Lerner Exoskeleton I

Midpoint Report

07/07/2017

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

Exoskeleton is a system to assist the old and people having disabilities to move from one place to another. These systems are available in different types and comfort the user in performing the task with minimal external help. This project aims at making improvements on the current existing exoskeleton design to develop a better functioning Adjustable Human-Exoskeleton Mounting Interface for Assisted Gait Rehabilitation. The gait rehabilitation is to help the people having disabilities on how to walk. Further, the health care industry usually utilizes robotic exoskeletons for improving walking biomechanics among people who tend to have neuromuscular disorders. Haptics, Kajimoto, Ando, and Kyung state that the system's powerful motors and their transmissions usually act together in providing assistance to an individual's ankle and their knee joints [1]. This project aims at coming up with a design that is adjustable and allows the exoskeleton's mechanical components to be mounted effectively to the lower-extremity.

In addition, the team seeks to operate under a budget of approximately $500 in coming up with the new design as well as ensuring that it is able to function as required. There are different targets that the team seeks to meet by the end of the project. For example, the team is looking forward to ensuring that the design can provide stiff mounting points to user's foot, shank, and at the thigh, to make adjustments to different sizes of users' limbs as well as accommodate people of different ages, make it easy to doff/don, minimize on the skin irritation by the physical interface, low profile foot portion, and make it lightweight. By attaining these specification and client's requirements, the team will have accomplished it mission in improving the exoskeleton design.

1.1 Project Description

Haptics et.al [1] argues that the health care industry usually makes use of a robotic exoskeleton in improving the health conditions of people that have issues relating to neuromuscular disorder. A system with powerful motors and transmissions act in providing guidance to ankle and knee joints [1]. However, attaching this transmission system to the body may at times prove to be quite a challenge. This project aims at improving on the current Adjustable Human-Exoskeleton Mounting Interface to an adjustable design that can be effectively mounted on the lower-extremity. The figure below, figure 1, shows the Adjustable Human-Exoskeleton Mounting Interface.

1.1 Original System

There are various systems that have been in existence used for purposes of assisting individuals with neuromuscular disorders. As stated by Walsh and Massachusetts Inst of Tech Cambridge Media Lab, the original systems have been faced with significant challenges, including being heavy for the users, not being strong enough, poor quality designs, not meeting demands by users, and inability to be adjusted, among other negative factors [2]. Such issues made people to seek for custom make exoskeletons that would meet their needs, which proved to be quite expensive to many users. However, the team seeks to look into these issues and come up with a better design that is able to provide greater satisfaction to its users as well as meeting the requirements of the client.

Figure 1. Adjustable Human-Exoskeleton Mounting Interface [1]

1.1.1 Original System Structure

The original structures for the robotic exoskeleton are made for purposes of suiting people from different age groups. Walsh and Massachusetts Inst of Tech Cambridge Media Lab (MITCM) [2] argue that the robotic exoskeletons are designed in a manner that they are able to fit individuals based on their sizes, where some are created to be small, used by children, while other are designed to be bigger, for use by adults. The materials used in their production are of good quality, where they are strong and durable and serve the expected purposes in an effective manner [2]. The materials are meant to ensure that the users remain comfortable when operating in them, such as ensuring that the skeleton is not heavy and the rate of injury is reduced in case of any accidents. The use of soft materials on points that are in contact with the body allow for increased comfort while operating them [2]. The general concepts of these designs are aimed at ensuring that the users are comfortable and that the designs serve their intended purposes.

1.1.2 Original System Operation

According to Walsh and Massachusetts Inst of Tech Cambridge Media Lab [2], the original systems come in different forms, where there were those that are controlled by the users and those that are controlled by another party other than the users. The design is fitted with sensors and operating systems that allow for the users to operate them while they are using them [3]. On the other hand, the designs that are operated by parties other than the users usually require the users to use the skeleton only when there is another person to operate it. According to Ceccarelli and Glazunov, both designed served their purposes in an effective way despite the different forms of challenges that are experienced [3].

1.1.3 Original System Performance

The original designs performed their intended purposes as expected but with minimal challenges. The systems are designed to provide assistive movements and strength for individuals with limited strengths in their muscles [2]. These systems served the purposes in an effective manner, since they have been used over the years to provide the assistance required. However, through development in technology as well as other factors, these systems need to be improved in order to make them function in a more effective manner.

1.1.4 Original System Deficiencies

There are different forms of deficiencies that are facing the original systems, which the team is seeking to look into and improve on them. For example, the systems currently use materials and components that make them heavy, which affect the amount of time that one can use them without taking a rest [3]. In addition, the mounting on the foot and thigh is not of the best quality and need to be improved for purposes of better grip. The systems are not adjustable, which is quite a challenge. This means that individuals have to seek designs that are custom made, which is a significant challenge in terms of cost and other factors [2]. In addition, some systems use materials that irritate the users, which make them uncomfortable to use.

2 REQUIREMENTS

There are various requirements that are tasked to the team to ensure that it improved on the currently being used designs and make it better and more liable. These requirements are the customer requirements, which may then be interpreted to the engineering requirements of the Customer.

2.1 Customer Requirements (CRs)

Our customer requirements already assigned to the team by the project description. After discussing with the client, the team weighted these requirements from 0 (less important) to 5 (most important) as shown in the table 1. The most important CR's are to provide rigid mounting points and be lightweight, because it will allow the individual to be more stable in the exoskeleton. The customer will be individuals with a disability and we need to ensure that no further harm or accidents come from the product. Other important CR's include minimizing skin irritation, allow foot portion to be adjusted, and strong material. Some people with a disability can have trouble healing from skin conditions and it is important for them to be safe and feel comfortable in the device. Allowing the device to adjust to the individuals foot and expand to fit shoes will add comfort and security to the individuals as they are stepping to a metal armor. These materials must be strong enough to ensure they benefit the individual and that they can be adjusted enough to work properly.

Table 1. Customer Requirements and Weights Scale

Customer Requirements	**Weights (0-5)**
Providing rigid mounting points to foot shank and the thigh	5
To allow the design to be Adjustable	3
To make the design easy to doff/don	2
To minimize skin irritation by the physical interface	4
To allow the foot portion to be low profile as well as insert into normal shoes	4
Make the design lightweight	5
Strong	4

2.2 Engineering Requirements (ERs)

Customer requirements have been listed out and ordered as per the priority. Certain physical parameters were identified and clubbed with each of the customer requirement. These physical parameters were measurable to ensure that the customer requirements were met. Specific acceptable tolerances were designated for each of the physical parameters and work was carried out to meet the customer expectations within the acceptable tolerances. Table 2 presents the details on the Engineering requirements. To provide a strong exoskeleton the device needs to exert a force of 500ksi and a modulus of elasticity. It must also withstand 10,000 stress cycles to be durable. There are specific weight and length measurements that will allow the device to meet the customer requirements. To be lightweight, the overall weight of the design should be 0.75 kg or less and the adjustable strap from the ankle to the knee will be 12” to 18”. To fit the customer’s shoes, the device can expand 10cm/in all around.

Table 2. Engineering Requirements

Customer Requirements	**Corresponding Engineering Requirements**
Providing rigid mounting points to foot shank and the thigh	Yield strength of 500ksi and Modulus of Elasticity 228Gpa
To allow the design to be Adjustable.	Adjustable from 12” – 18” on dimension from ankle to knee
To make the design easy to doff/don	Must take less than 20-40 seconds to don/doff
To minimize skin irritation by the physical interface	All hypo allergic materials that touches the skin
To allow the foot portion to be low profile as well as insert into normal shoes	No dimension outside of knee of 10 cm/in
Make the design lightweight	Weight of 0.75 kg or less
Reliability	Must be able to withstand 10,000 stress cycles.

