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Design and Development of Passive Exoskeleton

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ABSTRACT: Osteogenesis Imperfecta (OI) is a rare genetic condition which affects the skeletal system. According to a recent survey, about 5% of the world's population has a physical disability of some nature. In India alone OI affects about 0.007% of the population, roughly about 87,000 people, most likely these people dependent on an assistive device for mobility. OI has no obvious medical cause or a real cure, it shows a range of symptoms and signs. In the affected human under study, both the pairs of femur and tibia bones are severely and non-uniformly deformed. The deformities in the legs rendered the issues with load transmission and balancing while walking, for which the affected individual must use elbow crutches. There is scope for improvement. This paper presents the design and development of exoskeleton customized to an individual's needs. The exoskeleton transmits load to the ground, removing most stresses/impacts from the lower limbs. It consists of a rigid polymer ring worn around the waist/back, where most of the load is to be distributed/ transmitted. Links parallel to each leg will have six joints, two, 3 DOF joints aligned with hips, two, 1 DOF at knees and two 2 DOF joints at the ankles. The Exoskeleton is provided with cushioning and strapping to ensure stability, comfort and joint alignment.

KEYWORDS: Assistive Technology, Passive Exoskeleton, Osteogenesis Imperfecta, Bone Deformities.

ABBREVIATIONS: OI- Osteogenesis Imperfecta, FOS- factor of safety, BW- body weight, WAE-Wearable exoskeleton, DOF- degrees of freedom, HDPE- High density polyethylene

I. INTRODUCTION

Bone deformities occur in general due to limb length discrepancies, traumatic injuries, existence of tumours or due to medical conditions like OI. Osteogenesis Imperfecta (OI) is a rare genetic condition which affects the skeletal system. According to a recent survey, about 5% of the world's population has a physical disability of some nature. In India alone OI affects about 0.007% of the population, roughly about 87,000 people, most likely these people dependent on an assistive device for mobility. Most often, the affected bones are weight bearing ones, i.e., the tibia (lower leg bone) and femur (thigh bone). Bone deformities can affect the person by causing pain, restricting mobility and destabilizing joint alignment. If left untreated, bone deformities can lead to arthritis, back pain and in some worst cases bone fracture. On the long run, it can potentially prevent people from doing what they enjoy. [6]

A lot of research and effort was put on the exoskeleton technology, both on active and passive models. Most of the medical exoskeletons in the market today cater mostly to people with one set of problems, people who lack the muscular ability to move to be more specific, these exoskeletons are bulky, expensive and exist only in the US and European markets. The other exoskeletons in the market are there to aid able bodied people reduce metabolic costs while performing certain activities. Some powerful exoskeletons are used to help enhance the abilities of workers in an industry or on field also exist in the market. It must also be noted that the models in the market are designed keeping standard bodies in mind, for example a lot of the models can be used by people with 155-185cm standard height, for the people who have bodies that don't conform to such standards, customization will have to be done. The person under study has limb deformities and a short stature, it became clear after testing a prototype that standard straight pylons are going to cause joint misalignments, so none of the existing models will likely help people like the person under study. After realizing a fully working custom-made model, a standard model will be derived with some variables in design (like the geometry of pylon etc) so as to address a larger section of people in need. Most of the models used aluminium alloys to make their structures. [1][2][3][4]

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1.1 About the affected person under study: The person under study has severe asymmetric deformities in his leg bones because of the genetic condition of OI. The right femur and left tibia are severely deformed, the extent of deformities is such that cracks known as stress fractures have developed on the surface of these bones (marked 1,2,3,4 &5 in depiction). Elbow crutches help the person find his way around, however the progressive nature of his deformities and the stress fractures are a cause of deep concern. Naturally, mobility of the person is limited and might deteriorate as the deformities progress. The below figure gives the pictorial representation of body of the affected person under study where the detailed description of the bones are given.

