Design and Fabrication of Mobilized Lower Extremity Powered Exoskeleton System

D.Venkatesa Prabu
Department of Mechatronics Engineering
Mahendra College of Engineering
Tamilnadu, India
venkatprabu13@gmail.com

T.Sakthivel
Department of Mechatronics Engineering
Mahendra College of Engineering
Tamilnadu, India
sakthiveltms95@gmail.com

S.Praba
Department of Mechatronics Engineering
Mahendra College of Engineering
Tamilnadu, India
sivampraba98@gmail.com

B.Shabareesha
Department of Mechatronics Engineering
Mahendra College of Engineering
Tamilnadu, India
mechatronicsabari@gmail.com

***Abstract*— Powered exoskeleton system is an external structure that supports and protects the human body. It's human wearable mobile machine that is powered by a system such as electric motor, hydraulic and pneumatic systems. Four core parameters have been tackled that includes calculation, designing analysis, machining and assemble. Initially, the dimension of the exoskeleton leg has been taken from the average human and it is designed by using solid works software as a prototype model. The mild steel material has been chosen because of its less deformation, higher material properties and affordable cost. The solid work model is analyzed in ANSYS software by applying various weight load to checking the withstanding capacity. The pneumatic operation is non-linear system it is easy source availability & controllability in fluid power system. The pneumatic pressure works on 5 to 8 bar at constant supply through FRL unit & air compressor of pneumatic cylinder can be actuated. The direction control valve of the 5/2 solenoid is electrically operated to control the speed pressure & real time automation purpose. The arduino controller is used as a feedback system that can be diagnosis and rectify which can be acting as a close loop system to reduce the friction and wear factor using tribometer testing equipment. This project is designed and fabricated for various applications, such as for the individuals employed in military to carry heavy loads using backpacks. The fire fighters to carry heavy weapons and foot soldiers to walk for longer distances by carrying heavy loads. When the human foot is on the ground, the wearable powered exoskeleton suits will transfer forces point loads from the human backpack to the ground, so that the user will not feel any difficulties and physical fatigue. This suit will enhance the user's load bearing capacity, walking speed and efficiency and it also lessens the injuries and difficulty level. The analyzed design has been implemented and tested by lifting heavy loads, the result has been shown that the exoskeleton leg can withstand load from 100kg to 150kg. The exoskeleton leg can walk at the speed of 0.9m/s (2mph) and the Degree Of Freedom is obtained as 4, Where the exoskeleton leg consists of 4 links and 2 joints. It is demonstrated to human body as a exoskeleton system to transfers load as maximum of 90%. The powered exoskeleton leg is used to withstand heavy loads, enhances the human efficiency and reduces the work. It can also be used for social needs like physically challenged people to reduce the fatigue rate and enhance the human power.**

Keywords*— Exoskeleton, Lower extremity, Solid works, Ansys, Actuation, Robotics, Wearable and DOF

I. INTRODUCTION

When compared to other load carrying vehicles like JCB, cranes, etc. Exoskeleton suit have several advantages such as withstanding heavy load, protecting human body from any kind of damages during fire fighting, disasters, etc. Exoskeleton is an external structure which lifts & withstands heavy load. It was actually found in insects like grasshopper, cockroaches & in reptiles like tortoise. Later, it was designed to protect human body & it is also used by paralyzed people for walking purpose. The main function of a powered exoskeleton suit to assist the wearable its boosting their external strength and endurance of the exoskeleton can also be used by performance providing the specific practice. The wide most successful edition of an active powered exoskeleton is for rehabilitation of human paraplegic and multi challenged person. It is a wearable mobile machine that is used to power by a external input source from electric motor. Pneumatic and hydraulic individuals employed in military and defense pursuits often carry heavy load using variety of human backpack system. The one who carries backpack will have comfort & suitable items in it. The Fire fighters and other emergency environmental human carry oxygen tank for breathing for safe purpose of back-pack system. Further, the soldiers who walk for longer distance will carry items for the needs at their backs. The leg exoskeleton suit could be beneficial to peoples who carries heavy load which will enhance the load bearing capacity, speed, lessening of injuries, enhancing the efficiency & reducing level of difficulty.