2.3 Testing Procedures (TPs)

The engineering requirements as related to the proposed design can be ensured mainly by testing the materials and the components involved. The testing involved is to estimate the Modulus of elasticity, load bearing capability, buckling load and response time of the system and performance. All these mechanical factors can be estimated through modeling and analysis software. However, an experimental testing will validate the analytical results.

2.3.1 Modulus of Elasticity

The designed Exoskeleton has to withstand the required load and the same can be estimated through its stress-strain relationship. A sample of the material can be taken and fixed at both ends. The fixed sample will be loaded at different values. The corresponding strain for each of the loads can be taken is estimate the Modulus of elasticity (E). The stress-strain curve will give the value of E. The value of E can be used to estimate the maximum load. Some amount of margin factor has to be provided for taking extra load.

2.3.2 Load bearing Capability

The load bearing capability can be estimated by loading the load bearing components such as limb metals. A sample can be loaded to its failure limit to check for the maximum load levels. The limbs portion will be fixed at both ends and loads will be applied at the ends to check with the limbs gets buckled. The applied load will be 3 times than the design load. Factor of safety is assumed to be 3. The limbs can be considered as a beam that is fixed at both ends and the buckling loads can be evaluated using the formula

$$Buckling\ load = \frac{\pi^2 EI}{L^2}$$

Where E is the Young's modulus, I is the 2nd moment of area, L is the length of the limb

2.3.3 Critical Buckling

The critical buckling load can be estimated from the slenderness ratio. The slenderness ratio is the ratio of the length and the minimum width of the structure. It is minimal load at which the buckling starts. The critical buckling can be estimated by slowly applying the load and estimating the point at which the buckling starts. It will give the information on the amount of load that the structure can handle.

2.4 Design Links (DLs)

The design for any system is a combination of many components. They are linked to each other. In such a scenario the designer has to compromise at certain points for completing the design. The designer has to prioritize the requirements and try to establish the design as per the priority.

2.4.1 Adjustability

In this specific engineering requirement, our design is going to deal with different types of limbs and different sizes as well. For this certain area, the team decided to use another type of bolts and the design could be able to adjust different size of limbs. For illustration, the design can be stretchable be adding more sheet of aluminum on it so it could meet the various of different size of limbs. Furthermore, for the foot plate section, the design is going to be adjustable for many sizes by using different types of foot plate, so the design is going to handle the change of foot plate, by unscrew that part and insert another one with a different size.

2.4.2 Do on and Off

In this engineering requirements, which state that the design should be able to do on and off in less than 20 seconds. Our design is going to meet this ER, because the users will not face any obstacles while using the design, simply the user just have to insert his/her leg into the design and fasten the belts. By doing these simple instructions the user might take less than 20 seconds.

2.4.3 Hypo-allergic

The design is going to be built out of aluminum and Carbon Fiber, as it known that Carbon Fiber is a good material to minimize the skin irritation that might happen by the physical interface between the users and the design. Moreover, the design is going to have some foams in some certain areas toward avoiding the skin irritation that might happen to the users.

2.4.4 Size

As described in the engineering requirements, there should not be a dimension out side the knee of 10cm, in this specific one, the team used the CAD package to make sure our design is going to meet this engineering requirements before the manufacturing process for the design.

2.4.5 Weight

The design is going to be lightweight, and considering that the design will be built out of Carbon Fiber, which is a lightweight material. The team is going to be focused in this engineering requirements because, the team must make sure the users are not struggling with the weight of the design.

2.5 House of Quality (HoQ)

The HoQ usually helps in making analysis of the design based on different considerations. An analysis of the combination of the client's requirements and the engineering requirements will allow the team to come up with a better and more effective design. The interpretation made by the team will be incorporated within the design to make it function better despite any form of challenges that the team may face. The team seeks to come up with a design that fulfills all the client's needs and requirements. Attaining this may be a challenge but the team is determined to ensure that all the requirements are met. The team seeks to ensure that it sticks to is schedule as well as to actualize the different thoughts of the design in order to come up with the best product. Based on the analysis of the requirements by the client, the team interpreted that there are elements that are of great concern, including the power of the skeleton, the life expectancy, the weight, cost, ease of use, setup time, all-climate readiness, nonhazardous, level of incentives, and standard parts utilization. The elements may ensure that the design work in an effective manner and meets the needs of the client as well as those of the users. To make the design effective, the team will use the following HoQ table to make its analysis:

Table 3. House of Quality

Customer Requirement	**Weight**	**Engineering Requirement**	**Yield strength of 500ksi and Modulus of Elasticity 228GPa**	**Adjustable from 12' –18' on dimension from ankle to knee**	**Must take less than 20 seconds to DON / Doff per limb**	**All hypo allergic materials that touches the skin**	**No dimension outside off knee of 10cm (size)**	**Weight of 0.7 kg or less per limb**
Providing rigid mounting points to foot shank and the thigh	5		5	5	4	5	3	4
Adjustable	3		5	4	4	4	4	3
Easy to doff/don	2		3	2	1	2	4	5
Minimize skin irritation by the physical interface	4		3	4	4	4	3	4
Allow the foot portion to be low profile and insert into normal shoes	4		4	5	5	5	4	3
Lightweight	5		4	5	5	5	4	3
Strong	5		4	5	4	3	5	2
Absolute Technical Importance (ATI)			114	127	115	112	108	92
Relative Technical Importance (RTI)			3	1	2	4	5	6
Target(s)			700 ksi and 300GPA	'10-20'	15 Secon ds	Irritati on	Differe nt sizes	0.5 kg
Tolerance(s)	±3 kgs		±5ksi & ± 4Gpa	±1'	±3 sec	±0	±1 cm	±0.0 5 kg
Testing Procedure (TP#)	2.3.1		2.3.2	2.3.3	2.3.4	2.3.4	2.3.3	2.3.2
Design Link (DL#)								

3 EXISTING DESIGNS

Research in the powered human exoskeleton devices started in the 1960s, which was almost in parallel with other research groups within the United States and former Yugoslavia [4]. As state by Haruhisa, Ueki, Ito, and Mouri [5], the former, however, was mainly focused on the development of technologies for purposes of augmenting the abilities of individuals who are able-bodied, mostly for military purposes. Haruhisa et.al [5] adds that the latter was focused on developing technology that was assistive in nature for the physically challenged individuals. Ever since them, different designs have been developed over the years, where most of them were meant to improve on the existing designs while others were entirely new designs [4].

3.1 Design Research

There are various designs that have been created over the years to make individuals with lower body disabilities to improve on their effectiveness. The team looked into earlier designs and analyzed them into details. The analysis allowed the team to come up with issues relating to the existing designs. Based on these issues, the team was able to come up with ideas to improve on the design that it seeks to develop. The proposed ideas will improve on the issues that are being faced by the current designs. In addition, the team looked into different sources of information, inducing books and articles to find more information relating to the design and how to make the design work better and in an effective manner.

The existing exoskeletons have for many years centered on position and drive control. They go through three different phases in advancing over the past decade. The first system level was based on a system that was controlled by an administrator, such as the Hardiman exoskeleton [3]. This design grew into improved skeletons that could then be controlled by individual users. The team seeks to use a combination of various systems to make a better and more effective design that is able to meet the needs of the users.

3.1.1 Existing Design #1: *Berkeley Exoskeleton*

This is considered the most visible DARPA program exoskeletons, which is a Berkeley Lower Extremity Exoskeleton. The exoskeleton is designed to provide effective assistance to individuals with lower body disorders [4]. The design is energetically autonomous and carries its own source of power. Its developers state that it is considered as being an exoskeleton that is load-bearing and energetically autonomous.