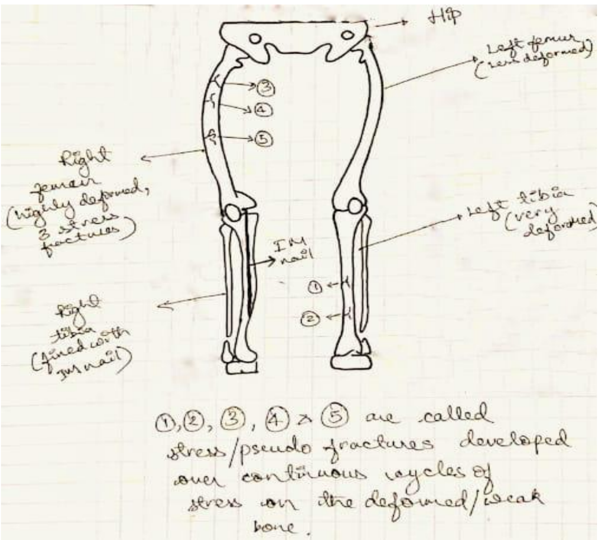

Fig. 1.1 Illustration of affected bones

1.2 A Passive Exoskeleton: With a passive exoskeleton, the idea is to remove stresses and impacts on the deformed bones, load is planned to be bypassed from the affected bones onto the upper body through links and straps. The exoskeleton is being developed to be anthropomorphic in joint movements, covering all necessary ranges of motion as the human joints, so as to not compromise on mobility. A passive model is preferred considering that the affected person has a fully functional muscular system. Active joints will be added in future prototypes, if necessary. If the exoskeleton bears 50% of the body load in the least, then the stress on deformed bones will be reduced, improving the mobility of the affected person.

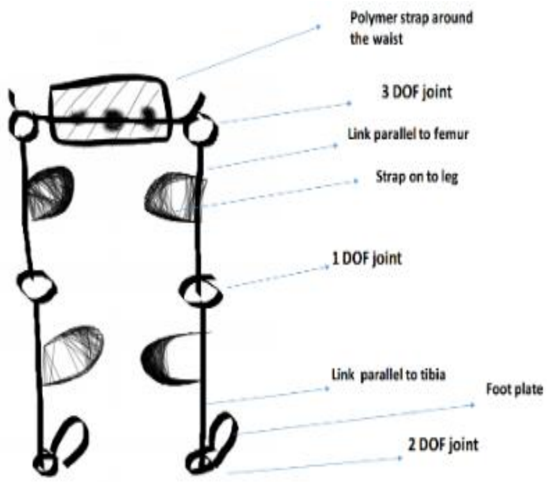

Fig. 1.2 Basic concept development of design

1.3 Basic human skeletal anatomy: The lower body of the human body can be considered as four groups: the waist group, the femur group (the thigh bone), the tibia group (lower leg bones) and the foot group (with many bones). All these groups play vital roles in load transmission when walking and have relative motion via joints. The main joints are hip joint the 3 DOF, knee joint 1 DOF and the 2 DOF ankle joint, all these motions are important during walking and keeping body balance while walking. These motions are simply rotating motions along different axes, that is, pitch, roll and yaw.

1.4 Objectives:

The main objective of thid project work is to design and develop an exoskeleton rendering to an individual's need. The ensuing objectives of the project work will hopefully lead to a final working exoskeleton model that will transmit load to the ground, removing most stresses/impacts from the lower limbs and hence improve mobility of the affected person.

The following are the objectives of the project work:

- Study of deformities in the legs of the affected person.
- Development of concept and progressively improve models in pursuit to improve mobility and bone stability of the affected person.
- Derivation of a more standardised exoskeleton model to cater to the needs of a larger set of people.