A. History of exoskeleton

Most of the previous works related to exoskeletons were only in concept studies that were explained in drawing board, but never actually built or experimentally validated. The main function of an exoskeleton is too assisted as wearable boosting for external power, strength and endurance limits of human body. So, the powered exoskeleton system made an evolution on the mentioned exoskeleton suit as model for human.

1) *Yagn's Walking Exoskeleton*

The fastest exoskeleton device was sets of bending, walking, jumping and running assisted degree of freedom to physically apparatus developed in 1890 by a Russian named Nicholas Yagn. It's apparatus unit used to compressed gas bags to store energy that would be assisted with movements and motion, although it was passive in operation and fixed to human power. It was a simple bowl leaf spring to be operating parallel to the two legs and was intended to 1 augment running and jumping motion is shown in Figure 1. Each legs carries single spring action it was fixed during the foot motion to contact effectively transfers the body's weight of the ground it will reduce the forces borne from the stance leg. The aerial phase of parallel legs spring motions was designed to disengage in order to allow the biological legs to freely flexible and enable the foot to clear the accurate ground clearance.

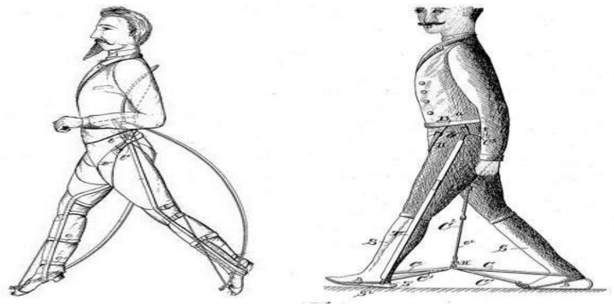

Fig. 1. Yagn's Exoskeleton

2) Hardiman Human Exoskeleton

Hardiman was the first suit attempt to build a experimental powered exoskeleton, by general electric system between 1965 and 1971. The exoskeleton machine was aims to per mutate the person who wear the exoskeleton to lift weights of 1500 pounds (680 kg) without any problem. The Ralph Mosher, who had previously worked on the Handiman. The project was not successful overall. A virulent uncontrolled action may create by exoskeleton while endeavourto use whole exoskeleton and its results a exoskeleton to mis understand with a wearer.

According to general electric's Hardiman Project Report from 1969 and it's turned on powered to operate the shoulder joint and motion, the arm lurched the elbow would not operate. Although it could lift its specified weight of 750 pounds (340 kg), it weighed three quarters of a tonnage, just over twice lift able weight. Until all the parts of hardiman exoskeleton projects works together for practical uses were limited.