Figure 2. Berkeley Exoskeleton [4]

3.1.2 Existing Design #2: *Sarcos Exoskeleton*

Der et.al states that this is a full body exoskeleton that is a wearable energetically autonomous robot. This exoskeleton is energetically autonomous implying that is usually carries its own power supply unit. It has advanced in its hydraulically actuated concept [4]. Instead using linear hydraulic actuators, it employs rotary hydraulic actuators that are located directly on its powered joints, which makes the devise more powerful and effective to its users.

Figure 3. Sarcos Exoskeleton [4]

3.1.3 Existing Design #3: *MIT exoskeleton*

The MIT exoskeleton is a quasi-passice exoskeleton concept that has been developed in Massachusetts Institute of technology Media Laboratory. The design exploits a passive dynamics of the human walking style for purposes of creating a lighter as well as more efficient exoskeleton device [4]. The design does not use actuators for powering the joints. Rather, it relies on controlled release of energy that is stored in springs during the walking gait phase. This system was based on the kinetics and kinematics of the human walking design.

Figure 4. MIT exoskeleton [5]

3.2 System Level

According to Wenger, Chevallereau, Pisla, Bleuler, and Rodicin their research, looking into the system components is important for making the design a success [6]. The system levels are usually made up of smaller components within them. Wenger et.alfurther explains that an analysis of these components will ensure that the team gets a better understanding of the concepts involved in the design and allow for the ability to come up with a better and more effective design to meet the needs of the clients as well as the needs of users [3]. For example, looking into finer components of the motors may allow for a better and effective understanding of the interactions between various parts of the skeleton, which will then allow for improving the design to allow the system to relate and function even better.

3.3 Subsystem

All the existing design has various sub systems and it works in combination to achieve the required task.

3.3.1 Subsystem #1: *Berkeley Exoskeleton*

As stated by Mankala, Banala, and Agrawalin their research, the Berkeley Exoskeleton features three degrees of freedom (DOF), where one is placed at the hip, the other at the knee, and the last one at the ankle. Mankala et.al [7] adds that out of these, four of them are actuated, including hip flexion/extension, knee flexion/extension/ hip abduction/adduction, and ankle flexion/extension. The hip rotation joints and the ankle inversion/eversion are spring-loaded [2]. On the other hand, the ankle rotation joint had been made to remain free spinning.

3.3.2 Subsystem #2: *Sarcos Exoskeleton*

Mankala et.al [7] states that the Sarcos exoskeleton usually uses force sensing that is between the robot and wearer in order to implements a systems referred to as “get out of the way” system[2]. The foot of the wearer usually interfaces with the system through stiff metal plate that contains force sensing elements, which makes the feet of the wearer to remain stiff and not to bend.

3.3.3 Subsystem #3: *MIT exoskeleton*

The MIT exoskeleton uses a 3 DOF hip, as explained by Mankala et.al, which usually employs a joint that is loaded with a spring in a flexion/extension direction that is used in storing energy at the time extension is being released during flexion [2]. The design includes a mechanism that allows the user to freely swing their hip towards the direction of the flexion.

3.4 Black Box Model And Functional Model

A human exoskeleton requires a slight limb movement which is translated into a movement of increased strength. Electrical and hydraulic energy is required to increase this strength. The input is the brain activity. Brain thinks about movement of the limb. For example, all out body movements are controlled and directed from the brain. So for all the limb movement a control signal has to come from the brain. So brain is an input for the limb movement. A signal from the brain reaches the limb. This signal can be taken as the control signal input. Now limb is another input and it has to be moved slightly. In order to increase the strength we need some form of energy. Hence electrical/hydraulic energy is another input that will increase the strength.

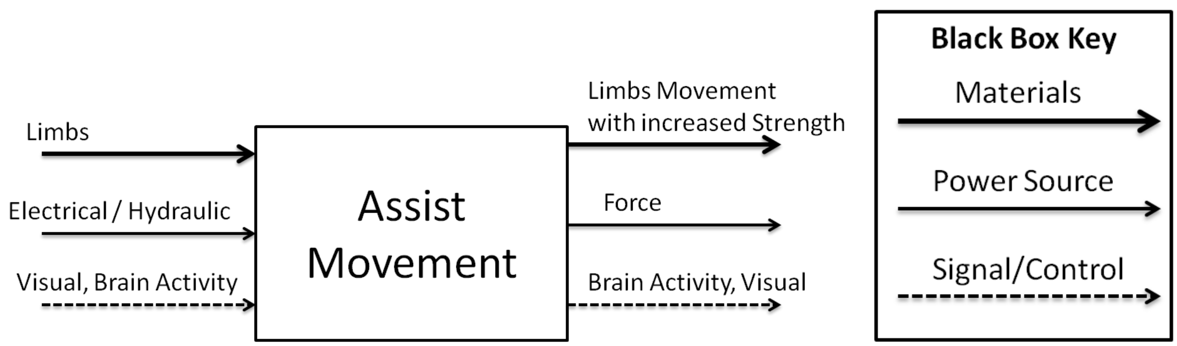

Figure 5. Black box Model

The output is the limb movement with increased strength. The increases strength is obtained through the force developed by using electrical/hydraulic energy. The control signal from the brain is also another output.

A functional model has to be generated by keeping the black model as the reference. For the proposed work user activity control signal is passed for the limb movement and the limb movement is sensed through sensors. The sensor output is processed and a control signal for the exoskeleton actuation is generated. Now electric energy is taken and the power is controlled depending upon the exoskeleton current movement and the strength required. The power is controlled on a feedback method. i.e. The exoskeleton movement is sensed at all the times and the control power is accordingly adjusted to deliver the required power. The exoskeleton will now move with the required force

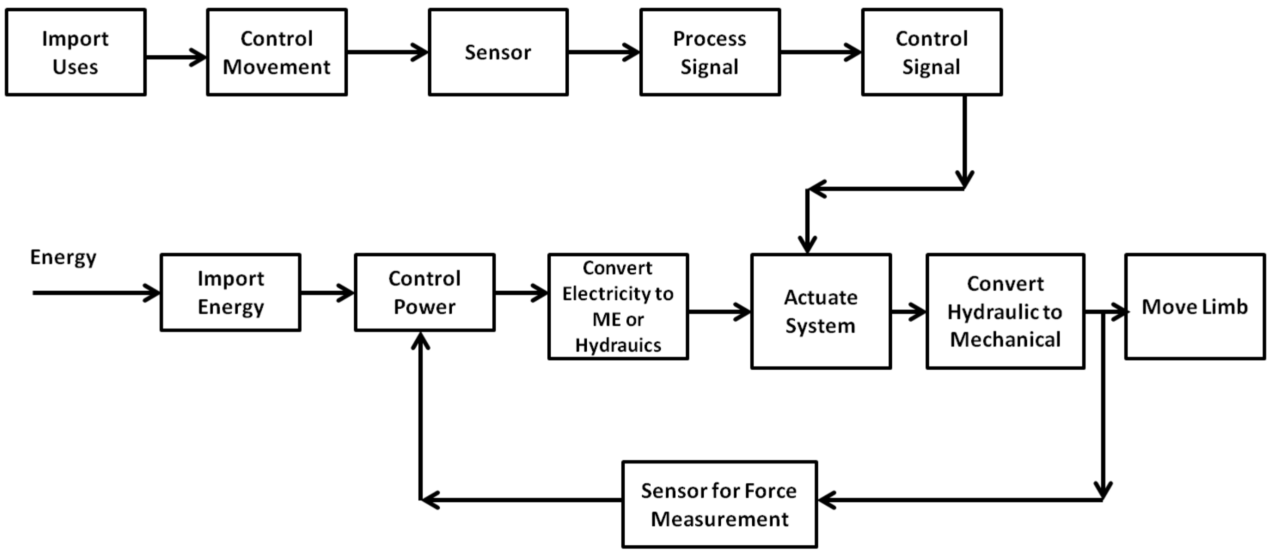

Figure 6. Functional Model

4 DESIGNS CONSIDERED

A total of 10 designs were generated through discussions in group and brain storming. Each of the designs were made by considering factors such as reduced weights, automation, higher load bearing capacity, power and other customer requirements. Eight of the generated designs are as presented in the sections below

4.1 Design #1: Joint with Two DOF Exoskeleton

This design is based on the ball and socket joint. A ball and socket joint has all the three rotational degrees of freedom. Generating a design by restricting the degrees of freedom to two rotational degrees will be beneficial for the exoskeleton design. Such a design will be idle for the knee, hip and ankle joints. All these three joints offer movement in two directions but restricts in the third. A ball and socket joint will be a simpler design and will serve the purpose. Figure 7 below gives the design of the proposed exoskeleton. This design has a simple joint but the load bearing capability is lesser. All the loads will come upon the joints and they may find it difficult to handle a bulky person.

