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Structural Analysis of Lower Limb Exoskeleton During Walking

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***Abstract*— The requisite of exoskeletons are expanding gradually in the field of medical rehabilitation which is mainly due to musculoskeletal disorders, spinal cord injuries, paresis, and military applications and as a consequence of accidents. Numerous researches and many new type of exoskeletons have come to the market that are benefiting the users in one or the other way. The foremost intent of this study is to analyze the static-stress through Finite Element Analysis (FEA) which can withstand and work in accordance with the human weight. To analyze the lower limb exoskeleton model, Ansys® is used, wherein von mises stress analysis is accomplished. Three type of materials are used for the analysis purpose to achieve a superior outcome.**

Keywords*—*exoskeletons, finite element analysis, von mises stress analysis

I. INTRODUCTION

"Exoskeleton" **-** External skeleton that supports and protects a body, in contrast to internal skeleton (endoskeleton) of humans and animals. Some insects and animals mostly have exoskeleton by birth. Whereas humans have endoskeleton. Due to some unfortunate situations like neurological conditions and injuries, mobility of human body gets restricted, rendering human musculoskeletal network redundant.

A. Robotic Exoskeleton

Exoskeleton is referred as "Wearable robots". Robotic exoskeleton has emerged in the past decade as a solution for people who suffer to locomote. Robotic exoskeletons, with the help of sensors, motors, pistons, and lightweight materials, help immobile beings (humans or animals) move.

B. Human Exoskeleton

External skeleton which covers an entire body, just the upper or lower extremities. a specific body such as hip or ankle is known as "Human exoskeleton". Human exoskeleton is characterized by its anthropomorphic nature. Actuators and motors play a vital role in contributing movement to the exoskeleton at human joint levels. They possess a level of intelligence of humans in conjunction with robot mechanical strength. Human exoskeleton has been grouped either into full body exoskeleton (provides various movements) or partial exoskeleton (provides limited movements).

C. Classification of Exoskeletons with respect to end-users

Exoskeletons are vast and they are used in various sectors like medical, military, etc. Based on user, in general they get classified as:

1) Medical Exoskeleton

Exoskeletons used in medical sector aid joint and limb motion of patient. Such exoskeletons include ankle for drop foot applications or a hip and knee exoskeleton for rehabilitation. Paraplegia – "Paralysis of lower body caused due to SCI". Paraplegia is a medical condition which restricts the sensory-motor functionality of lower limb preventing movements like walk and stand. Exoskeleton developed in medical sector are developed mainly for paraplegia patients. Conventional methods like braces, crutches, wheelchairs, and orthotic devices can be an optional solution. But braces and crutches fail to provide person full motion autonomy. Wheelchairs perform well in flat surfaces, contributing an effective movement, but fail in terrains. Hence, Exoskeletons becomes the valuable solution for paraplegia patients, as of now.

2) Non-Medical Exoskeleton

Exoskeletons which fall under the category of personal care robots that assist user function like strength augmentation for workers to perform physically demanding tasks, military applications such as for soldiers to carry heavy equipment under war circumstances and for supplementation services where normal human requires help to perform daily chores fall under the category of "Non-Medical Exoskeleton".

D. Benefits Of Exoskeletons

Exoskeleton is beneficial as it provides increased efficiency and productivity. Industrial robots can be replaced by exoskeletons by eliminating the need for completely automated solutions.

Exoskeletons can make aging workers sustain their intensive tasks as it is. Exoskeletons are especially beneficial by decreasing worker injuries, cost of disability and valuable healthcare. Reduction of employee turnover.

II. LITERATURE SURVEY

Jose Gonzalez-Vargas et al. (2019) have analyzed about 52 lower limb wearable exoskeletons which on the whole focuses on three main aspects of compliance that is, actuation, structure, and interface attachment components. This paper provides the importance of the mechanical design and increasing the efficiency and effectiveness of the interaction with the users with comfort. They have created and made available a set of data sheets that contain the technical characteristics of the reviewed devices, with the aim of providing researchers and end users with an updated overview on the existing solutions.