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1.5 Methodology:

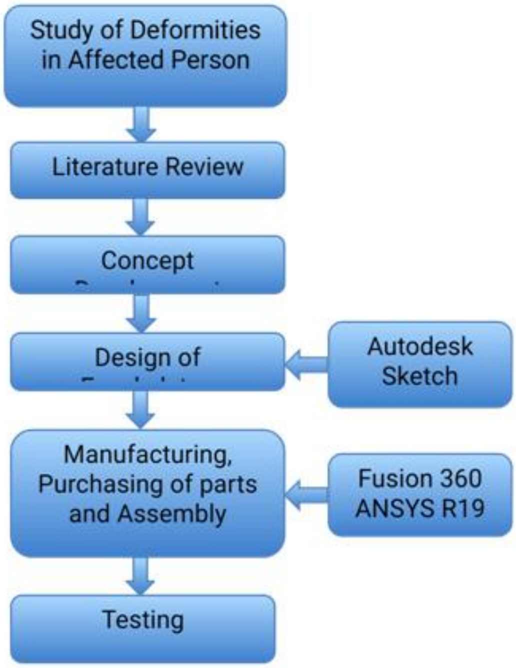

Fig. 1.3 Flowchart shows Methodology of the project

Through the course of this project, the deformities of the affected person's bones were studied; weaknesses and strengths in the body of the affected person were identified. Previous works of similar projects were studied and analysed and the appropriate concept was developed. Using different tools, CAED models and FEA simulations were realized. The first prototype was fabricated and tested on the affected person. The feedbacks from these tests were used to design a second prototype. Testing of a working model will be done after interfacing the model to the affected person using straps, intuitive feedback about the comfort and ease of movements is to be taken. If comfortable walking is possible (with the elbow crutches initially), an intuitive feedback about stresses on the legs as compared to without the device will be taken. After clearing these intuition-based tests, motion sensors are going to be used to collect kinematic data. And then gait analysis will be done, followed by electromyography (EMG) to compare the gait cycle and metabolic cost with and without the exoskeleton prototype strapped on respectively.

II. DESIGN DETAILS OF THE PASSIVE EXOSKELETON

The project is being realized via progressively improving prototypes. Prototype-1 was built and possible tests were conducted. With the inputs from prototype-1, an improved prototype-2 was designed.

2.1 Prototype-1: Prototype-1 was built solely to test the concept of load transmission. The concept is to have an anthropomorphic external structure correspondingly attached to each limb of the body.
The components of the prototype-1 include the following parts:

- Pylon
- Knuckle Joint for knee
- Rod-end Bearing
- Foot unit

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Fig.2.1 a) Knee joint b) Rod-end Bearing c) Foot Unit

The external structure was made up of metallic pylon with necessary joints in between them. Straight cylindrical pipes were used as pylons along limbs, a square cross section pipe was used around as hip reinforcement and foot plate was used under foot. Aluminum 6061 was the preferred for the pylon owing to its high yield strength of 276 MPa. Rod end bearings are 3 DOF joints and are available in the market, these components perfectly fit the motions of the hip and ankle joints and hence used in prototype-1. A simple knuckle joint was fabricated out of a block of Aluminum 6061 for the 1 DOF knee joint. Bolts were used to connect joints to pylon. Plastic sheets and straps were used to connect the external structure onto the body.

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FEA simulations were run for each and every component, the person under study weighs 45Kg, but considering the average weight of human beings, the components were designed to bear a load of 100Kg at the least with a factor of safety of 2.5 and more.