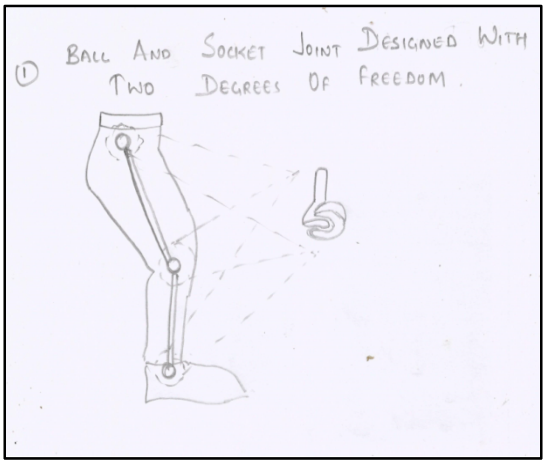

Figure 7. Joint with Two-DOF Exoskeleton

4.2 Design #2: Piston Based Exoskeleton

A piston can assist the movement in one direction and at the same time can take loads. It stores energy when loaded and releases it when the load is removed. Exoskeleton having multiple pistons can take load as well as assist the movement in another direction. A combination of pistons as shown in figure 8 can be useful to design an exoskeleton. This exoskeleton while bending forward will be loaded on the front piston and the movement will be allowed by the back piston. The condition will be an exact reverse when the exoskeleton moves backward. The piston positions have to be in such a manner that its one ends is above the knee, hip or ankle joints and other end is below that. This design is simpler to assemble but is not adaptive to people of different age groups. One among the piston will be always loaded and will try to release and exert a load on the exoskeleton. This can make the user uncomfortable.

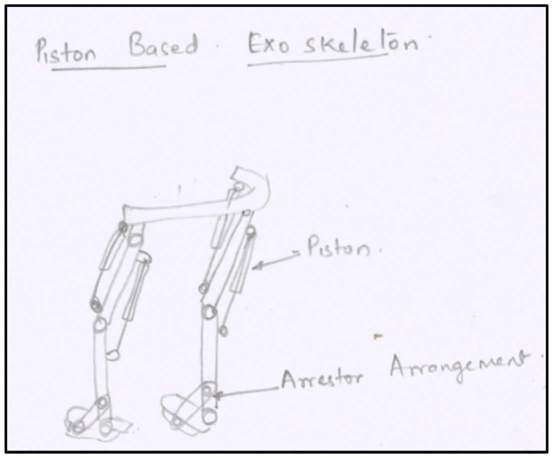

Figure 8. Piston Based exoskeleton

4.3 Design #3: Frame Based Exoskeleton

Battery powered motors can generate power to drive the exoskeleton. A gear arrangement can be provided to transmit the required power. In the proposed design a small chargeable battery will be used. This battery will be placed in a manner that is not a hindrance to the user. The motor will activate on switch operation and will provide a required torque to the gear arrangement. The gear will transmit the power to the exoskeleton for its movement. This user of this exoskeleton will have to apply a very little effort for the movement and the rest will be taken by the motor. The mechanism will be controlled by a switch and the user can use as per the convenience.

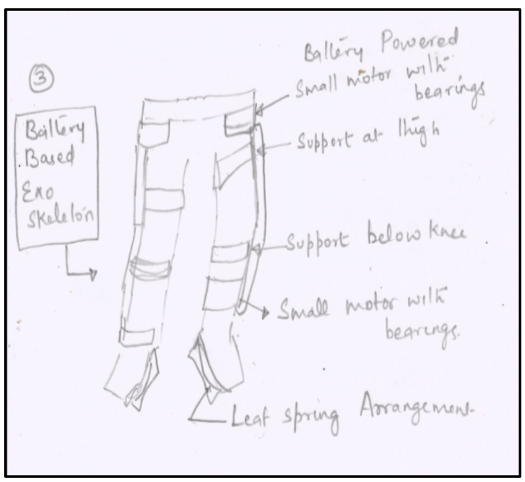

Figure 9. Battery Powered Exoskeleton

4.4 Design #4: Motor Based Rollers

The Motor based exoskeleton will consists of 6 motors at 6 joints (3 per leg). These joints will be operated by the motor based rollers. These rollers will wait for a pre-torque and will operate as soon as it receives a slight external load. For example, a small movement of the knee will cause the motor to sense and move the rollers. The rollers will operate until it gets a slight reverse torque. The reverse torque will be provided by the user. This power for the motor will be through a spring loaded mechanism at the foot. The springs will store energy while walking and the energy can be converted into electricity. This arrangement can be comfortable to the user but its practical realization may be difficult.

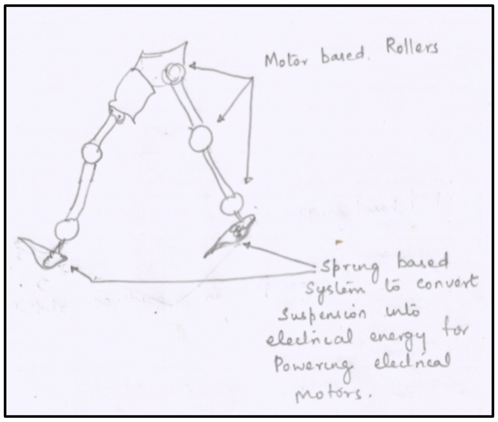

Figure 10. Motor based Rollers for exoskeleton

4.5 Design #5: Solar Powered Exoskeleton

Solar powered exoskeleton can be used to operate the mechanism using the solar power. This will reduce the need for carrying the heavier power source. However, the weight associated will the power generation component will be almost equal the power generation source. The back surface of the user can be used to place the solar array. This power generated can be used to power the driving mechanism.

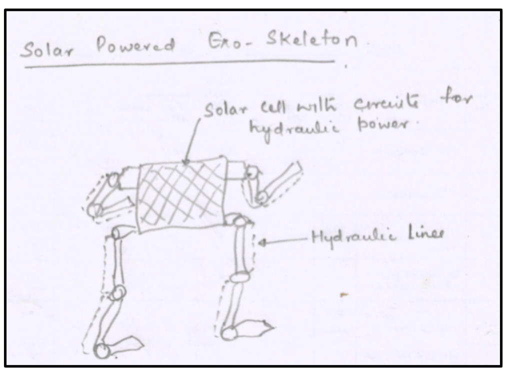

Figure 11. Solar Powered Exoskeleton

4.6 Design #6: Piezoelectric based exoskeleton

Piezoelectric based exoskeleton will be of self generating type and can be used to generate the power required for the exoskeleton. The piezo-stack will be fixed on the user's foot and the user load will walking will act upon the stack to generate charge. This generated charge will be converted into voltage using charge to voltage convertor. The voltage will be the power for exoskeleton. This method will be of self generating type and will not be dependent upon any power source. It can be used in without the fear of the power getting drained. The power generated however may be small and a large number of electronics may be required to generate the required power. The weight of the proposed power source may be some times uncomfortable for the user.

