SETSCI Conference Indexing System, Volume 3 (2018), 239-245

ISAS 2018-Winter

2nd International Symposium on Innovative Approaches in Scientific Studies

November 30 – December 2, 2018, Samsun, Turkey

Mechanical Design and Finite Element Analysis of a Pneumatic Artificial Muscle Powered Lower Limb Exoskeleton

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Presentation/Paper Type: Oral/Full Paper

Abstract – Lower limb exoskeletons are wearable robotic devices which either augment human power or facilitate a walking ability for those who lost it by injury or aging. They have been getting more and more attention in the scientific community thanks to its increasing functionality and availability. Today, several devices are being utilized by people themselves or rehabilitation centers. Except the fixed gait training systems, these devices are anthropomorphic mechanical structures which actuated by electric motors, hydraulic or pneumatic cylinders. However, another actuation system so-called pneumatic artificial muscle (PAM) promises great advantages over its antecedents. It's more compliant, lighter and more powerful. Due to it being a newer system, one can encounter with it in a few devices and these are either fixed or poorly investigated. This study, along with its mechanical design choices, gives a deeper insight on usage of PAMs in a lower limb exoskeleton. First, the mechanical system is designed in SOLIDWORKS with the principles of gait biomechanics. A light-weight design is aimed and a crutch-free system are planned by placing PAM both sides. In order to examine its strength, finite element analysis is conducted for posture in ANSYS. It is concluded that the structure can carry both its own and wearers weight. Besides the strength analysis, this study infers a proof-of-concept that finite element analysis can be used to determine muscle forces for different scenarios when they are placed properly.

Keywords – Lower limb exoskeletons, pneumatic artificial muscle, PAM, finite element method, ANSYS

I. Introduction

As a most basic definition, exoskeletons are powered bionic devices which can be wearable by the operator [1]. They integrate with human body to make variety of tasks performable which otherwise are impossible or too hard. The possibility to make such type of devices opened a door for researchers into building exoskeletons such as rehabilitation robots or super-soldiers which provide additional power.

Hardiman project of General Electric is accepted as the first attempt to build a valuable exoskeleton with the support of DARPA. It was a huge one arm master-slave hydraulic system to amplify body power [2]. But the progress on exoskeleton studies were stopped for 20 years although works of Prof. Vukobratovic in Serbia around 1970's and some similar works in MIT in 1980's because of technological insufficiencies. When the rapid progress on the computer sciences had place in the scientific work, the studies were started again with the leadership of DARPA [3]. And studies that started in 1960's resulted as commercial products from companies such as Lockheed Martin, Cyberdyne, Honda, ReWalk etc.… Similarly, many research prototypes, domestic or international, were builded at a number of institutes.

Mainly there are two types of exoskeleton such as lower limb and upper limb. Upper ones are primarily dedicated to carry loads with ease and they are used by persons who must carry heavy loads like workers and soldiers. Lower limb exoskeletons, on the other hand, are utilized for both augmenting power and rehabilitation purposes. These commonly consist of legs and back structures.

Berkeley Lower Extremity Exoskeleton (BLEEX) is one of the most widely known exoskeleton structures and is the first field-operational robotic system that was designed in University of California, Berkeley by Zoss et al. [4]. It mainly consists of two anthropomorphic legs, back structure on which the payload and the power supply are placed. What they tried to accomplish was making a device that could be utilized by soldiers, wildfire fighters, emergency personnel etc… Its main goal was to make people carry heavy loads without feeling strain by transferring the payload force to the ground. They composed a foot-shank-thigh-hip structure to have 7 degrees of freedom (DOF) where the hip, the knee and the ankle had 3,1 and 3 does respectively to emulate human movement. They obtained natural walking dataset via the clinical gait analysis and selected actuators and servo valves according to these datas. They managed to make BLEEX walk successfully while carrying its own weight and payload. Although BLEEX was produced and tested physically it didn't become a long-term in industry [5].

MIND-WALKER is one of the widely known commercial exoskeleton products which is designed by Wang et al. [6]. It is a powered assistant device that claims to help spinal cord injury patients to walk. They designed a foot-shank-thigh-pelvis-torso structure with a back support which has 10 DOFs such as 1 ankle, 1 knee, 1 hip and 4 for pelvis. The joints were aligned with human joints except the hip. In order to make the structure safely wearable, they placed braces at the footplate, chunk, thigh and pelvis. As a result, they ended up with stable walking with crutches.

