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# Design for Customized Additive Manufactured Exoskeleton Using Bio CAD Modeling

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**ABSTRACT—** Additive Manufacturing (AM) refers to a process by which components are built in layers by depositing material from 3D CAD data. CAD along with medical images and AM technologies has the capacity to create anatomical models that have diagnostic, therapeutic and rehabilitative applications. Disabled people require assistance for moving their lower limbs to enable them in the walking process. Exoskeleton is an assistive electromechanical device that are worn by a human operator and designed to increase the physical performance of the wearer. With the advent of new medical and manufacturing technologies, three-dimensional (3D) CAD model reconstruction from Computerized Tomography (CT) image has recently become a promising choice for exoskeleton design. The integration of CAD and medical technology is referred to as Bio-CAD modeling. The aim of the paper is to design a lightweight structure with a portable energy supply, without undermining the autonomy of the device. Initially the design is focused in designing an exoskeleton model to assist the knee joint and its associated structures to aid in walking. CT image of the lower limb is obtained from the patient in Digital Imaging and Communications in Medicine (DICOM) format.The CAD model of the stacked CT image is developed using Bio CAD modelling (MIMICS + 3-MATIC) software to obtain the final geometry of the Exoskeleton. The exoskeleton model may be fabricated in AM system with Acrylonitrile Butadiene Styrene (ABS) material, and tested for its compatibility in real time. The combination of AM and Bio CAD modelling gives a high level of accuracy in terms of shape, size and position of the Exoskeleton and significantly shorter lead time when compared to the conventional (manual) technique. It also provides more comfort to the patients while walking, standing and sitting conditions.

**KEYWORDS—** Additive Manufacturing, Bio CAD Modeling, Lower limb Exoskeleton, Rehabilitation, Customization.

## I. INTRODUCTION

The realization of wearable robots for rehabilitation of neuromuscular patients has seen in 21st century. Because a neuromuscular disease leads, the patients in pathetic condition due to the causes of mobility impairments and depending on the affection level, gait may be affected drastically making it even impossible. In 1960s, the first robot introduction in the industrial workplace [1], that have developed at an incredible rate and now encompass almost every aspect of modern society. Wearable robots are defined as "a mechatronic system that is designed around the shape and function of the human body, with segments and joints corresponding to those of the person it is externally coupled with" [2].The exoskeleton was implemented for rehabilitation, while individual who have lost their motor functions in their lower limbs.

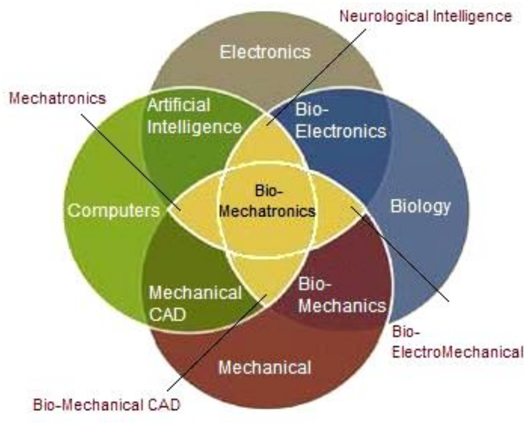


Fig. 1 Bio Mechanics Integration concept [5]

The main concept of using an exoskeleton for enhancement or protection has been around for hundreds of years. However, it was the powered exoskeleton makes reality."HARDIMAN" is one of the first powered exoskeleton; it gives contribution for early development. In 1960s, General Electric Co. had designed a full body exoskeleton, comprising an inner and outer exoskeleton which operated on a master control scheme [3]. The major developments in exoskeleton systems has been achieved at last five years [2].System such as the Berkley's BLEEX, display cutting edge modern technology and Hybrid Assistive Limb (HAL), which is now in the fifth generation. The researchers at the University of Tsukuba, Japan has been designed a HAL- 5 system and aimed at meeting both rehabilitation requirement and strength augmentation.

Two control schemes namely "Cybernetic robot control" and "Bio- cybernetic control" which is used to control a full body exoskeleton of HAL -5 [4]. Bio – cybernetic control utilizes the Electromyography signal for augmenting operation. Cybernetic robot control is used for repetitive activities. There is no viable EMG signal used in this controlling scheme. The University of California, Berkley researchers developed a BLEEX lower limb exoskeleton. The operator movement is predicted by sensors, placed on the exoskeleton. The main aim is to improve the operator load bearing capability at the same time Interaction force between the operator and exoskeleton is not measured through any sensors [6]. Motor disorder patients are effectively rehabilitated by exoskeleton robotics, which is derived from mechanical and biomedical technology. Much research has been done for improving the strength beyond the limits of human being, but this information has been looked at for augmenting exoskeleton for military purpose. Interaction between the exoskeleton and user has been done by wearable pieces of robotic exoskeletal structures.