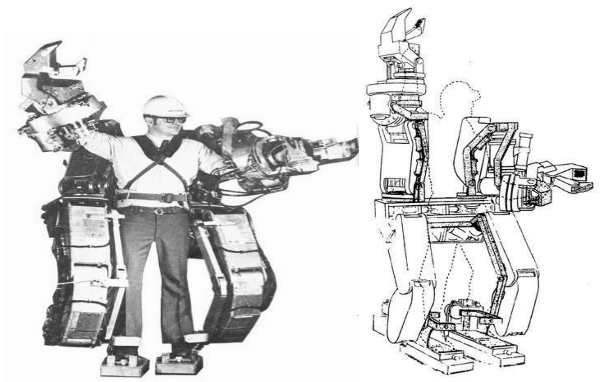

Fig. 2. Hardiman Exoskeleton

3) BLEEX DOF Exoskeleton Suit

The most prominent of the DARPA programmed exoskeletons suit has used in Berkeley Lower Extremity Exoskeleton. This project used to carry power source in various application of human. It's developed to claim the first load bearing component and energetically autonomous powered exoskeleton suit. BLEEX system having 4 degree of freedom at the hip, 1 at the knee, and 3 at the ankle. These four are actuated by hip flexion and extension, hip abduction and adduction, knee flexion and extension, and ankle flexion and extension. The kinematics of actuation requirements in exoskeleton were designed by assuming the physical behavior similar to that of a 75-80 kg human and utilizing medical gait analysis data's for walking. It consumes an average of 1143W of fluidics hydraulic power during level of ground clearance walking, 200 Watts of electrical power for the electronics and control system, while a similar sized human consumes by 165 Watts of metabolic human power.

Fig. 3. BLEEX Exoskeleton

4) *Exoskeletons Rehabilitation Power*

Exoskeletons suit plays a major role in rehabilitation of patients affected by spinal card injury and brain injury of action potential, who have lost motor functions of the lower limb. Physically challenged people are met with lot of trouble with respect to the actuation and retraction deal with many emotional issues. Also, the human body is physiologically designed stand perfectly, walk and move around, but a wheel chair user loses this ability and leads to having a negative impact on the human body. To avoid such problems the exoskeleton suit plays a major role in rehabilitation and enhances an independent wheel chair, enabling human body to walk around. In technological insist of that tide in Mihailo Pupin institute powered exoskeleton suit wasn't a very possible option, even though it was precedent. The advances technology, today ground breaking research and development in the field of exoskeletons in various application of rehabilitation has started to enter the field of commercialization in world. Exoskeletons brands are ReWalkTM, eLEGSTM, MindWalker, HAL, REX, and Vanderbilt Exoskeleton. Each one of them has a unique and different mechanism. Bio signals to direct, as someone intricate algorithm with a lot of sensor tidings. A few workers as reciprocating gait orthosis while someone employ joystick.

5) *Wearable Exoskeleton Technology*

This exoskeleton technology produces and develops to be wearable to the users. It is mainly used for the rehabilitation, assistance and human power augmentation. This technology has been improved in its mobility, enhanced force capability. In this technology can be easily worn by the persons and it is also very flexible. This will also enhance the human's physical activity and a person's motion. Wearable exoskeletons suit are electro mechanical operation designed to assist, augment and enhance parts movements and mobility in a changing of human body actions. These ranging applications are providing power supplementation to assist the wearable suit in any situations, where human movements are resisted for exercising the applications. Its cover a wide range of bio medical devices for human in rehabilitation training recovering from trauma, movement and position aids for multi disabled persons. Human personal care robots for providing daily living assistance and reduction of physical burden in industrial needs and military applications. The design and manufacturing of effective and affordable wearable powered exoskeletons suit poses it several designs to control and modeling challenges for researchers and developers. The novel technologies are developed in adaptive motion controllers through human-robot interaction control, biological sensors and actuators such as materials and structures.

B. *Powered Exoskeleton Degree Of Freedom*

The powered exoskeleton suit was implemented with 3 degree of freedom at the hip, 1 DOF at knee at the ankle. Flexion & extension of the exoskeleton knee was accomplished using a universal joint. The dorsiflexion & plantarflexion of the powered exoskeleton ankle was accomplished by talocrural human joints. The flexion, extension, abduction & adduction of the powered exoskeleton hip movements were accomplished by ball joint & socket joint. The exoskeleton suit is interfaced with human body via through shoulder straps, waist belt, thigh cuffs and shoe connections. This physical interface between exoskeleton and the human parts is used to track the human's leg motion and human leg joints. The exoskeleton suit attached with standard military backpack through accurate parts. The clearance between the harness and wearable pars to minimize the disturbance to the wearer and increase more comfort-ness.