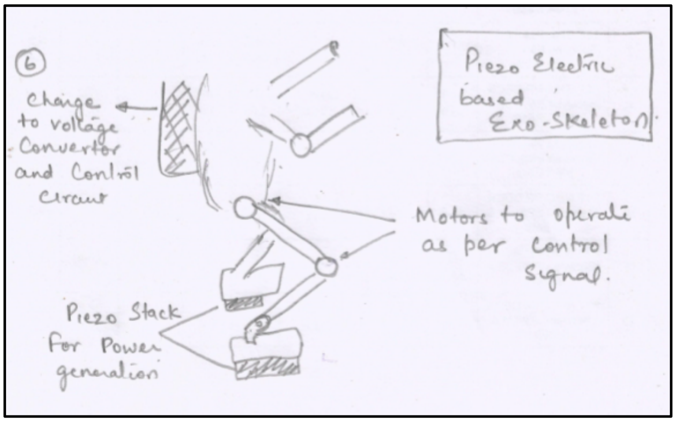

Figure 12. Piezoelectric Based Exoskeleton

4.7 Design #7: Exoskeleton with spring load mechanism

The spring load mechanism will be typically like a wrist watch mechanism where the dial is rotated every 24hrs approx. to load the spring. The spring will be loaded and slowly release the energy to move the hour and the minute hand. The same mechanism is proposed here.

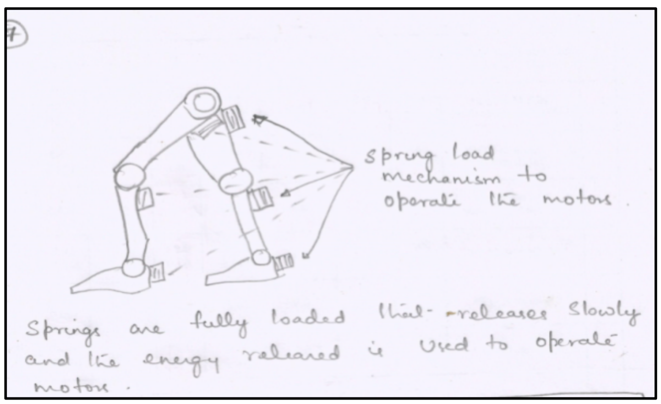

Figure 13. Exoskeleton with spring load mechanism

The spring will be manually loaded at regular interval depending upon the operation. The loaded spring will release itself slowly and release the energy. The released energy will be used to move the exoskeleton. This technique may deliver the required amount of energy. However, the mechanism may be difficult to operate.

4.8 Design #8: Exoskeleton with Sensor Based Controls

This design will be sensor based and fully automatic. All the human movements will be captured by the sensors and appropriate action will be taken. Sensors will be assembled at different point on the human body and the sensor will sense to give the feedback to the operating mechanisms. The corresponding mechanism will act as per the sensor signal. A control circuit will be provided to read the sensor signal at continuous intervals and to take the corresponding control action. The proposed system will be highly sophisticated but will be dependent upon the control circuit and any failure of the control circuit will severely affect the system performance.

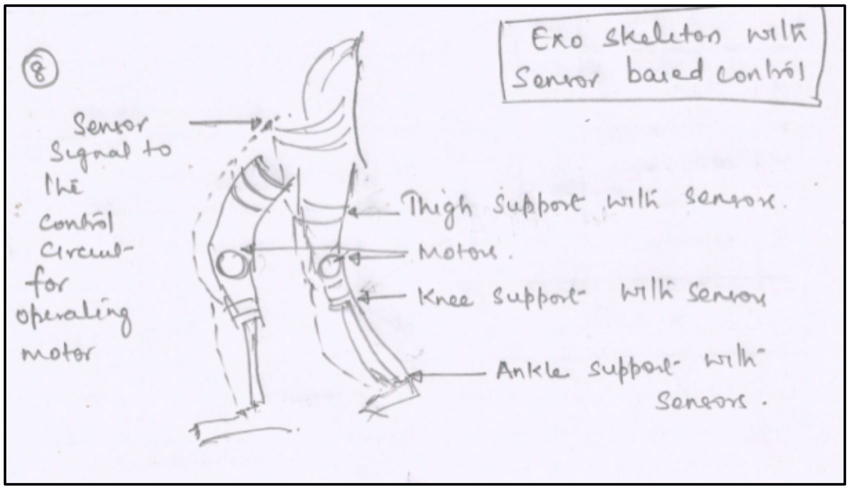

Figure 14. Exoskeleton with sensor based controls

5 DESIGN SELECTED

All design process involves identification of possible alternatives and selecting the best among them. Each of the alternatives is thoroughly analyzed and its suitability for the given requirements is considered. The suitability is put in terms of the numerical value and the alternatives are ranked depending upon various factors such as cost, efficiency, performance etc. The best among the alternative is then chosen for the final design.

5.1 Rationale for Design Selection

All the proposed 10 designs were thoroughly analyzed and the design criterions were considered to converge at top three. The best among the three were considered for the design. The final selected design was Design #3 as shown in Figure 9. The first step in the design process was to generate a Pugh chart and to perform the analysis accordingly. The Pugh chart is as represented in the figure below

Table 4. Pugh Chart

Criteria / Design #	1	2	3	4	5	6	7	8
Providing rigid mounting points	+	-	+	D	+	+	-	-
Adjustable	-	-	+	A	-	+	+	-
Easy to do on and off	+	-	+	T	-	+	-	-
Minimize skin irritation	+	+	+	U	-	-	+	-
Allow foot portion to be low profile	-	-	-	M	+	-	+	-
Lightweight	+	+	+		+	-	-	-
Strong material	+	-	+		-	-	+	-
∑ +	5	2	6		3	3	4	0
∑ -	2	5	1		4	4	3	7

The Pugh chart in Table 4 shows that Designs #1, #3 and #7 are good in terms of design criteria. These three designs are more suitable in terms of the design criteria. Design #3 is on the top and seems to be perfect for the customer requirements. Design #3 has rigid mounting points, more adjustable and light weight. It satisfies all the required design criteria to a larger extent when compared to the other proposed designs. The selected designs were further confirmed using the decision matrix as introduced in Table 6.

Table 5. Decision Matrix

Customer Requirements	Weightings	Design #1	Design #3	Design #7
Rigid mounting points	15%	5	5	4
Adjustable	13%	5	7	3
Easy to do on and off	10%	5	6	5
Minimize skin irritation	12%	4	6	4
Low profile foot portion	10%	4	5	4
Lightweight	20%	8	3	4
Strong material	20%	2	8	3
	100%	33	40	27

The decision matrix was built and it estimated that design #3 has the maximum weight. Design #3 is good at critical customer requirements such as material strength, easy don/doff and skin irritation. The selected design has the best rigid mounting points. It is adjustable and can be used in the age group 13years to 65years. The irritation caused by this design is limited and the structure is light weight.

5.2 Design Description

Frame based Exoskeleton can be simple, cost effective and suitable for people in age group (13-75) years. This design will be easier to use and will be comfortable for the users. Figure 17 gives the schematics of the exoskeleton. The design will have a stiff frame made of lightweight material such as carbon fiber. The knee and the thigh areas will have strap arrangements for support. The knee area will have two nearby joints to comfort the knee movements. The back portion of the frame will be completely covered to hold the thigh. The foot area will be made of soft plastic to avoid itching and discomfort.

Figure 15: Frame Based Exoskeleton

5.2.1 Components Involved

The main components involved in this design will be

- Frame made of carbon fiber.
- Corrugated metallic structure to cover the body parts
- Foot rest made of soft plastic and buckles for adjustments.

Apart from these three main components the proposed design will also have bolts and nuts of different dimensions. Adhesives will also be used for assembling the foot rest.