Incorporating the use of exoskeletal robotics in treating myopathy patients who possess motor function disorders is pertinent in making successful in the medical field and whose motor functionality has been compromised by recovery process. Neurological injuries or disorder cannot be fully recovered by physical therapists. The important aspect of future technology will be a continual development of combination of biomedical and mechanical technology [7].Sarah Webster et al [8] designed and fabricated an Assistive Device for Emma Lavelle. She was diagnosed with arthrogryposis multiplex congenita (AMC), a non-progressive condition that causes stiff joints and very underdeveloped muscles. Emma was born with her legs folded up by her ears and her shoulders turned in. Emma was introduced to the Wilmington Robotic Exoskeleton (WREX), Wilmington Robotic Exoskeleton (WREX), an assistive device made of hinged metal bars and resistance bands.

They are preferred an Additive process to fabricate a WREX device, because easy to build complex human shapes with particular finishes. The aluminum and steel device was a lifesaver for Emma, which helped her to pick up objects and lift her arms toward her mouth for the first time. But the supporting structures were heavy for little Emma, so as an alternative, printed structure with light weight ABS material was designed.

Surachai Panich et al [9] designed and fabricated a lower limb exoskeleton for rehabilitation. The typical habilitation for lower limb is separated in three types, which are active, passive and active –assistive mode. Active mode is one important aspect of rehabilitation for increasing or maintaining joint function providing appropriate resistance to the muscles to increase endurance and strength. The relative positions of each joint are determined by Denavit- Hartenberg method.

A semi-automated methodology consists of Computer-Aided Design (CAD) and Additive Manufacturing (AM) technologies was developed for Exoskeleton development, and demonstrated in a real-life case. The correct geometry of Lower limb is ensured by stacking the Computed Tomography images of patient in reverse order and joining them using a medical modelling software program. The CAD model of the stacked CT image is developed by using 3-MATIC software, to obtain the final geometry of the Exoskeleton. The CAD model is incorporated with the actual model, the simulation is done to find the user comfort and also the required muscle force for the various actions that includes walking, running, climbing, and etc., Final Exoskeleton models will be fabricated in AM systems, and its used for fitting it in patient's lower limb. The quality of life for the people has been improved due to the impact of advancing modern medical technology.

## II. TECHNICAL DEVELOPMENT

The exoskeleton has been categorised in to two different lines based on the technical development; the mechanical development including actuator selection and the electronic systems development including controls system, sensors, and Data acquisition system [10]

The bio mechanical analysis of the human morphology and the human gait is used for mechanical development. Based on the analysis result we have to select a suitable drives for muscles actuation, because the exoskeleton must be able to support patients during gait and make more comfort to the patients in an ergonomic way. This concept includes both drives design and mechanical structural design. In this direction, experimental analysis has been performed for the preliminary exoskeleton; a complete knee model from the entire lowerlimb has been designed.

The control system of the exoskeleton includes the method to identify the user intention and decision is made to support patient in an adequate way during gait with the required torque in each joint. From these data, torque of the knee joint has been considered to select a proper control system. In the modular development, the control system makes to achieve robust system [11] [12]. Initially knee joint prototype has been produced in order to test and validate the control systems of knee exoskeleton. The control system of full lower limb exoskeleton has been launched based on results of knee joint prototype.

## III.MECHANICAL STRUCTURAL DESIGN

The structural design and drive designs are considered as the mechanical development of exoskeleton. Actually, selection of proper drives and adequate mechanical structure is a challenging task because during gait, the human joints require high torques but at the same time, the structure must be compact and adopt with low weight drives to overcome the aesthetic issues [10]

### *A. Design of Drives*

In these knee exoskeleton, to determine which degree of freedom have to be actuated and analysed the most common daily live activities: gait cycle, going upstairs, going down stairs, standing up and sitting down. The three primary joints comprises from the lowerlimb of the human skeleton, namely hip, knee and ankle. In fig 2 the Degree of freedom of each joint conditions are illustrated [4]. In this work mainly focused on the motion of the system and initially neglected the stability of lowerlimb. Since main aim is to rehabilitate the motion of a patient knee joint. In the walking cycle, internal rotation, hip abduction and hip adduction do not play a significant role [13], and were eliminated from the design. The ranges of motion for the joints are constrained such that hyper-extension and hyper-flexion do not occur. Table 1 shows these ranges of motion [14].