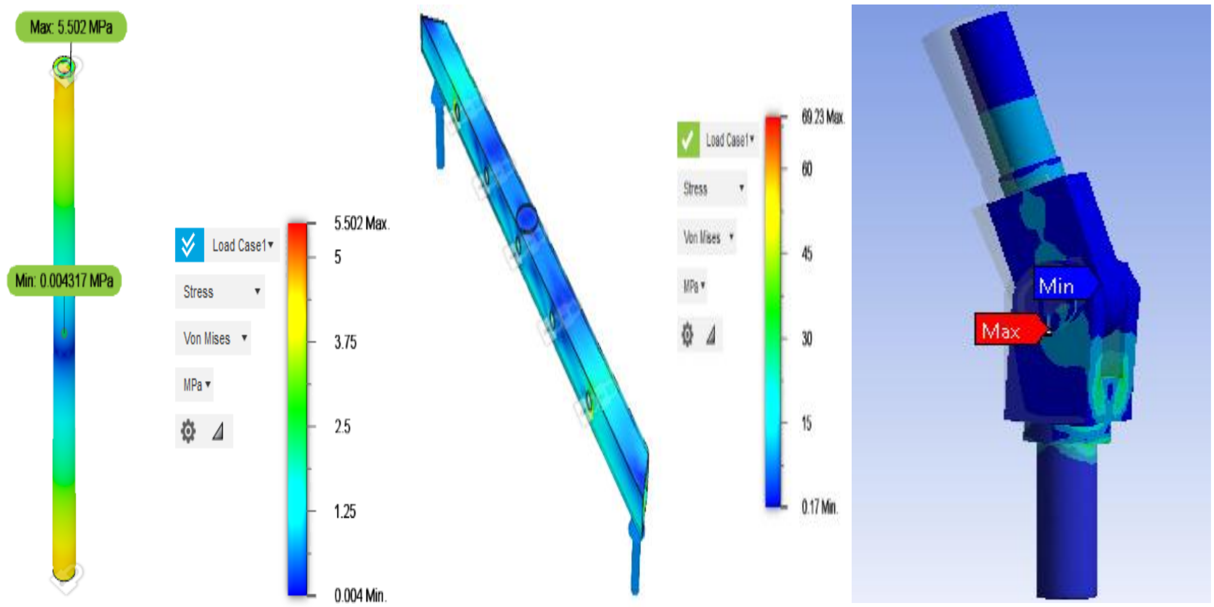


Fig. 2.2 **FEA of the Pylon** **FEA of the Knuckle Joint**

Theoretical calculations of the knuckle joint

i) Diameter of the rod (D) = 14 mm
ii) Diameter of the knuckle pin (d) = 10 mm
iii) Thickness of eye of rod (b) = 15 mm
iv) Thickness of eye of each fork (a) = 7.5 mm
v) Load (P) = 1000 N

Possible Failure Criteria,

i) Tensile Stress in rod,
$\sigma_t = \frac{P}{\frac{\pi}{4} \times D^2} = 6.49$ MPa ≤ (Allowable tensile strength of Al 6061 = 240 MPa)

ii) Shear Stress on pin,
$\tau = \frac{P}{2\left(\frac{\pi}{4} \times d^2\right)} = 6.36$ MPa ≤ (Allowable shear strength of Al 6061 = 120 MPa)

iii) Crushing Failure of pin in eye,
$\sigma_c = \frac{P}{bd} = 6.67$ MPa ≤ (Allowable tensile strength of Al 6061 = 240 MPa)

iv) Crushing Failure of pin in fork,
$\sigma_c = \frac{P}{2ad} = 6.67$ MPa ≤ (Allowable tensile strength of Al 6061 = 240 MPa)

Hence, design is safe.

2.1.1 Testing: The assembled prototype was worn by the affected person and evaluation was done. The affected person was also asked to give a detailed user's evaluation, solely based on intuition. The prospect of walking with this prototype model was not comfortable as interferences occurred withing the range of motion of the structure, indicating alignment issues, further exploration and assessments needed to be carried out. The one positive prospect was that when the user tried to push a chair with his leg, reaction forces were felt near the hip and not on the affected bones, indicating that walking and partial stress removal is a likelihood if the misalignments are removed.

2.1.2 Assembly with straps:

A total of five straps were used:

- 1 waist strap which is the load interface between the body and the model,
- Four straps to ensure the model and the limbs to move as one.

Fig. 2.2 a) CAED model of prototype-1 b) Prototype-1 fabrication c) Prototype-1 ready for testing

2.1.3 Feedback to the next prototype:

- The pylon needs to be plastically deformed to the shape of the bones of the affected person to ensure joints don't overlap and interfere in any position.
- Even the straps need to be made according to the body contours of the affected person. And must not slip up and down along the body.
- Better materials and mechanisms need to be used to optimize the weight and weight distribution area on the body.
- Further the overall weight of the prototype-1 is to be reduced.

