	-0.9929
Hip Moment Reaction Y Axis	-0.9086
Ankle Moment Reaction Z Axis	-0.8645
Knee Moment Reaction Z Axis	0.7294
Hip Moment Reaction Z Axis	0.7316
Ankle Moment Reaction Total	0.0000
Knee Moment Reaction Total	0.3726
Hip Moment Reaction Total	-0.9876
Ankle Force Reaction X Axis	-0.9888
Knee Force Reaction X Axis	-0.9880
Hip Force Reaction X Axis	-0.9899
Ankle Force Reaction Y Axis	0.1036
Knee Force Reaction Y Axis	0.1154
Hip Force Reaction Y Axis	0.1218
Ankle Force Reaction Z Axis	0.3264
Knee Force Reaction Z Axis	0.3343
Hip Force Reaction Z Axis	0.3198
Ankle Force Reaction Total	0.0000
Knee Force Reaction Total	0.0000
Hip Force Reaction Total	0.0000
Total Deformation Maximum	0.9844
Equivalent Stress Maximum	-0.6145
Maximum Principal Stress Maximum	0.0000

Fig. 9. Sensitivity and Correlation Matrix, Lifting DoE

Fig. 9 shows the correlation coefficients against the corresponding output variables. It suggest:

- The height shows positive coupling, strongly with moment along X and Z axis knee joint and Z axis of hip joint while, weak with Y and Z reactions of all the joints.
- The height shows negative coupling, strongly with Y moments of all the three joints and X reactions forces of all the three joints.
- The ankle X moment and total reaction forces are independent of the height
- The total Deformation shows a strong positive correlation with height while Maximum Equivalent stress shows a negative coupling with height.

Based upon the two DoE, the crucial design parameters were found out to be, the ankle and hip joint angles and the height of the entire system. The knee joint angle shows independence with almost all the output parameters, with an exception of a weak relationship with a few.Based upon the observations and inferences of DoE, the joint ratchet and the backrest plate design are discussed in succeeding sections.

B. Modeling and Simulation of Ratchet

The moment reaction along the X axis are borne by the ratchet mechanism. The Ratchet mechanism will fail when the moment exceeds the yield strength of either ratchet or the pawl pin. The maximum load moment is found out as the function of the height was found during the DoE, is depicted in the Fig. 10.

Thus, a load of 29 N.m was applied at the ratchet center. The Ratchet and pawl material is AISI 1018. The Results are

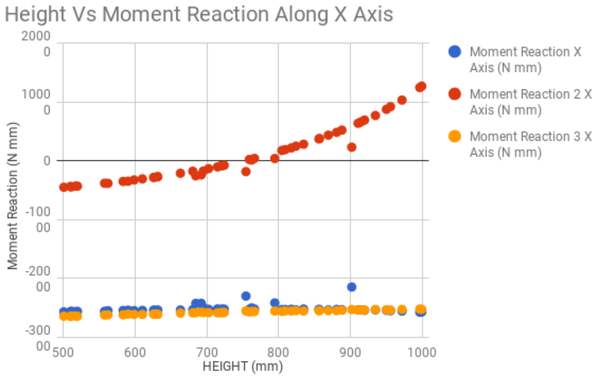


Fig. 10. Moment about X axis Vs Height in Hip, Knee and ankle joint. Joint 1:hip joint; Joint 2: Knee joint; Joint 3: Ankle joint.

as shown in Fig. 11 & 12. The Maximum deformation was found out to be 6.89e-4 mm which is in the acceptable limits. The Maximum Equivalent Von-Mises stress was found out to be 14.353 MPa. The yield strength of AISI 1018 is 370 MPa. Thus we get a high Factor of Safety of about 25.