The knee DOF was actuated, while the hip and ankle joint was designed to be passive. The joint torques for the actuated DOF has been determined by the evaluated data from clinical gait analysis [15].The torque required for knee extension during stair climbing was 140 Nm and 50 Nm during walking. Actuators were selected such that the maximum torque was met, which allows for the operator to be raised or lowered from a seated position. When compared to direct mounted rotational actuators, the linear actuators offered a high speed/load capabilities and less bulky design.

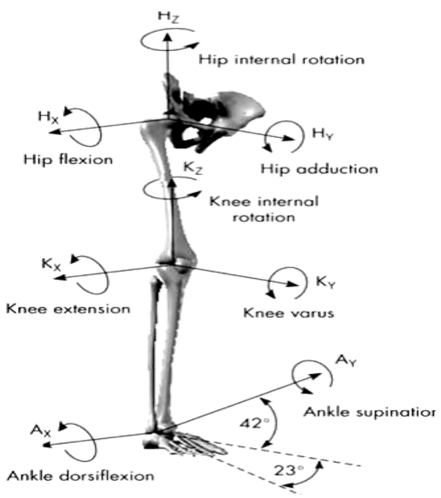


Fig. 2 Lower limb degree of freedom

In the lowerlimb joints forces, power and angle pattern data in the sagittal plane have been largely studied [16], [17] Different gait experiments have been conducted to arrive a data of gait cycle for the exoskeleton drive calculation [17]. This experiments are developed in normal conditions by regular size users and at normalized speed. For the biomechanical consideration this data gives an enough precise base, even though this data depends on user involved in experiments. If the patient has balance through well controlled external balance aid system, the lack of force in the sagittal plane will impede to perform the most of the daily live movements. Therefore three degree of freedom are mechanically actuated like, hip flexion – extension, the knee flexion – extension and ankle dorsal – plantar flexion. In this work consideration hip and ankle degree of freedom are not considered.

TABLE I
MAXIMUM POWER OF HIP, KNEE AND ANKLE

| **Joint** | **Movement** | **Gait** | **Upstairs** | **Stairs Down** | **Max** |
|---|---|---|---|---|---|
| | | **Power (W)** | **Power (W)** | **Power (W)** | **Power (W)** |
| Hip | Flexion | 82,5 | 87,75 | 33,75 | 87,75 |
| | Extension | -42,3 | 0 | -114,7 | |
| | Abduction | 26,2 | 0 | 0 | 26,2 |
| | Adduction | -25,5 | | | |
| | Ext. Rotation | 4,9 | 0 | 0 | 4,93 |
| | Int. Rotation | -2,2 | | | |
| Knee | Flexion | 67,4 | 195,8 | 13,5 | 195,75 |
| | Extension | -131 | -20,2 | -325 | |
| Ankle | Flexion | 165 | 195,75 | 67,5 | 195,75 |
| | Extension | -39,5 | -13,5 | -249 | |
| | Abduction | 2,97 | 0 | 0 | 2,97 |
| | Adduction | -0,81 | | | |

In this first mechanical prototype the knee flexion – extension are driven by pneumatic muscles actuators. The most appropriate drives for the exoskeleton has been determined by based on the specifications of each actuated degree of freedom table I [18].In this drive selection the volume, the weight and the aesthetic also have to be considered.

Three different actuators are considered for exoskeleton actuation like, hydraulic cylinders, electrical motors and pneumatic muscle actuators.

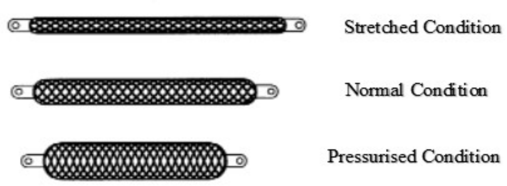


Fig. 3 Braided muscle [19]

In knee joint hydraulic cylinders are situated transversally for actuation of joints. The pneumatic cylinders have angle restriction during gait condition and the patient will have more difficulties to sit down. Minimum 20 kg total weight of hydraulic system has been estimated excluding batteries, electronic and control while all system has been determined. As a result, hydraulic system has been ruled out and shifted to another alternative way, to actuate the exoskeleton.

The second choice is the electrical motors. This choice would simplify the design and the aesthetic effect is considerably lower than with the other options. Finally these devices are not preferred for the actuation of joints; it's usually heavy and bulky, affecting their practicality in the daily motion assistance.