5.2.2 Design Criticalities

The proposed design will have many criticalities and can be properly tackled with proper application of the engineering principles and the available tools. It is proposed to use carbon fiber for the design. Realizing a structure to suit the required design will be a challenging task. The joints especially at the knee and the ankle have to be made in such a way to provide maximum comfort to the user.

The weight of the design should be less than 0.75kg. People use the design in age group of (13-75) years. The adjustability part of the design has to be appropriately carried out. Buckle arrangements will be the best suited for the proposed application.

The feet area will have to take the maximum load and at the same time should not have any sharp edges to cause discomfort to the user. Soft plastic material having sufficient strength has to be selected.

5.2.3 Analysis and Experiments

A lot of analysis and experiments are involved in this work. In certain cases, mathematical analysis along with experimental validation may be required to proceed with the work.

Mechanical analysis is required for accessing the strength and the load carrying capacity of the material under use. Modeling and analysis software can be used for accessing the stiffness and strength of the material under use. Stress – strain relationship has to be obtained for estimating the modulus of elasticity.

Experiments have to be carried out to validate the analytical results. The analytical results are based only upon the inputs and missing of any input may vary the analytical results with respect to the true value. It is thus better to perform experiments for further validating the analytical results.

6 PROPOSED DESIGN

6.1 Intended Design Construction

The exoskeleton proposed for this design will have a framework and joints at the knee and the ankle area. The frame of the structure will have three joints in the ankle, knee and the hip area. The joint at the ankle will be a simple joint with a single degree of freedom. The joint at the knee area will have additional stiffness to take care load. This joint in turn will have two joints to support the shin-knee movement and the thigh-knee movement. A small frame is connected at the knee area with joints at both ends. Figure.18 shows the details of the joints. The joint at the thigh area will take care of the hip to thigh movement. All the joints will be of nut and bolt arrangement and the design will ensure that no parts are projected outside.

The footrest will have a flat base and protection all around the sides to avoid slipping of the foot to outside area. 2-inch of support will be provided in the ankle area to prevent slipping of the foot.

The back portion of the thigh and the shin area will have protection to adjust the body shape during the movement. The surface near these areas will have metallic corrugated bellows like arrangement that expands and contract to adjust with the body movement. These metallic surfaces will be connected to the framework through riveted arrangement.

The front portion of the knee area is covered with a metallic strip to shield the knee during its bending. The knee will tend to move forward during bending and has to be restricted. A metallic strip is bent and fixed near the knee area to restrict it during the movement. Adjustable arrestors are provided at the thigh area to fix the exoskeleton and adjust it as per the thigh dimension.

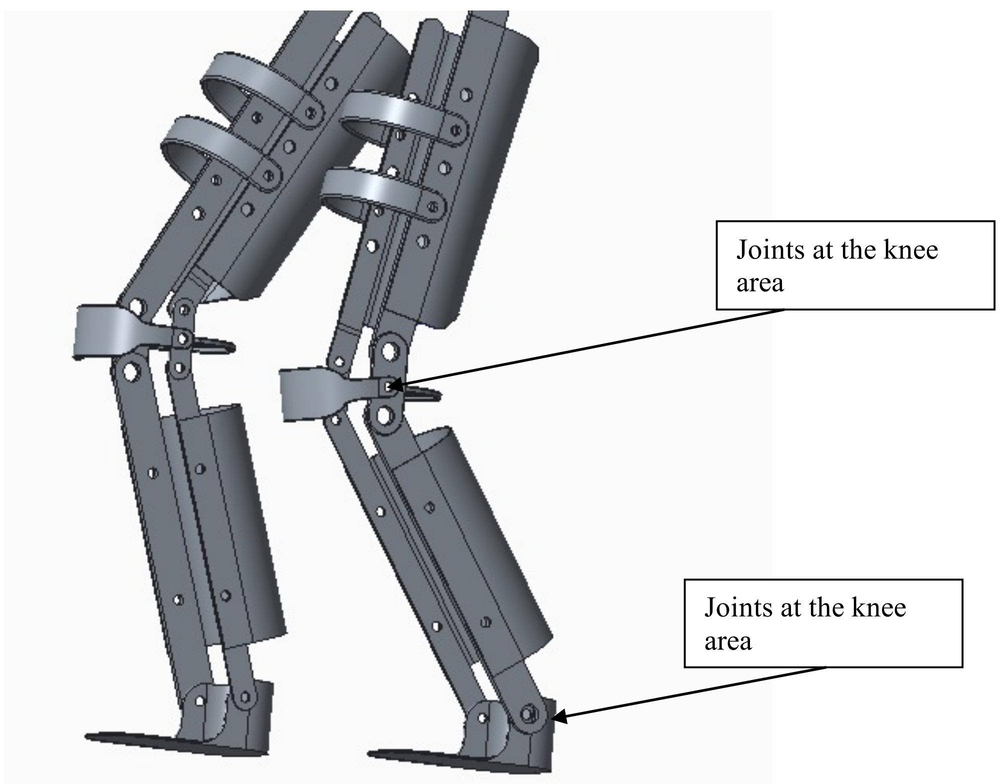

Figure 16. Proposed Exoskeleton

6.2 Materials

The right material selection is an important criterion for the project success. It must be in line with the design objectives. The designed exoskeleton has three parts namely framework, footrest area and the arrestors at different locations.

6.2.1 Frame-Carbon Fiber

The material to be used for the exoskeleton will be the prime factor for weight reduction. Carbon fibre based material will be used for the framework. The carbon fibre materials are mainly used in aerospace industries for weigh reduction. These materials are extremely lightweight, non-corrosive and can carry large loads. A carbon fibre based material consists of 90% carbon fibre that is woven to make sheets. These sheets are later combined to form the material. The pattern used for weaving the sheet decides the direction in which the material can take maximum load. Some of the properties of the carbon fibre materials are as discussed

- Lower density : ~80 lb/ft^3
- Higher strength : ~290 ksi
- Cost : $10/lb.

Properties of the carbon fibre is dependent upon the pattern in which the fibres are weaved and the number of layers. The strength and the density vary from one type to another.

6.2.2 PVC based material - Footrest

The footrest has to be made comfortable and PVC based materials will be used. These materials can take sufficient loads, less reactive, easily machined and does not cause any discomfort to human body when designed properly.

6.2.3 Aluminum –Arrestors

The arrestors at the back of the exoskeleton has a corrugated bellows shape and aluminum based construction is the ideal choice. Aluminum structures are stiff and can deflect as per the movement to protect the body.

6.2.4 Bill of Materials

The bill of materials (BOM) was based on the selected material. The materials will be purchased and machined. A market survey was carried out and the BOM was prepared. Table 4 shows the BOM for the proposed design. Moreover, the team contacted a company in Flagstaff, and they gave the team an estimation of the cost. The estimation cost is described in Table 4.

Table 6. Bill of Materials

Part	Part Name	Description	Functions	Material	Manufacturing Process	Dimensions (ft)	Cost
1	Frame	Strips with holes at different points for holding the system	To take the full load coming on the structure	Carbon Fiber	Weaving of the carbon fiber.	4	$150
2	Footrest	For footrest design	To hold the foot during movement	PVC	Cutting and machining	1	$5
3	Arrestors	At the back of the exoskeleton	To hold the thigh during movement	Aluminum	Corrugated Bellow arrangement	2	$50
Total	$205						

As shown in the previous table, our budget will remain with $295. The remaining budget is going to be distributed between the repairing to the damage that might happen to our design. Nevertheless, the cost might be affected depending on the machine shop that the team will contract with.

6.3 Cost and Budget

The budget allocated for this work is $500. This amount has to cover all the expenses starting from the design to the final product. Currently analysis and prototyping of the model is completed. Figure 17 shows the generated prototype.