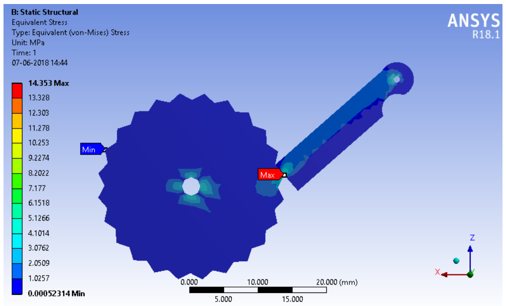


Fig. 11. Equivalent stress contour in ratchet and pawl.

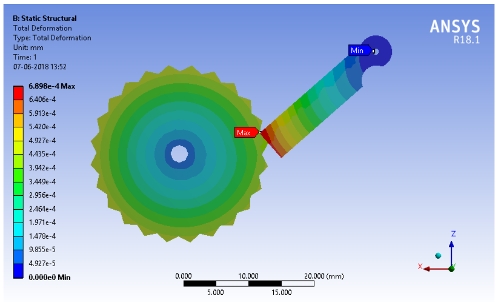


Fig. 12. Total Deformation contour in ratchet and pawl.

C. *Modeling, Simulation and Optimization of Back plate*

All the load is transferred to the exoskeleton through the back plate. It is the component with most of the weight and opportunity for optimization. The simulation setup and the load case for the analysis is as shown in Fig.13.

The height was kept to be 600mm from the ground. The results, after validation are shown in Fig. 15 & 16 The Back plate and linkages are made up of AISI 304 alloy . The stress concentration between two vertical harness joints is negligible and can be removed for weight reduction. For topology optimization, with 60% retain mass goal, the objective was to maximize the stiffness.

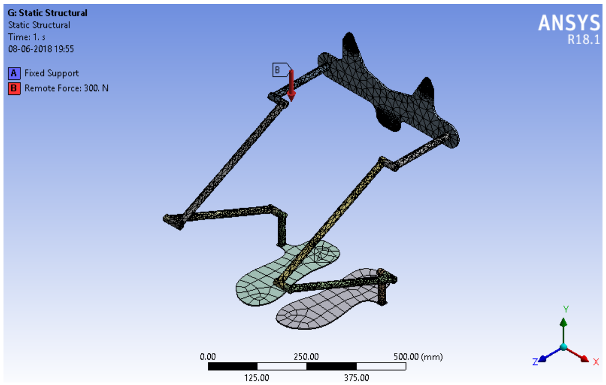


Fig. 13. Simulation setup: topological optimization and static analysis

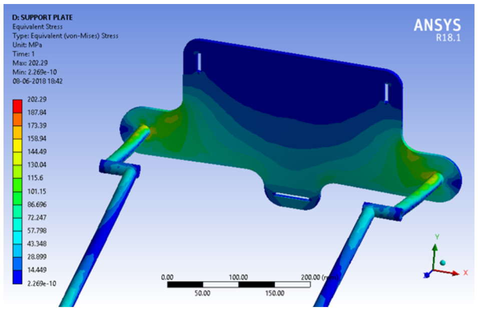


Fig. 14. Equivalent stress contour of back plate before topological optimization.

The maximum stress was reduced from 42.8 MPa to 39.6 MPa. The maximum deformation was 4.3 mm initially and 4.01 mm. Initial mass was 3.58 kg while the final mass was 2.16 kg. thus a considerable improvement over the initial design was achieved.

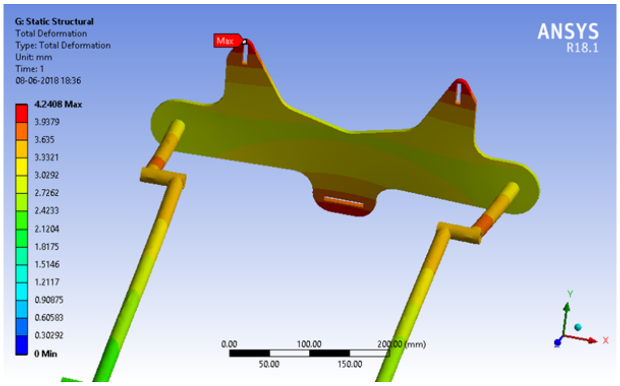


Fig. 15. Total deformation contour of back plate after topological optimization.