Topic of finite element analysis on exoskeletons were studied by several researchers such as Zhao et al. [7] who performed a design and analysis of a human lower extremity exoskeleton. Like BLEEX, it was tried to reduce the load that is felt by human to carry loads on rugged terrains. Each leg has four degree of freedoms. A harness was used as an attachment between human and exoskeleton and is placed in front side of the back bracket. For the sake of simplicity in modeling, they assumed that the exoskeleton had three distinct phases as single support, double support and double support with one redundancy.

Low et al. [8] presented another platform that enhances and assists the human ability to carry loads using FEA. It was aimed to make an anthropomorphic, ergonomic, size adaptable, lightweight and impact absorbing device with a spring or cushioning. They utilized a control algorithm by using ZMP method. The structure consisted of the trunk, the pelvis, two shanks, two thighs and two feet. It has 3 active joints as trunk, hip and knee, thus 3 degree of freedom. There were also passive joints to allow stability.

As discussed earlier, one of the biggest motivations to build power augmenting devices is to make soldiers capable of carry heavier loads with less strain. In order to build such a system Zhao et al. [9] carried out FEA on a soldier lower extremity exoskeleton. The structure has 3 joints as hip, knee and ankle and all of them has 3 degree of freedom to allow human leg movements in all directions. There is also one degree of freedom on the foot. Therefore, it has 7 degree of freedom in total. There are adjusting rods to be compatible with different body sizes. In the analysis phase, only key parts such as thing, lower leg, connection seat, clamping ring etc. are taken into ac-count instead of whole body. As a result, they obtained that the structure that can withstand the maximum load they offered.

Riener et al. [10] proposed a structure which can support the standing-up motion of complete paraplegic patients. It is called as Hybrid Assistive Leg (HAL) and the first commercial wearable rehabilitation exoskeleton. The suit has the ability to estimate patient's indentation to stand up by calculating his/her upper body motion. It executes the standing-up act based on this preliminary motion and consists of power unites, exoskeletal frames, sensors and a controller. Motion is divided up to three phases such as sitting posture, standing-up and standing posture and three types of experiments are conducted to verify the algorithm. They obtained a system which safely realize standing-up motion for a real paraplegic patient.

Another study which focuses on finite element analysis of a lower extremity exoskeleton is carried out by Ding et al. [11] which is also supported by Natural Science Foundation of China. They examined the static intensity and rigidity of the structure by considering the weighting of the design. They created two identical legs which have 6 degree of freedom in total including ankle joint. One of the legs were analyzed in the fact that two legs are identical. Small features like screws, chamfers, screw holes were ignored for simplification purposes according to Saint-Tenant principle. As a result, they accomplished to reduce the weight by %10 while meeting the static intensity, rigidity and vibration characteristics.

In human walking, force distribution along the body varies during the gait cycle. A study which investigates this issue during walking is the work of Pan et al. [12] They examined the structural static characteristics of a lower limb by considering five different gait positions. Like Ding et al.'s study, they removed some features such as back frame, motor and reducer transfer auxiliary support system in order to simplify the finite element model. It is tested for a load of 1200 N. The design could satisfy the requirements for a person weight of 100 kg.

In addition to the structural capacity of an exoskeleton, it must be ergonomic, wearable and assist walking of a person. Generally, size adjusting systems are being used to meet this requirement. However, Liu et al. [13] proposed a different solution by utilizing Chinese Adult Body Size datas as structural parameters. They applied a load of 800 N while one of the legs is off the ground and the ankle joint that contacts to the ground is fixed in all directions. As a result of FEA, it's concluded that while the key parts of the exoskeleton meet the requirements stress value on joints exceeds the materials strength.

All of the exoskeletal systems which are examined so far uses electric motors, hydraulic or pneumatic cylinders as the actuation systems. However, another actuation system so-called pneumatic artificial muscle (PAM) which is proposed by McKibben [14] in 1950's promises great advantages over its antecedents. It's more compliant, lighter, more powerful and easy to manufacture. Due to it being a newer system it's not employed on exoskeleton systems unlike the other systems.

A Pneumatic artificial muscle is a contractible rubber membrane. It contracts and enhances with pressurized air; thus, its length shortens to actuate motion [14] as can be seen in Fig 1.

Fig. 1 Pneumatic Artificial Muscle

There are several researches that attempted to build a pneumatic artificial muscle powered exoskeleton like Caldwell et al. [15], Sawicki et al. [16] and Beyl et al. [17]. Yet, these systems are either fixed platform or aimed to be used as an assistance device rather than providing a full sport walking ability.