TABLE I. DEGREE OF FREEDOM

S.NO	JOINT	DOF	DESCRIPTION
1.	Hip	**3**	Extension, Flexion, Abduction & Adduction
2.	Knee	**1**	Flexion & Extension
3.	Ankle	**1**	Dorsiflexion & Plantarflexion

TABLE II. MILD STEEL

Density	7.87 g/cm^3 (7851 kg/m^3 or 0.286 lb/in^3)
Young's Modulus	200GPa (29,000,000 psi)
Carbon Content	0.05 to 0.30%
Specific Gravity	7.8
Modulus of Elasticity	210-260 GPa
Yield Strength	260-405 MPa
Tensile Strength	355-590 MPa
Elongation	28%-49%
Hardness	108.5-173.5 HV

C. *Mild Steel*

It is plain-carbon steel and low-carbon steel were sued to build exoskeleton suit. It is mostly a form of steel because its low cost, which meets the properties for many applications. It is very cheap and easy to form through carburizing, surface hardness can be increased. Steel containing a small percentage of carbon, it will be strong and tough but not tempered.

D. *Heat Treatment of Mild Steel*

The possible heat treatment processes are, each material will have its different properties and it is necessary to build a system with higher material properties. Without the knowledge of properties of a material, the material will deform, crack or break, which will result in the failure of the system. Material properties can be developed and implemented by the commercial manufacturers. The material properties decide the quality of a product.

- Spheroidizing
- Full annealing
- Process annealing
- Isothermal annealing
- Normalizing
- Quenching
- Martempering or Marquenching
- Tempering
- Austempering

TABLE III. HEAT TREATMENT OF MILD STEEL

IRON	**Copper %**	**Silicon %**	**Meganewton %**	**S%**	**P%**	**Fe%**	**Cu%**
Mild Steel	0.29	0.28	0.10	0.10	0.04	98.41	0.2

TABLE IV. COOLING TREATMENT OF MILD STEEL

Condition	Annealed	Normalized	Hardened	Tempered
Temperature	910	910	910	450
HoldingTime, min	70	70	30	70
Cooling medium	Ash	Air	Water	Air

III . DESIGN SPECIFICATION

A. *Rigid Frame Structure*

Specification of components is a set of standard requirements that should be satisfied by materials, design, product and services. It is also referred to as technical standards. There are different types of technical standards used in different field of technical contexts.

Specification is the clear detail about the components used in a particular product. Each product will have its own specifications and each component in the product will also have different technical specifications. Without the knowledge of specifications of a component, the project will result in failure or defect. Specifications can be developed and implemented by both public and private sectors. The specification of the components decides the quality of a product. Specifications are used mainly by the suppliers, purchasers and users to determine the quality of the product. It is provided and maintained by the purchase department, government, trade organization, trade, etc. The verification of an item is done by considering its specifications.

TABLE V. RIGID FRAME STRUCTURE

Hip length	340mm
Hip width	10mm
Hip height	90mm
Thigh length	90mm
Thigh width	10mm
Thigh height	490mm
Shank length	90mm`
hank width	10mm
Shank height	450mm
DOF of hip joint	3
DOF of knee joint	1
DOF of ankle joint	1
Like	3
Joint	2
DOF	3(1-1)-2j-h
DOF	3(3-1)-2(2)-0
DOF	3(2)-4
DOF	2

TABLE VI. HIP JOINT

Range of motions	-20^0 to 45^0
Maximum joint velocity	4 rad/s
Maximum joint torque	130 Nm
Spring constant	115 Nm/rad

TABLE VII. KNEE JOINT

Range of motions	0^0 to 90^0
Maximum braking torque	50 Nm
Spring constant	136 Nm/rad

TABLE VIII. ANKLE JOINT

Range of motions	-15^0 to 15^0
Maximum joint torque	90 Nm
Spring constant	301 Nm/rad

B. Air Tank

The air tank converts power into potential energy stored in pressurized air, the most widely used air tank is electric gas diesel powered compressor. In large applications, centrifugal compressors are used. Most compressors are reciprocating piston type, rotary vane type or rotary screw. t increases the pressure of a gas by increase the fluid pressure & transports the fluid via pipe. As the gas can be compressed, the compressor also decreases the gas volume, is shown in figure no. 4. Its power is measured in HP & CFM.