Jung-Hoon Kim, et al. (2017) have defined about the concept of Centre of Pressure (CoP) with respect to the lower limb exoskeleton structure which is also referred as zero moment point (ZMP) has been introduced to make it more trouble-free. Mechanical stoppers comes into the role to prevent the actuators causing injuries or any dysfunction and to ensure safety movements in the structure. Kinematic analysis is made with respect to the DOF for the initial step of processing it. The COP data and the values of pressure measurement systems are compared and analyzed in which the errors were identified and later operated in a stable mode.

Rifki Atmaja et al. (2017) processed the stress analysis of lower limb exoskeleton through finite element analysis. Here, the authors had chosen ABAQUS software for FEA and Aluminum Alloy 7075-T6 was used since it is a light weight material which is the main advantage for the wearer to use on a daily basis. By figuring out the von Mises stress, they concluded that the structure is all set for the walking movement. Analyzing the structure with limited loads the authors have also inferred that the design is safe and comfortable to use.

Haldun Koktas et al. (2018) proposed a 4-DOF lower limb exoskeleton structure which is a lightweight structure powered by pneumatic artificial muscles (PAM) and FEA is being carried out to evaluate the stress and deformation values of limbs and PAMs. With the help of SOLIDWORKS, the mechanical structure is designed in accordance with the gait biomechanics. To ensure its strength and stiffness FEA is done in ANSYS software and they received the expected results of having the capacity to withstand if a particular stress is applied. This virtual result showed a positive move and the authors wanted to increase the range of motion so that it will be an adaptable device.

Umesh K et al. (2021) performed Ludwig von mises stress analysis for the patients suffering from paraplegia. Here, three type of materials: Alloy steel, 1060 aluminum alloy and titanium are used for the static-stress analysis. Designing of the exoskeleton model is achieved through SOLIDWORKS and sit-to-stand transition is attained by comparing the stress with the weight of the patient. Voronoi-Delaunay meshing method is used for the finite element analysis. The authors have implemented rectangular blocks for developing the model which makes the analysis trouble free.

Therefore, this provides an overview of the previous research papers to enhance the improvement and knowledge in the idea of the project. It is mainly to scope out the key data collection required for developing the project. A synthesis of the early works provides many suggestions to be included in the objective of the project. It has highlighted the ideas behind various journals published earlier and focuses on several aspects that helps in the development of the project. The ideology related to the development of lower limb exoskeleton structure is discussed below.

III. METHODOLOGY

In this research work, an exoskeleton is developed to support the patients with spinal cord injury-paraplegia and static structural von-mises stress analysis (Finite element analysis) is performed on the model designed. Finite element analysis is to analyze the behavior of a part or assembly on the given conditions. Autodesk Fusion 360 is used for analysis. The methodology, design consideration, materials are explained briefly in this section. The block diagram of the methodology is shown in the Figure 1.

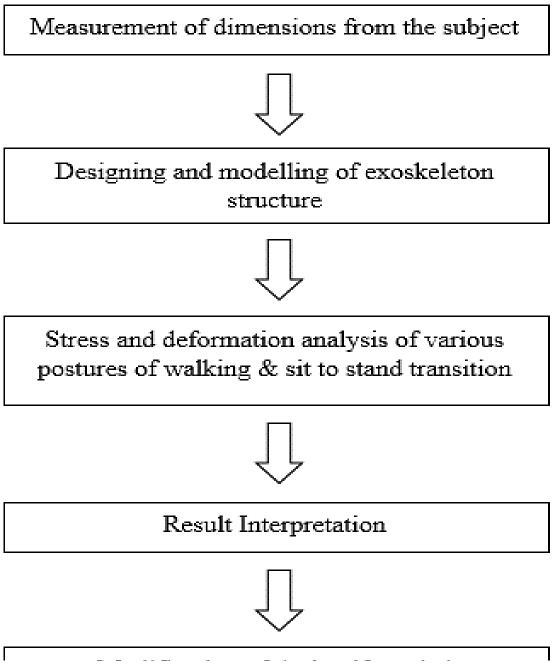

Figure 1. Methodology of the analysis

A. Design of lower limb exoskeleton

Most of the lower limb exoskeleton consists of four segments: Hip, upper leg, lower leg, foot. This is because the lower limb exoskeleton should bear the entire weight of the subject and should be sheltering the movements of joints. There are good advantages of having four segments. (i) Can limit the movements of joints (ii) can place the joints on the natural anatomical position (iii) controlling movements will be easier. In our work, we focus on the measurement of the anthropometric parameters of the subject, to develop customized suitable four segment design. This type of customization will make the subject more comfortable to wear the exoskeleton. The exoskeleton is individualized so that there is no average values of dimensions. The dimension of four segments are given in the Table I.