This study proposes a lightweight, self-balancing and compliant lower body exoskeleton as shown in Fig. 2. It is powered by pneumatic artificial muscles and it carries both its own and wearers weight.

The paper is organized as follows. Section II explains the mechanical design process and the most important design choices. In section III, finite element analysis is introduced. In section IV, results are presented and the paper is sum up in section V. Lastly, future works are suggested in section VI.

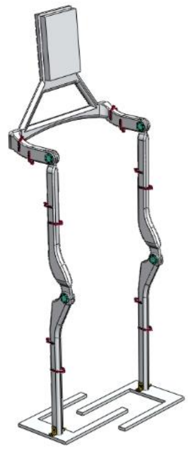

Fig. 2 Pneumatic Muscle Powered Lower Body Exoskeleton

II. Mechanical Design

Mechanical design process starts from selection of the overall architecture and finishes with the actuation selection which is pneumatic artificial muscle for the current study. Determining the degrees of freedom, joint selection and the design choices for the limbs are introduced in this section.

A. Architecture

Structural architecture is the layout of joints and limbs to form a functioning leg and it's generally classified into three main categories such as "Anthropomorphic", "Non-Anthropomorphic" and "Pseudo-Anthropomorphic" [4]. One architecture is called as anthropomorphic when its limbs and structure are nearly complete replicas of human body and follows human movements kinematically. In this point of view, proposed design is called as pseudo-anthropomorphic. While its overall structure and kinematics resemble the human movement, its kinematic is not a human replica. This issue is brought up especially when the knee joint is studied and is discussed its own topic.

B. Degrees of Freedom

The structure is composed of mainly three limbs: torso, thigh and shank. Foot is fixed to shank and is not considered as a distinct limb. Whole movement acts on the sagittal plane and is realized by rotational joints.

Design has 2 degree of freedom in each leg: 1 hip and 1 knee. Since the both legs are identical, it has 4 DOFs in total.

C. Joint Design

Human knee is not a pure rotational joint and its centre of rotation changes during the motion [4]. This movement can be approximated with a four or six-bar linkage [18] [19]. These mechanisms are especially used when there is a need to replicate human movement like prosthesis. However, this approach brings complexity in both design and control-wise. In the proposed study; producing the most simple structure possible is aimed to provide a walking ability for non-able persons. Therefore, single-axis rotational joint is used for knee joint as seen on the Fig. 3.

Human hip joint, on the other hand, acts almost exactly like a ball joint and it has degree of freedoms. However, only the sagittal plane movement is necessary for a basic walking motion. Taking this into consideration, only this DOF is selected for simplicity purposes and realized as a rotational joint as seen on Fig. 4.

If a full human movement is being tried to accomplish, ankle is one of the most important joints as it consumes great amount of energy [4] and mainly depends on the stride length. Since the stride length for the proposed design is fairly small, ankle is considered as a fixed joint as seen in Fig. 5. This choice gives some advantages. Number of muscles required reduces by 4 and so do the control complexity.

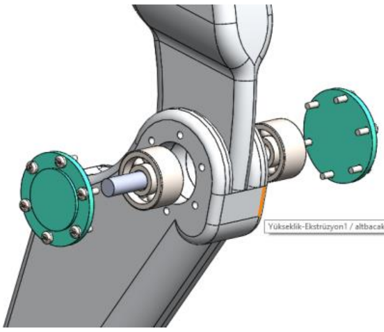

Fig. 3 Knee Joint

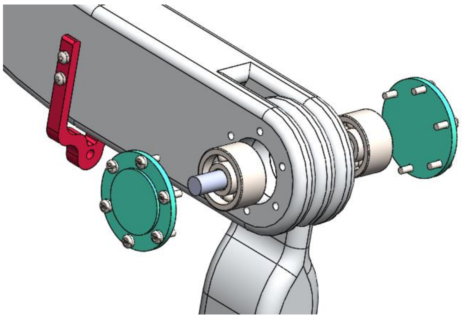

Fig. 3 Knee Joint

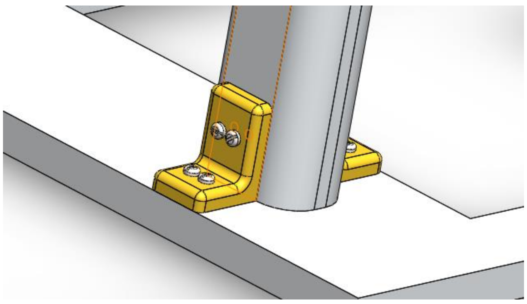

Fig. 5 Ankle

D. Torso, Thigh, Shank, Foot and Muscle Holder Design

Torso, in this design, is responsible for keeping the human upper body steady. It is connected to the thigh both sides by counter-acting pneumatic muscles. It's shown in Fig. 6.