Fig. 4. Air Tank

TABLE IX. HEAT TREATMENT OF MILD STEEL

CAPACITY	4KG
FLUID	COMPRESSED AIR
MAX WORKING PRESSURE	5-8 BAR
NET WEIGHT	6.5KG
DIMENSIONS	41*15*15

IV. DESIGN CALCULATION

A. Pressure Calculation

In pneumatic cylinder specification is,

TABLE X. PNEUMATIC CYLINDER SPECIFICATION

Bore Diameter	= 25mm
1 inch Rod Diameter	= 15mm
Stroke Length	= 210mm

TABLE XI. AREA CALCULATION

Area	π x $(D/2)^2$

	= π x $(1/2)^2$
	π x $(D/2)^2$
Area	= 0.785 in^2

Pressure, P = 1 to 8 Bar or (14.5 to 116.03 psi)

Let the pressure, P be 5 bars (72.5 psi)

Therefore,

TABLE XII. FORCE

F	=	P x A
F	=	0.785 x 72.5
F	=	56.9 lbs or 25.86 kg

B. Degree Of Freedom

Here, by applying the formulae of DOF, by using Degree of Freedom = 3- (l -1) – 2 j - h

We found that the DOF of hip is 3 and the DOF OF knee is 2

V. CONSTRUCTION AND WORKING OF EXOSKELETON

The exoskeleton suit is made of a hollow square pipe, which is made of a mild steel material. Various joints are used to connect the links. The ball and socket joint is used in hip, the universal joint is used in knee, and the knuckle joint is used in ankle. For the purpose of actuation, four pneumatic cylinders have been used, in which two cylinders are fitted in right leg and two cylinders are fitted in left leg. When one side is actuated, another side will remain constant and vice versa. The inlets are connected to the solenoid valve and the valve is powered by using the compressor. When the wire is connected to both the positive and negative of the battery, the right leg will be extended and when positive of the battery is removed, the left leg will be extended. The battery is connected to the valve. The compressor is adjusted by a pressure regulator. The air is transferred via hoses (6mm). The Arduino controller will also control the solenoid valve. The full body parts can be actuated or the arm upper extremity alone is actuated or the leg lower extremity alone is actuated.

Adaptation to User Size Variations

Humans differ in their physical size and their skeletal bone lengths differ from one person to another. So, if one sized fixed exoskeleton will not work for all the human bodies. The military would uses adult sizes and civilian uses all suit sizes. The solutions to these problems are:

- Different ranges of sizes can be constructed and issued to different users. The cost may be expensive, but the users will be very comfortable and different users will be benefited. The parts used in the exoskeleton suit models will also vary and the users should choose their desired size.
- The user should require a specific physical size. In military the physical body size is mandatory and they will have a fixed size, so it will be easy for them to wear the exoskeleton suit.
- Alignment of adjustable length in exoskeleton suit limbs and frames can be constructed, which makes the user feel comfort-ness while wearing. However, due to bone lengths the size should be made adjustable. Each suit must cover certain size ranges for example, only one suit model should be made for the people of size 1.5 to 2.1 meters (5 to 7 feet) height.
- This difficulty variation will not be only in human bone lengths, but also climb girth manufacturing defects due to bone geometry, muscle build, fat and it may also feel difficult by wearing clothing such as insulation wearing of extreme cold or hot surroundings.
- Exoskeleton suits were designed for particular upper and lower limb girth will fits majority of soldiers and military users. Many human users will not feels the comfort-ness due to improper wearing of powered exoskeleton suit.