Figure 17. Prototype of the Model

The cost incurred in the realization of the prototype is presented in Table 5.

Table 7. Cost Breakup for Prototype

Materials	Cost	Place
Machine Screw kit	$1.46 [8]	Walmart
Velcro Tape, 3/4" x 15'	$11.92 [9]	Walmart
2 ft. Aluminum Vent Pipe	$3.88 [10]	Home depot
Brass Hinge	$1.97 [11]	Walmart
5 in. Steel Zinc	$1.78 [12]	Home depot
4 in. Zinc Plated (2-Pack)	$2.94 [13]	Home depot
10 in. Zinc-Plate	$2.78x2 [14]	Home depot
Total	$29.06	

6.4 Schedule

A Gantt chart was generated and it was decided to keep the design within a specific schedule. Figure 18 shows the Gantt chart to be used for the proposed work. The work until now is as per the Gantt chart and further efforts will be taken to keep up with the deadline.

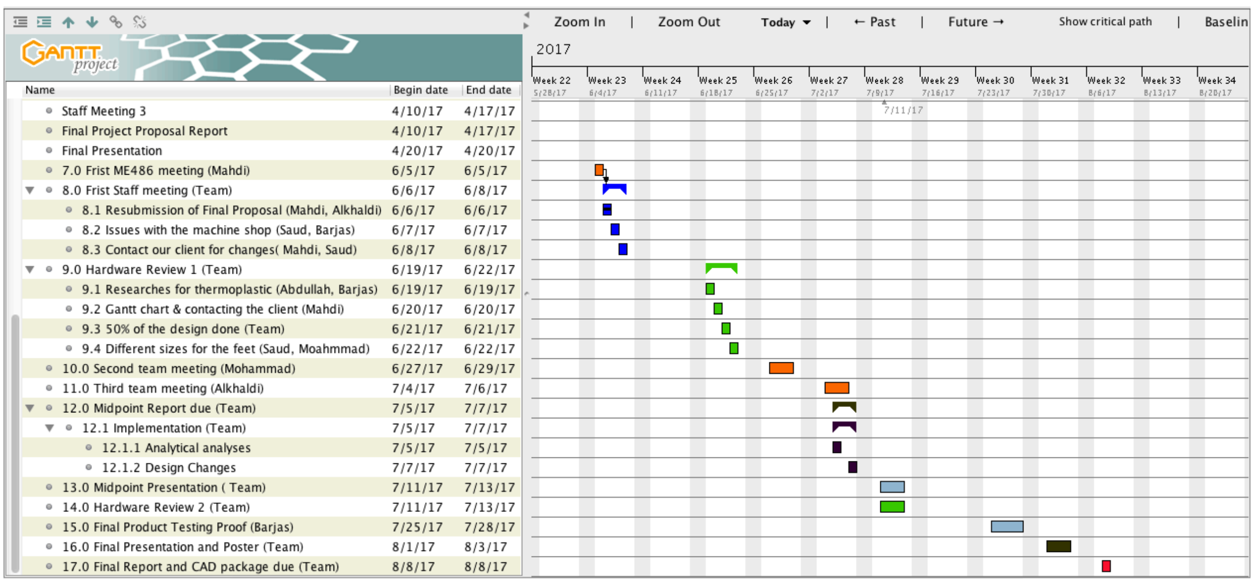

Figure 18. Gantt chart

6.5 Individual Analytical

In the Individual analytical analysis, the engineering requirements will be demonstrated into six parts among the team members. Each of the requirements was analyzed by individual team members and a separate analysis was carried out. The findings by the individuals are presented in this section. These engineering requirements are listed below:

6.5.1 Ability to use by people of (13-75) ages

6.5.1.1 Introduction

The present world has large number of supporting systems for the persons having disability. These systems can give maximum comfort to such persons and assists them to perform their daily chores. The performances of these supporting systems are being improved with time. The improvements are with respect to the usability, efficiency and features. Engineering concepts are being embedded in this area for further improvement.

This project deals with the design of an exoskeleton for supporting persons having disability who find it difficult to walk. The exoskeleton is a system that has powered motor arrangement to assist the person to move from one place to another.

My individual responsibility in the design of the exoskeleton is to make it usable by all persons in the age-groups 13-75years.

6.5.1.2 Discussions

For making the exoskeleton to be used by all persons the analysis must be carried out in different dimensions.

Requirement analysis: The requirement study will be carried out for people of different age group depending upon their age and the extent of disability. The requirements will be analyzed under three age groups, children, adults and old. A note will be prepared and the work will be progressed as per the prepared notes. The analysis must begin with the identification of the problems faced by people of different age groups and finding a common solution.

Mechanical Design Issues: After performing the requirement analysis the design aspects must be considered. The system should be designed in such a manner to make it adjustable. The adjustability will increase the capability of the system to be used by different age groups.

Adjustability: The adjustability should be introduced mainly in the limbs, external frame, and waist/thigh belt and on the foot rest. The design can include adjustable belts in the holding areas. The adjustability for the limbs and the footrest must be considered and the design must be such a way to provide adjustability and at the same time sufficient strength to the system. A telescopic arrangement can be provided to adjust the lengths. For example, a metal part will be projected out when the footrest size has to be increased. It will have a telescopic arrangement and will be folded for the kids and stretched for adults and old people.

Load Calculation: The loads coming on the limbs should be analyzed to make sure that the same could withstand different input conditions. The limbs can be considered as a beam that is fixed at both ends and the buckling loads can be evaluated using the formula

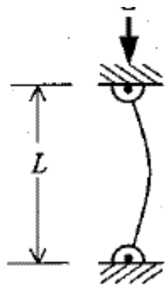

Figure 19 Buckling load on a beam [3]

The buckling load coming on the limb can be calculated using the formula

$$Buckling\ load = \frac{\pi^2 EI}{L^2} - - - - (1)$$

Where E is the Young's modulus, I is the 2nd moment of area, L is the length of the limb

Carbon Fiber material is being used for the exoskeleton and its properties at room temperature are as follows

E = 45E4 MPa

I = 400mm^4 (Maximum Expected)

L = 200mm

$$Buckling\ load = \frac{\pi^2 \times 45E4 \times 400}{200^2} = 44413\ N$$

The center of gravity (CG) and the overturning moment (OT) of the system also must be calculated to make sure that it does not cause any discomfort to the person using it. The formula used for the calculations are as given below

$$CG = \sum_i \frac{m_i x_i}{m_i} - - - - - - - - - (2)$$

The designed exoskeleton can be considered as an I section and the CG can be calculated as

$$CG = \frac{(0.2 \times 10) + (0.4 \times 5) + (0.1 \times 5)}{0.2 + 0.4 + 0.1} = 6.428mm$$

Where m is the mass of different elements and x is its distance from the center. The mass of different elements of the exoskeleton and its relative distance from the center will be used to measure the CG. The overturning moment is used to look for the mass distribution and the effect that occurs when the human weight interacts with the exoskeleton weight. The exoskeleton weight must not be very large to topple the human using the system. The information from the CG is used for the calculation of the OT moment.

Operability: The system must be designed for easier operation by the people of all the age groups. This feature can be introduced by making all the operations in a simpler format so that the same can be used by all people.

Material Selection: The materials used for this application will be lightweight. The most preferred material for this adjustable design will be carbon Fiber. The Carbon Fiber based materials are reinforced carbon Fibers in some suitable adhesives. These materials are extremely light and can take large loads. This material is non-corrosive and can be fabricated to the required dimensions. The load bearing capability of this material is very high.