The static structural analysis of the entire system was done thereafter. The results of the same are shown below. The

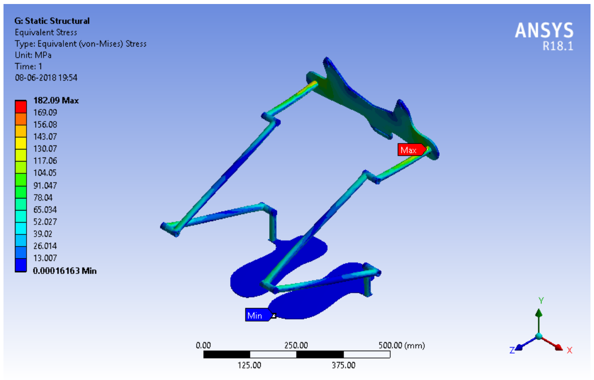


Fig. 16. Equivalent Von-Mises stress contour of the exoskeleton.

maximum stress was found out to be 182.09 MPa near the hip revolute joint along Z axis and the maximum deformation was found to be 4.2 mm at the harness mounting point. The Factor of safety thus is about 2 which is satisfactory.

V. COST ANALYSIS

The cost of LPE is significantly lower than the powered and quasi-passive exoskeletons. We built our entire model in 26,000 INR (approx. 400 USD), while the SuitX company product legX costs about 4000 USD [1] which is quasi passive exoskeleton and ReWalk which is powered exoskeleton for paraplegic costs about 70,000 USD [7].

VI. RESULTS AND CONCLUSION

In this paper we have discussed some of the advantages of LPE over Powered and quasi-passive exoskeletons. They have higher flexibility, light weight, energy efficient and user friendly compared to their counterparts, as discussed above. For these intrinsic virtues of LPE, we decided to build EXoS. To absorb the vibrations and bear the weight and recoil of power tools, additional custom attachments can be provided as well.

Despite these advantages, there are certain limitations accompanying our design. It cannot be used with paraplegic people. The weight of the system is high as we have used metallic structural members.Also, bio-compatibility is a challenge right now. It will not assist the wearer on uneven terrain. More research is needed to realize the human gait.

The design of our system is robust. For structural members a low factor of safety of about 2 is maintained to reduce the weight of the system. The crucial and intricate parts have a high factor of safety. The design of experiments analysis highlighted various design parameters that needed a close consideration. It also demonstrated certain design advantages intrinsic to the system, like, the force and moment reactions were fairly independent of the knee joint angle. As this angle is prone to change continually as well as drastically during operation, the joint reactions are less susceptible to change. Also we can accommodate various height of users without altering anything in the system and get a satisfactory performance as well. Furthermore, the design is fairly modular and adaptive as the individual links can be detached from the mechanism and replaced easily for user comfort or upon failure.

VII. FUTURE SCOPE

The exoskeleton is rapidly growing technology many universities and industries are now showing interest in developing the exoskeleton. Some have succeeded in building the device that can be used in real world. The passive exoskeleton is not a power enhancing or augmenting device, it simply assists the wearer to carry load by transferring the forces to the ground without putting strain on the limbs of user. So this device helps in increasing the endurance of the user. The limitations discussed in previous section are a pretty straight forward problem and can be resolved. We can use composites to build the structure to not only reduce the weight, but also improve its bio-compatibility and agility. Use of an appropriate linkage for gait correction can be done.

At this stage we have built only lower limb device thus in a logical progression the next step will be to design an upper body exoskeleton which can help to enhance the weight lifting capacity of the user. The complete exoskeleton needs to be a lightweight, bio-compatible, user friendly device, easily accessible to all.

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