Thigh segment is the segment which has rotational joint on both ends. It is connected to torso and shank by 4 pneumatic muscles. What should be noticed is that joint at the bottom at is not at the same direction with the upper one as seen in Fig. 7 (left). This alignment is considered to compensate the kinematic difference between structure and human leg.

Shank has one rotational joint at upper end and is fixed with foot at the bottom end. It's only connected to the thigh with two muscles and has the same unidirectional joint structure as shown in Fig. 7 (right).

Feet, unlike traditional exoskeletons, intersect each other as shown in Fig. 9. This is to balance the structure on the single-support phase of gait. Single-support is one-leg support phase of the gait cycle. Humans shifts their centre of gravity to maintain the balance. This shifting is done by ankle and hip joints on the … plane. However, for the proposed design, it's tried to accomplish statically. This approach reduced the actuator number by 4 and the design complexity.

Another mechanical part is the muscle holder. It is designed as a separate part for modularity purposes as seen in Fig. 10. Its task is only providing a place a muscle can hold on like tendons in human muscle anatomy.

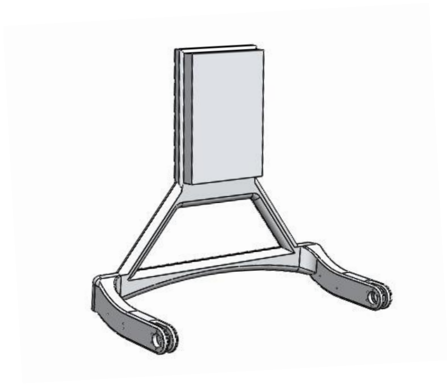

Fig. 6 Torso

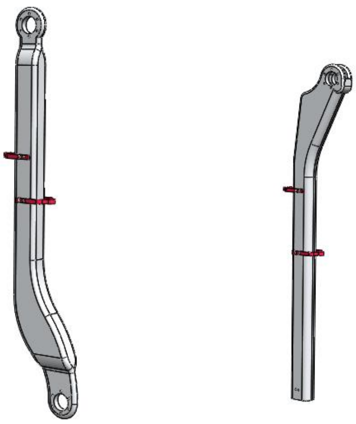

Fig. 7 Thigh (left), Shank (right)

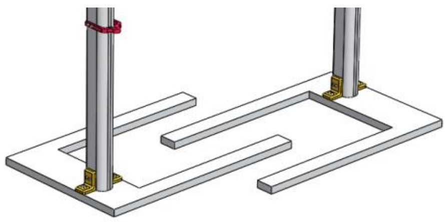

Fig. 8 Feet

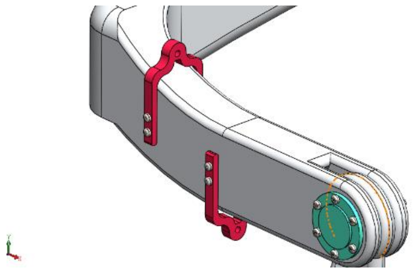

Fig. 9 PAM Holders

E. Pneumatic Muscle Selection

The structure has 4 pneumatic artificial muscles to achieve the walking motion for each leg. These are: hip flexor, hip extensor, knee flexor and knee extensor.

The main parameter when the PAM is chosen is the maximum force the artificial muscle can carry. Festo pneumatic muscle features, shown in Table 1., are utilized for determining and choosing the actuator parameters.

Table 1. Properties of Festo Pneumatic Muscles

Diameter (mm)	***Maximum Contraction/Nominal Length***	***Maximum Force at 6 Bar (N)***
5	%20	140
10	%25	480
20	%25	1500
40	%20	6000

According to the study of de Leva [20], body segment weight ratios are shown in Table 2. Head, neck, upper arm, forearm and hand are lumped as a torso since the structure carries these segments as a whole.