TABLE I. DIMENSION OF FOUR SEGMENTS

Segments	Length (mm)
Hip	360
Upper leg	410
Lower leg	570
Foot	230

B. Materials

For construction of exoskeleton, there will be a need of lightweight material which can bear large force. Most commonly used materials for exoskeleton are alloys. In our work we incorporated various materials and analyzed it. The materials used for realization are Aluminum alloy, Wood, Titanium alloy. The material should withstand the entire weight of the subject. In case of walking, one limb should bear all the weight, while coming to the human usage the material should be biocompatible, also cost, availability and durability should be considered. These materials are chosen based on the criteria given above. As this exoskeleton is of external use, so there would be less uncomfortable feeling for the subject. The materials with their yield strength is given on the table II.

TABLE II. MATERIALS

Material	Yield Strength
Aluminum alloy	280
Wood	47.76
Titanium alloy	930

IV. RESULT AND DISCUSSION

A. Finite Element Analysis

The assembly model of the lower limb exoskeleton is analyzed under a certain condition using the Ansys®. The model is created using Autodesk® Fusion 360™. The model of lower limb exoskeleton is shown on Figure 2. Initially materials is defined. Analysis using all three materials will be carried out.

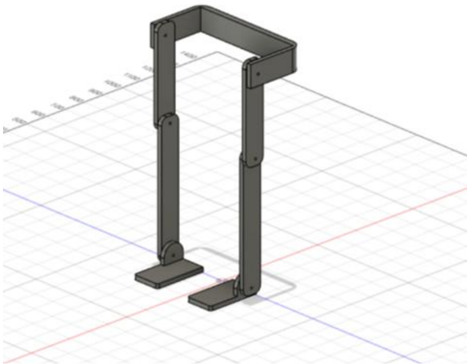

Fig 2. Model of lower limb exoskeleton

B. Constrains, Force & Meshing

(i) Standing Posture

The exoskeleton is considered to be in the standing position. When a human is standing, predominant force is applied on the foot. Likewise the exoskeleton is constrained as a standing model. The base of the foot is fixed and standard earth gravity is applied for more accuracy. The structural constrains are shown in the figure 3.

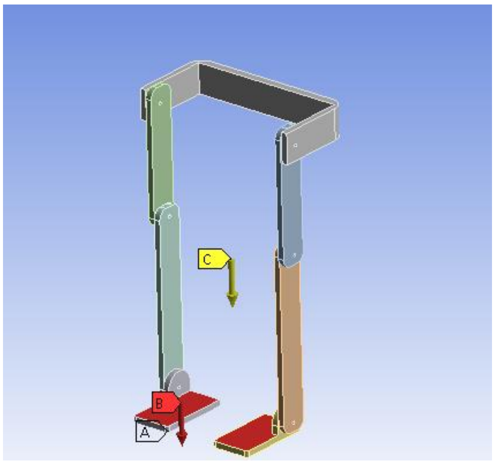

Fig 3. Yellow arrow is standard earth gravity, red arrow is the force given, 'A' indicates Fixed Base of the foot

The force applied for analysis is 1600 N. The force given is based on the weight of the subject. The weight of the subject is 80 kg which in terms of force is 800N.The weight is doubled and applied to the foot. After giving the conditions, meshing is important. Meshing is process in which continuous geometric shape of an object is broken down into thousands of shape or more to properly define the physical shape of the object. The more detailed a mesh is, more accurate the model will be for simulation (FEA). The meshing used in the work is automatic method meshing. The meshed exoskeleton is shown in the figure 4.