Fig. 4 Pneumatic Artificial Muscle [19]

The third option is Pneumatic Artificial Muscles (PAM) use as actuators, due to their lightness, flexibility and their capacity to produce a high amount of force. To reach the specifications needed in each actuated knee joint the muscles would have a diameter greater than 20 mm and a weight is less than 800g. Moreover as they are simple effect actuators, two muscles are necessary to actuate each dof that means 1600g considering only the PAMs without any other additional system. In this kind of actuation, the high torque requirement of the joint is a problem that needs to be solved.

The artificial muscles developed in the Bioengineering Laboratory [20], [21] consist of an internal latex bladder surrounded by a braided nylon shell that is attached at either end of the fittings. When the internal bladder is pressurized, the high pressure air or gas pushes against its inner surface and against the external shell, and tends to increase its volume. Due to the braided nylon shell properties, the muscle shortens according to its volume increase and, if it is coupled to a mechanical load, produces tension.

Finally the designed drive shown in Fig.4 has a dimensions of 30mm Diameter and 202.35 mm length.

### *B. Structural Characteristics of exoskeleton*

The main aim is to design a suitable exoskeleton for most muscular disorder peoples. The changes in anthropometric measurements depending on weight, height, sex. Some important factors are considered during the exoskeleton design to cover different physiognomies of people in a height range from 1550mm to 1850 mm: the thigh is adjustable from 380 to 470mm and the calf from 360 to 450 mm [22]. One more important aspect to be considered is the easiness of the exoskeleton's regulation. Quick adjustment method with simple butterfly screws and belt arrangement has been included.

The range of motion of each joint is considered as important one while designing the mechanical structure of the exoskeleton. The exoskeleton can't move farther than beyond the minimum range of movement of patient in each joint in order to avoid any damage but at the same time it must allow free movements to wearer with in the ranges of motion required during gait or sitting down. Regarding this range of motion in each joint are a bit smaller than values allowed by the biomechanical joints to avoid any kind of injuries. The patient comfort is one of the important consideration in structural design process of exoskeleton and also consult with orthopedics specialist for getting assurance to using materials and shapes,because the structural elements are in contact with the user and it assures the patient comfort but rigid enough to guarantee the transmission of the movement to the patient.

## IV.CUSTOMIZED EXOSKELETON STRUCTURAL DESIGN

The design of exoskeleton suit are carried out by using Bio CAD modeling software ( Mimics & 3 Matic software)(Figure 5).Reverse engineering techniques used for developing a structure of exoskeleton. Because anotomy of Human lower limb is very complicated shape. So the dimensions of the structures are obtained from the patients CT scan in DICOM format.Advanced 320 slices CT scanner is used for taking the image. Slice thickness is 1mm. Minimum slice thickness can lead to higher accuracy of solid model and avoid reconstructing a slices.After that slices of the DICOM data are imported to MIMICS software.All the slices are stacked together and converted in to solid model by using 2D segmentation and 3D region growing techniques.Initialy creating a mask for Thresholding operation,it has been used to increase a density of soft tissue (muscles) and Hard tissue (Bone).

Select a particular region (knee) of lowerlimb based on the requirement (in no of slices) of corresponding dimensions. Edit a mask whether draw it or erase the slices.

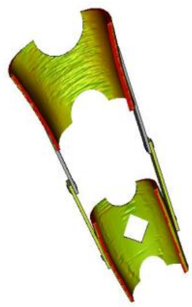

Fig 5. Knee Exoskeleton

Then generate a solid model for the corresponding mask.Measurements are taken using scaling options. After the solid model conversion, 3Matic modeling software used to modeling a structure of exoskeleton with supporting arrangements.Setting a scale factor 1:1 uniform thickness level. By using Boolean operation to

form a top and bottom brace structure. Then smoothening operation is performed on the edges and surface of the braces for removing a sharp corner. Select a fit plane and create a suitable location for actuators and sensors placement. In both sides, supporting arrangement also created using CAD tool at corresponding plane. Figure 5 shows the design model of knee exoskeleton. This model will be fabricated by AM techniques.

## VI. CONCLUSION

In this work, customized exoskeleton is targeting a specific pathology, it will benefit to the patients with muscular disorders. Regarding the patients, a biomechanical analysis has been made in order to determine the common characteristicsthat the patients will be benefitted from the exoskeleton (weakness, balance control, Lowerlimb mobility control). It's providing better conditions to develop a standard gait next to the physiological one. One of the important aspect of patient comfort has been achieved by using reliable technique of Bio CAD modeling with additive manufacturing for the purpose of customization. Advances in actuation technologies of Pneumatic muscle actuator gives benefit to the user during sitting and gait condition, and also it provides more strength.

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