Table 2. Body Segment Weight Percentages

Body Segment	***Quantity***	***Percentage***	***Weights for a 90 kg male (kg) (rounded)***
Torso (lumped)	1	60.28	55
Thigh	2	14.16	13
Shank + Foot	2	5.7	6

Hip flexor and extensor are responsible for carrying the upper body of the person (torso). Similarly, knee flexor and extensor carry both torso and thigh. When the highest moment occurs across the joints (90 degrees between limbs), these muscles carry all of the load that are produced by the limbs. These moments vary with the angle between the limbs. For safety purposes, the structure is considered to carry the maximum force even when standing right. Thus, the diameters are chosen to withstand these loads according to Table 3. These parameters, along with nominal lengths, are shown in Table 3.

Table 3. Properties of Selected PAMs

	Weight to Carry (N)	***Diameter (mm)***	***Nominal Length (mm)***	***Stroke (mm)***	***Stiffness (N/m)***
Hip Flexor	270	20	384	96	15625
Knee Extensor	794	20	508,6	127,15	11797,1

III. Finite Element Analysis

A. FEM Model

According to Saint-Tenant Principle and for the sake of simplicity, some features are removed. Besides being a simpler model, this approach increases the simulation speed dramatically. Removed features are screws, screw holes, bearings and joint covers.

Another important stage of creating the FEM model for this study is deciding how to model pneumatic muscles. To make it more realistic, a part is designed in SOLIDWORKS the way muscles take shape when it’s assembled in the real-world situation. Property values shown in column 3 in Table 5 is used for modelling a rubber tube of 20 mm outer and 16 mm inner diameter. With these principles, FEM model to be analysed can be seen in Fig. 11.

Fig. 10 Finite Element Model

B. Constraints and Boundary Conditions

As a constraint input, model is fixed by both feet to be able to observe whether the structure can support the load in standing position or not. This load consists of structures own and the operator’s weight. Structure weight is given as input by enabling the standard earth gravity in the vertical direction. Operators weight, on the other hand, is determined by considering point of force like it’s worn by a human. This point is ideally the hip joint. Yet, it is applied on a wider surface to compensate any irregularities as shown in Fig. 11.

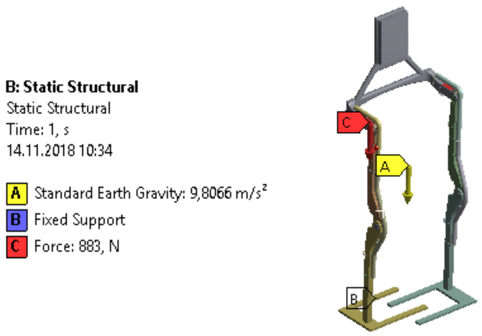

Fig. 11 Constraints and Boundary Conditions

C. Material Properties

Aluminium alloy is used as a main material across the body such as back, thigh, shank, foot and PAM holders while the pins at the joints are structural steels and are shown in Table 5. Pneumatic artificial muscle material is generally rubber as pointed in the introduction. However, to eliminate non linear effect; PAM material here is manually determined by the property datasheet from Festo.

Table 5. Material Properties

	Aluminium Alloy	***Structural Steel***	***PAM***
Density (g/cm^3)	2,77	7,85	2
Young's Modulus (MPa)	71000	200000	54,03
Poisson's Ratio	0,33	0,3	0,3
Tensile Yield Strength (MPa)	280	250	-
Tensile Ultimate Strength (MPa)	310	460	-