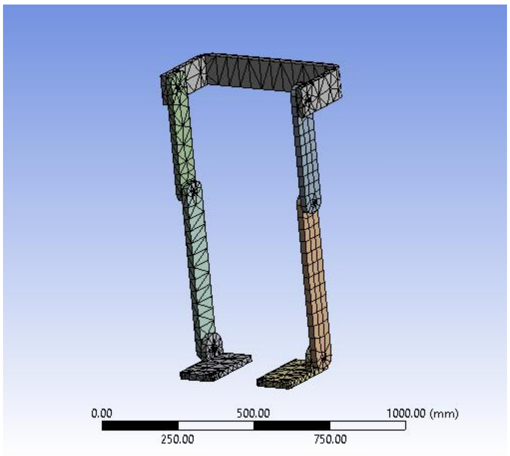

Fig 4. Meshing of lower limb exoskeleton

(ii) Sit to stand transition

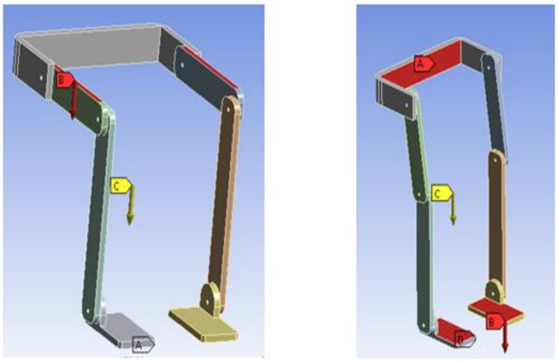

Fig 5 (a) - Constrains for sit to stand, 5 (b) – Constrained final posture

A force of 1600 N is applied on the thigh part pf the upper leg component and to the bottom of foot is fixed, as the foot will be grounded during the sit to stand movement. The constrained model is shown in this figure 5 (a). For the final stabilization posture, 1600 N force is given to foot and 500 N on the anterior part of the hip as shown in the figure 5 (b). It is because the subject may use exoskeleton as a support during the lift, so 500 N is given. Meshing is done using automatic method for this analysis.

C. Von-mises stress for the lower limb exoskeleton

(i) Standing Posture

In the standing position of the lower limb exoskeleton, stress is concentrated on the foot component. The applied force predominantly acts on the foot component. The complete stress output of lower limb exoskeleton is shown in the figure 7.The stress from 0.042896 MPa – 0.37239 MPa is observed on the interior and anterior part of the upper and lower leg component. The maximum stress of 0.37239 MPa is observed on the posterior superior part of the knee joint as shown in the figure 7(a). The minimum stress of 0.0017091 MPa is observed on the Knee joint of the lower limb exoskeleton as shown in figure 7(b).

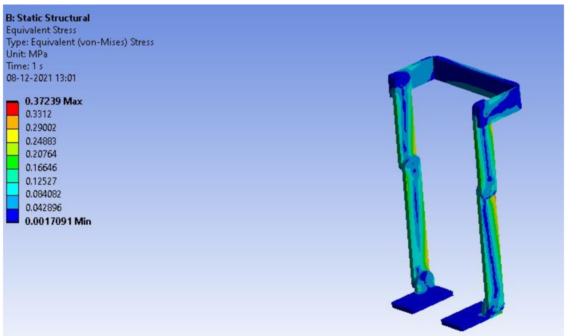

Fig 6. Von-mises stress analysis of exoskeleton in standing position

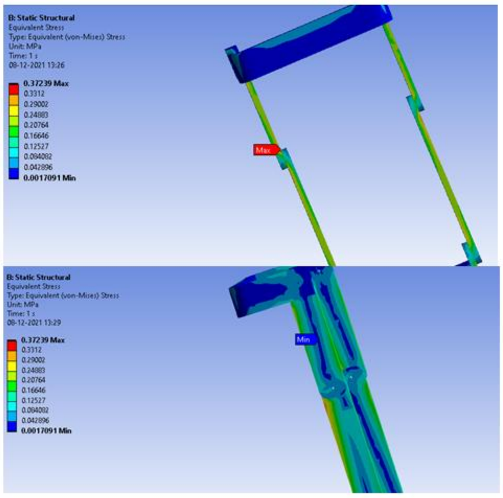

Fig 7(a) - Maximum Stress area, 7 (b) - Minimum Stress area

The stress analysis is carried out using three different materials. There is a stress difference of 0.24681 MPa between the aluminum alloy and wood. While comparing aluminum alloy with titanium alloy, there is a stress difference of 0.24826 MPa. Similarly while comparing wood with titanium alloy there is stress difference of 0.49507 MPa .So we can see that titanium alloy has more stress concentration while comparing with other two materials. The wood observed less stress but the yield strength of the wood is lesser when comparing the other two. Titanium alloy has a great yield strength but practically the manufacturing cost will go high. So aluminum alloy is more suitable. Wood can also be used if cost is main concern as lower limb exoskeleton can be done in very cost using wood. From this it is evident that aluminum alloy more suitable and wood is also quite good for building the exoskeleton structure. The stress and deformation comparison of three materials is shown in the table III.