2.2 Prototype-2:

The Components of the Prototype-2 include the following parts:

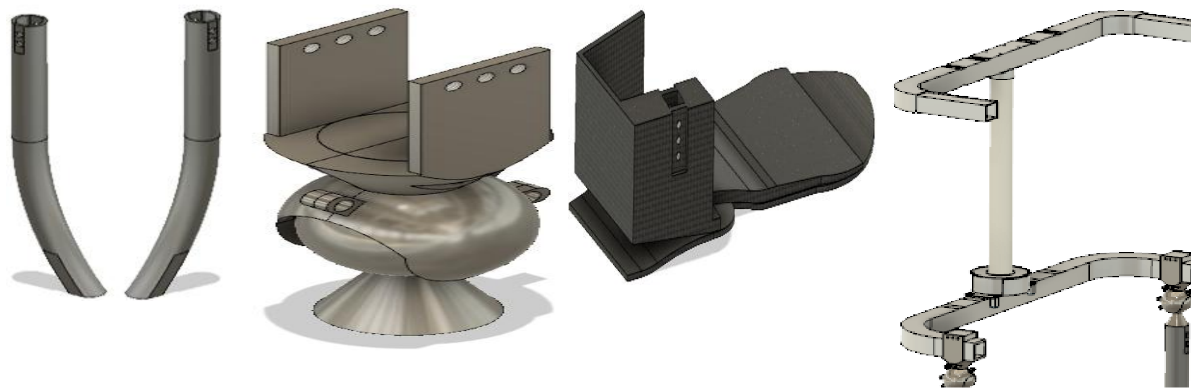


Fig. 2.3 a) Bent femur pylon. b) Ball and socket joint used as the hip joint. c) Foot unit (Carbon fiber) with single-leaf leaf spring under the foot plate. d) Backbone unit.

The most major change made in this prototype-2 is that pylon along the deformed limbs are also plastically deformed, this means that the pylon parts are much more stressed, for which a stronger material needs to be used. Aluminum 7075 with a yield strength of above 400 MPa is best suited. The rod end bearings are not suitable for long term load bearing and they are really heavy. So, the rod-end bearings were replaced in the design by 3 DOF custom made ball and socket joints made of Aluminum 7075. The socket openings are designed as per the required motions of the ankle and hip joints. The knuckle joint design is improved to have lesser contact for a smoother motion. The fulcrum of load distribution is increased from just around the waist region in prototype-1 to waist region in addition to the under-arm region in prototype-2 (refer Fig 2.3), this calls for the requirement of a spine member in the model, something that can withstand both a compressive load and be flexible enough move along with the natural backbone. The first choice to this was to have several links with ball joints in between, but that would require careful tensioning of each ball joint and would prove to be really bulky. So, a single unit spine of circular cross-section was designed, the design requirement of this component demanded a material of low elastic moduli, something that could survive the compressive load of the body and the bending stresses the backbone applies, the polymer HDPE perfectly suited the required design features with an elastic modulus of about 1.5 GPa. The next change made from prototype-1 is the foot. The foot in the prototype-2 was replaced with a carbon fiber foot with a single-leaf leaf spring under the foot plate. The idea is to store some of the energy in one part of the gait cycle and release it another part of the gait cycle, increasing comfort and reducing metabolic cost of the user, much like the Achilles tendon does naturally. A carbon fiber layup was designed for this which has excellent strength and fatigue properties when the layup is designed and fabricated in the right way [5].