IV. RESULTS

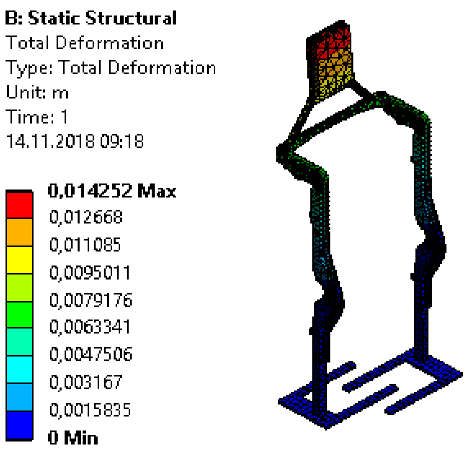

Fig. 12 Total Deformation

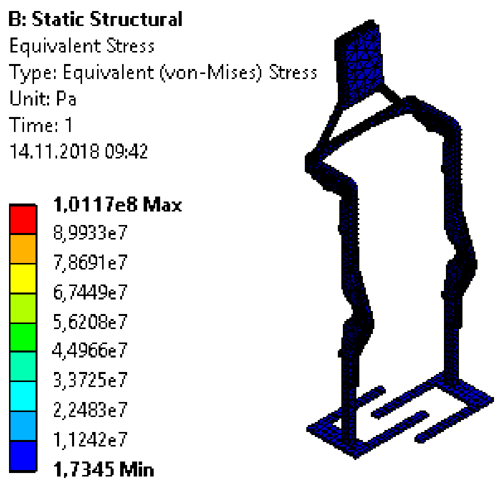

Fig. 13 Equivalent Stress

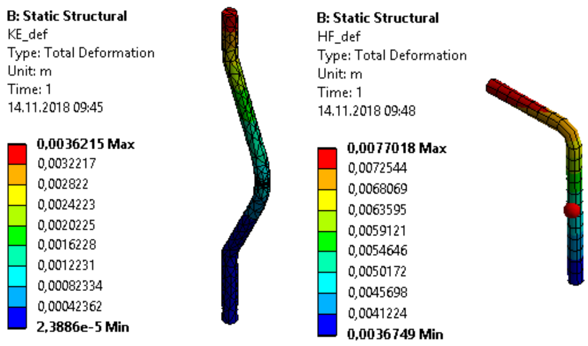

Fig. 14 Total Deformation across knee extensor (left) and hip flexor (right)

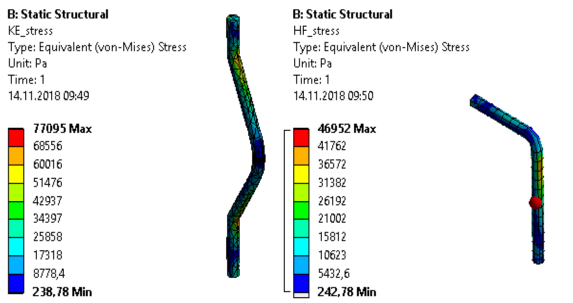

Fig. 15 Equivalent Stress across knee extensor (left) and hip flexor (right)

Table 6. Stress and deformation values for limbs and PAMs

	Maximum Stress (kPa)	***Total Deformation (mm)***	***Force (N)***
Hip Flexor	46,95	7,7	14,75
Knee Extensor	77,09	3,6	24,21
Torso	12224	14,25	-
Thigh	101170	6,49	-
Shank + Foot	12336	0,81	-

V. DISCUSSION

As seen in Fig. 12, maximum deformation across the whole structure is 14 mm. This is acceptable since the structure carries the whole human body and its relatively lightweight. And this deformation occurs on the back end which means the joints are safer deformation-wise.

Tensile yield strength of the aluminium alloy used in this study is 280 MPa as shown in Table 5. Thus, maximum stress value must smaller across the whole body. The maximum equivalent (von-Mises) stress is 101 MPa as seen in Fig. 13 which means the structure can withstand the load by staying on its linear. Fig.14 and Fig.15 shows the deformations and stresses occur on the pneumatic muscles. These stress values give the required forces to hold the structure in a given structure. And these forces can be applied to a control problem. That forces are obtained for this scenario are shown in column 3 in Table 6.

As seen in column 2 in Table 6, hip flexor and knee extensor contract 7,7 and 3,6 mm respectively. When it's compared to the stroke length, contractions are 0.08 and 0.0028 of the strokes for hip and knee muscles. This means that very small contractions of the muscles are enough to hold the structure in standing position.

VI. CONSCLUSION

In this study, an assistive lower body exoskeleton is designed and analysed. It is aimed to make a crutch-free, self-balancing structure to provide a walking ability for non-able persons. Unlike traditional devices, a relatively new actuation system called as pneumatic artificial muscles are used. First, mechanical design is performed on SOLIDWORKS. Since the available devices on the market has a great price tag, the simplest, yet effective structure is the goal of the study to create an accessible and functioning exoskeleton.

To test its structural characteristics, a static analysis is conducted on ANSYS Finite Element Software. The testing environment is designed so that the exoskeleton carries a 90 kg male in standing posture.

As a result, the structure shows success on virtually carrying the human model. The maximum stress is in the elastic range and the total deformation is at an appropriate level. Besides, the forces that each artificial muscle must exert to support a certain posture is obtainable. This information is especially important when a control algorithm is applied because the force values obtained from the FEA can directly be applied.

What are pointed out so far can be drawn into a conclusion that a more compliant, cheaper and accessible walking lower body exoskeleton can be realized by using pneumatic artificial muscles and utilizing finite element analysis which means that more non-able bodies will be able to benefit from the wearable robot technologies.

What can be done to further this study are increasing the range of motion to make a more versatile device, adding more muscles to improve the strength and adding joints at hip and ankle for both smoothing the walking motion and helping the balance.

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