TABLE III. COMPARISON OF STRESSES, DEFORMATION OF THREE MATERIALS

Material	Von-mises stress (MPa)	Deformation (mm)
Aluminum alloy	0.37239	0.030794
Wood	0.12558	0.032407
Titanium alloy	0.62065	0.037993

(ii) Sit to Stand transition

Sit to Stand transition consists of four phases. (a) Flexion phase, (b) Momentum transfer phase, (c) Extension phase, and finally (d) Stabilization phase. Each phase has some postures, for each posture von-mises stress is computed. The maximum stress observed and its location in each posture is shown in the table IV.

Pose 1, Pose 2 – Flexion phase,
Pose 3, Pose 4 – Momentum transfer phase,
Pose 5, Pose 6, Pose 7 – Extension phase,
Pose 8, Pose9 – Stabilization phase.

TABLE IV. MAXIMUM VON-MISES STRESS FOR CONTINUUM OF POSTURES

Postures	**Maximum Von-mises stress(MPa)**	**Location of maximum stress**
1	15.3	10 mm along Posterior superior edge of the lower leg component.
2	11.334	
3	10.148	
4	8.2968	
5	5.2796	
6	6.6213	
7	6.0002	
8	2.3201	25mm along lateral superior edge of the lower leg component
9	10.149	20 mm along the medial inferior edges of lower leg component

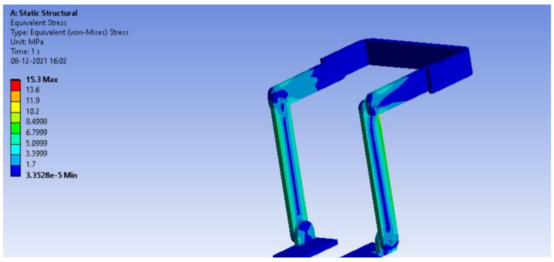

Fig 8(a) – Stress at pose 1

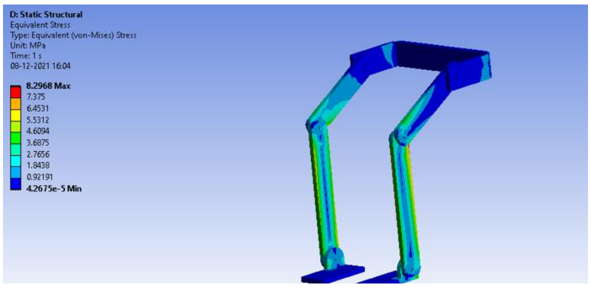

Fig 8(b) – Stress at pose 4

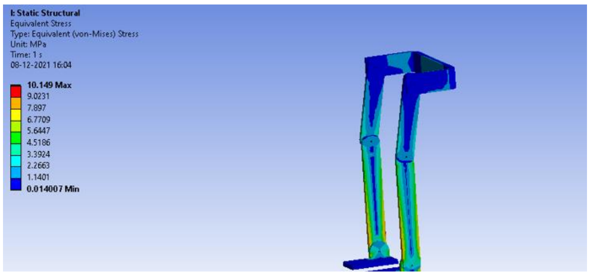

Fig 8(c) - Stress at pose 9

The proposed model has been tested for its endurance during the sit to stand transition. From flexion phase to Momentum transfer phase the stress is reducing as the stress moves from thigh to foot through lower leg. The pose 1 is shown in figure 8(a) has observed the maximum stress in the whole sit to stand transition. In pose 4, the maximum stress is observed in the posterior superior part of the lower leg component as shown in figure 8(b) this indicates that the stress is distributed from thigh to foot. In pose 9, the hip component is stable even though a force of 500N is given and it is safe for the subject to hold exoskeleton. In the complete phase of sit to stand the stress value doesn't cross the yield strength of the material, so the structure is strong and stable is this condition.