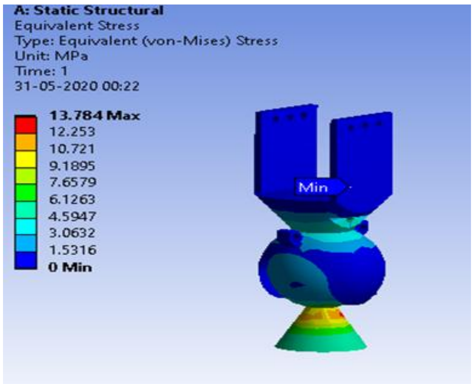
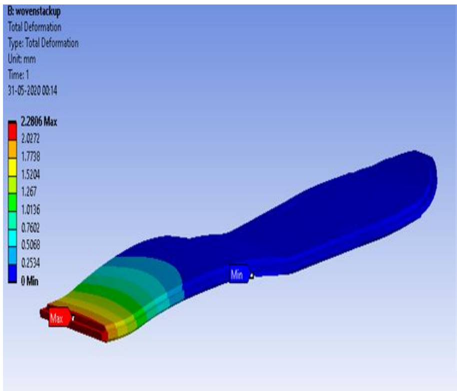
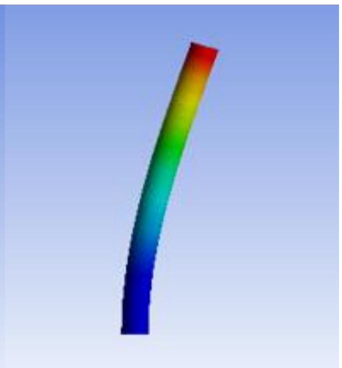


Fig.2.4 FEA of Ball and Socket Joint



FEA of Foot Joint



FEA of HDPE Back Element

Another important factor of not choosing metals for the leaf spring or the footplate is weight. In the Fig 2.3, do note the plastically deformed pylon designed in view of eliminating any joint misalignments. Also, note the single unit HDPE spine, designed to withstand both compressive strengths of the body and the bending stresses applied by the backbone. Take note of the carbon fiber foot units, designed to be comfortable and reduce metabolic cost of walking.

Necessary FEA simulations were done to the verify parts and certain assemblies for rigidity and strength of the second prototype.

Theoretical Calculation of HDPE Back Element

E = Young's Modulus ≃ 1.5 GPa

Using $\Delta = \frac{WL^3}{3EI}$, d_o = 20 mm, d_i = 11.17 mm

Possible Failure Criteria,

i) Compression,

$\sigma = \frac{F}{A}$ = 2.78 Mpa < (yield strength of HDPE = 5-23 MPa)

ii) Bending,

$\sigma_b = \frac{M_b}{I} \times C$

$\sigma_b = \frac{W \times L \times d_o}{2I} = 38.78$ MPa $\leq$ ($\sigma_{flexural}$ $of\ HDPE = 48.3\ MPa$)

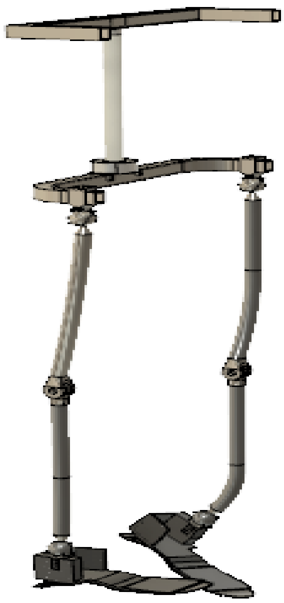


Fig. 2.4 Assembly design of prototype-2.

III. CONCLUSION

With the successful fabrication and testing of the first model, a few inputs were derived and the same were used to design the second prototype. The first prototype served the purpose of a testing model. The second prototype was designed to remove the misalignment issues that were come across in the first prototype. From experience gained on testing prototype-1, the second prototype might just bear the load of the affected person and might be comfortable in a safe laboratory environment, but more safety parameters like joint tensioning will have to be incorporated in the design to ensure full independent, non-supervised mobility. And elements like springs and easily operable joint locks might help in giving more comfort in a standing position respectively. The future works to be done in regard with this project would be to fabricate the second prototype and run the necessary tests. This prototype will get us closer to realizing a working model for full independent and non-supervised mobility of the affected person. A generalized model will soon be proposed and presented after the completion of the final working model.

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