VI. EXITING POWERED EXOSKELETON SYSTEM

Most of the exoskeleton system present today is having fixed sizes, which will not fit all the users. If one exoskeleton suit is made with no adjustable lengths, then only one person will be able to use. Though, in military use various adult size are used, which will be adjusted. The existing system is not accurate, is shown in figure no. 5.

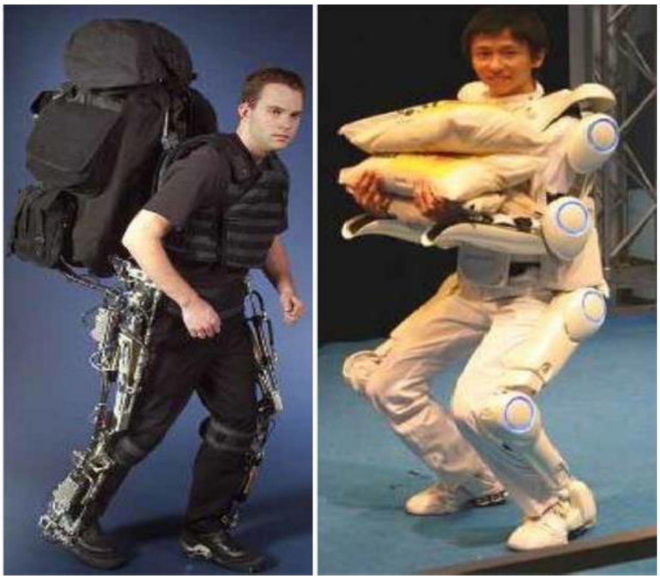

Fig. 5. Exiting Exoskeleton

VII. FABRICATED POWERED EXOSKELETON LEG

The fabricated exoskeleton leg is more accurate and is more users friendly. The angle of leg and the distance between the both legs are obtained as expected. Arduino controller is used to control the system accurately. The rate of fatigue level in hip, knee and ankle joints is probably reduced. The complexity of design is low which results in high flexibility. The synthetic rubber is used, so as to reduce the fatigue rate, is shown in figure no. 6

Fig. 6. Fabricated Powered Exoskeleton

VIII. Result and discussion

Exoskeleton leg can be widely used for withstanding heavy loads. The materials used here is mild steel (MS), which has the ability to form easily and through carburizing the hardness can be increased. The exoskeleton leg can be easily worn and it is portable. The main objective of this project is reduction of work related human injuries, saving millions and billions of dollars in medical fees, sick leave and law suits. These problems are completely dropped by the newly developed powered exoskeleton leg. This exoskeleton leg lessens the users fatigue level, which will probably, leads to increased user alertness, productivity and work quality. This leg will withstand up to 100kgs and the leg weights about 30kgs. This suit is very user friendly and is more flexible indeed.

IX. Conclusion and scope of future work.

Exoskeleton leg can be widely used for withstanding heavy loads. The materials used here is mild steel (MS), which has the ability to form easily and through carburizing the hardness can be increased. The exoskeleton leg can be easily worn and it is portable. These problems are completely dropped by the newly developed powered exoskeleton leg. This exoskeleton leg lessens the users fatigue level, which will probably, leads to increased user alertness, productivity and work quality. This leg will withstand up to 100kgs and the leg weights about 20kgs. This suit is very user friendly and is more flexible indeed. The recently developed lower extremity powered exoskeleton suits was designed using anthropomorphic mechanical parts and motions are included the human walking postures. These statically analysis was done on different human postures of the human stress values have to be obtained in future work.

- The high complex of different control system gets the more difficult for the users to learn easily.
- The powered exoskeleton system should be considered as a simple and complicated wearable tool and the level of automation may be changed.
- The exoskeleton leg needs basics from the biomechanics, ergonomics and bionics. This system not only has a great value in military but also in various applications like sports, medical, disaster relief management, mountain climbing and helping the disabled human beings.

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