D. Walking

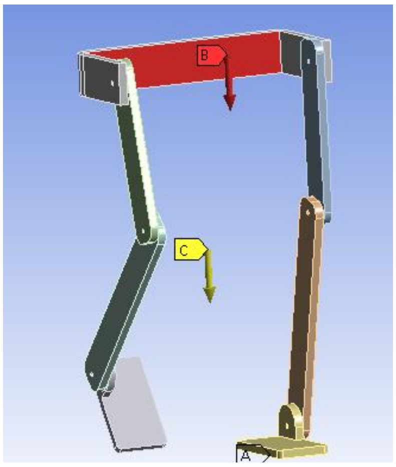

Fig 9 – Constrains for Walking

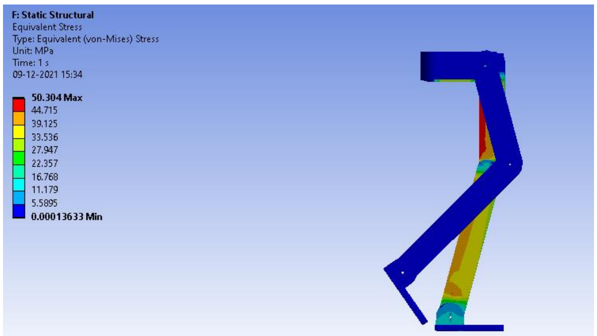

Fig 10- Von-mises stress during initial and mid-swing

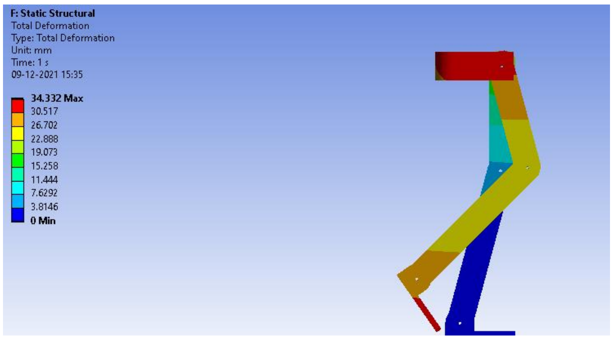

Fig 11 – Total deformation during initial and mid-swing

The proposed design has been tested for its stress withstanding capability and deformation during walking. There are several forces involved during walking. For the purpose of analysis, the assumptions have been made to pin point the real problems associated with the real time challenges of an exoskeleton during walking. The normal gait pattern of an individual has been adopted to evaluate the walking pattern of the proposed model. The model has been evaluated on a rigid horizontal surface without any obstacles. The design need to be reworked independently for every individual of consideration. The anthropometric parameters need to be accounted for every individual before making any design changes. In this proposed model, the design has been strictly confined to an individual having an average 80Kg mass and dimensions as described in Table I.

For a horizontal movement the maximum stress is observed at the posterior edge of the toe region during the heal strike. Just before the mid-stance and after the loading response of the gait cycle, the maximum stress is shifted towards the anterior edge of the lower leg component. During the mid-stance the stress is further shifted towards the superior edge of the hip component. This indicates that the maximum stress is shifted at various location of the exoskeleton based on the walking pattern. The peak value is almost the same as the design have rectangular bars. The peak stress may be changed if the cross section of the design varied along the length of the exoskeleton. The maximum stress observed in the entire range of walking cycle indicates that the value is well below the elastic limit of the material chosen for the exoskeleton. The stress and deformation during various stages of walking are indicated in table V.

TABLE V. STRESS AND DEFORMATION DURING WALKING

Sl. No.	Posture	Stress (MPa)	Deformation (mm)
1	Heel strike	17.08	13
2	Loading response	52	35
3	Mid stance	47	28
4	Terminal stance	45	32
5	Pre swing	46	33
6	Initial and Mid swing	50	34
7	Terminal swing	51	34

From this overall analysis it is proven that the structure can withstand the human weight and the strength of the design is within the limit for a normal application of an exoskeleton.

V. CONCLUSION

Robotic exoskeletons are of great demand in research sector and in military. Medical rehabilitation means assisting a person suffered from illness or injury contributing maximum self-sufficiency and restoring lost skill of the patient. Exoskeleton is the new generation medical rehabilitation device which are popular now a days. The proposed project, falls under the category of medical rehabilitation. Medical rehab exoskeletons already exist, but they are too expensive. The objective of the proposed model is to develop a cost effective exoskeleton structure for walking assistance, test the structure for its mechanical acceptance and also to test the material under consideration for its weight withstanding capability.

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