Electrical Design Issues: The electrical design analysis required with respect to the usage of the system for age group 13-75 is very limited. The actuation mechanism will be tested for different configurations and will be designed to make the system usable by all age groups. A component will be introduced to bring in some lag to the system. The system lag can be estimated by finding out the second order equation of the system and to find the properties such as natural frequency, damping and stiffness. The system will be considered as the second order system and the transfer function will be evaluated as

$$F = M\frac{d^2x}{dt^2} + K_d\frac{dx}{dt} + k_s x \text{ ------}(3)$$

$$damping = \frac{K_d}{2\sqrt{MK_s}} \text{------}(4)$$

$$Frequency = \sqrt{\frac{K_s}{M}} \text{ -------- } (5)$$

The factors M, K_d and K_s can be used to estimate the system behaviour and other performances.

Modelling and Analysis: Some of the designs such as external frames and limbs may require to be analyzed through modelling software such as AutoCAD and Proe. This software will be useful in generating the design and to bring out any flaw if any. The important part of the design such as the external frame and limbs will also be analyzed through analysis software such as Ansys. A complete modelling of this system will give the complete information and the designer will get all the inner aspects of the system functioning.

Dimensions: The dimension for this system will be finalized as per the outcomes of the modelling and the analysis work. The height of the exoskeleton will be 6ft in total. The radius of the individual structure will be 3-4inches.

6.5.2 Weight of 0.7Kg or less

6.5.2.1 Introduction:

Exoskeleton is an equipment to assist people with disability. It is helpful for those people to move from one place to another with maximum comfort.

We as a group are assigned with a responsibility to develop an exoskeleton that will be assist the people with disability to move from one position to another. It is like an artificial limb that takes the complete load of the person and helps them to move. It will be a kind of wearable device that will be used by the person with disability.

My individual responsibility for this design is to make the system light weight. The weight of the system has to be kept at 0.7kg or lower per limb. Different analysis has to be carried out for performing this weight reduction. The design used for this work is as shown in Figure 1 below.

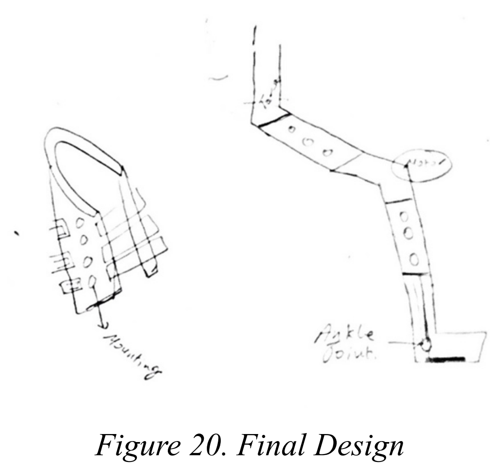

Figure 20. Final Design

6.5.2.2 Material Selection

The material to be used for the exoskeleton will be the prime factor for weight reduction. It is planned to use carbon fiber as the material for the system under design. The carbon fiber materials are mainly used in aerospace industries for weigh reduction. These materials are extremely light weight and can carry large loads. A carbon fiber based material consists of 90% carbon fiber that is woven to make sheets. These sheets are later combined to form the material. The pattern used for weaving the sheet decides the direction in which the material can take maximum load [1]. The Figure 2 below will be the pattern that is proposed exoskeleton.

Figure 21. Carbon fiber material proposed for the work [16]

6.5.2.3 System Design

The weight reduction has to be carried out and at the same time the required mechanical properties have to be maintained. The yield strength of the system has to be maintained at 500ksi and the modulus of elasticity (E) has to be kept at 678 ksi. The materials used for the system must be designed to meet the required criteria of light weight. Weight reduction of the system can be carried out through load modelling and analytical calculations. The formula used of calculation of yield strength and E are [2]

$$E = \frac{Stress}{Strain} - - - - (6)$$

$$Stress = \frac{Force}{Area} - - - - - (7)$$

$$Strain = \frac{Change\ in\ length}{Original\ Length} - - - - - - (8)$$

The value of E and the yield strength can be derived from the stress-strain curve of the material. The mechanical properties can be derived analytically using the properties of the materials. The values can be validated through experiments.

The theoretical calculations for modulus of elasticity

$$Stress = \frac{80}{0.6} = 133.333N$$

$$Strain = \frac{0.01}{50} = 2E - 4$$

$$E = \frac{133.33}{2E - 4} = 666.65\ Ksi$$

6.5.2.4 Mechanical Load Calculation:

The exoskeleton will experience two types of load. First is the axial load of the person using it and the second is the lateral loads while the person bends his/her knees while walking. The axial load will be mainly compressive in nature because one side will have the human load and the other side will be on the ground. The exoskeleton will be compressed in between the knee and the human weight.

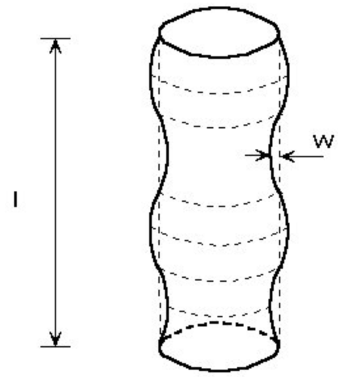

Figure 22. Buckling of the cylindrical structure [3]

The buckling stress can be estimated using the formula [2]

$$S_{cr} = \frac{E}{\sqrt{3(1-n^2)}}\frac{t}{r} -----------(9)$$

$$S_{cr} = \frac{666.65}{\sqrt{3(1-0.5^2)}}\frac{0.6}{0.05} = 37129 \text{ Ksi}$$

Where, E is the elastic modulus, t is the thickness, r is the cylinder radius, n is the poisons ratio. The buckling stress has to be maintained at a higher value around 37129 Ksi.

The lateral load may be only during the movement of the knees and it can be calculated using the formula [4]

$$s_q = \frac{r}{t} P -------------(10)$$

$$s_q = \frac{0.6}{0.05} 2296 = 27557 \text{ Ksi}$$

Where p is the pressure or the load that is acting laterally to the exoskeleton. The lateral stress must be at least 27557 ksi to take care of the lateral loads.

6.5.2.5 Accessories Weight:

The exoskeleton designed using the carbon fiber will have many accessories for connecting different parts. The accessories may include metal parts, plastics and other materials. The weight of these accessories will also contribute to the total weight of the system. The selection of these accessories has to be made depending upon their strength and load bearing capability. Usage of nuts and bolts for connection is conventional and may increase the weight of the systems. The nuts can be replaced by the usage of rivets. The efficiency of a riveted joint can be estimated using the formula

$$Efficiency = \frac{Loads}{P \times t \times \sigma_t} ------(11)$$

Where p is the rivet pitch, t is the plate thickness and is σ_t the permissible tensile stress. The stress has to be maintained at a particular value. The accessories used for the exoskeleton can be made up of aluminium or other lighter material. Polymers and adhesives can also be used in the areas where the expected loads are smaller.

6.5.3 Analysis of Yield Strength of X Modulus of Elasticity of Y

6.5.3.1 Introduction

The yield strength of substances refers to extent to which they give in to pressures and adverse changes. It is often affected by constraints like temperature and pressure. In the case of an integrated level system, it is desirable to note that it will have many components such as rods, joints, bearings, clamps and many others. For the purposes of this discussion, the yield strength of the complete system will be analyzed theoretically as well as mechanically. The analysis will be done in four steps, 1) Each and every mechanical component of the system with its dimensions, mass and material properties. 2) I will do a theoretical analysis of each individual component to find the yield strength will be identified. The available information will be utilized to find the respective values. The obtained yield strength will be compared with the design values. 3) The mechanical software will be used to confirm and validate the theoretical results. Then again, software analysis on each identified components will be done. 4) After confirming the individual components with the design standards, an integrated level analysis will be done. An integrated level system will have many components such as rods, joints, bearings, clamps and many others.

6.5.3.2 Discussion and Analysis

In this discussion, the lab that uses robotic exoskeletons was used to improve walking biomechanics in the individuals with neuromuscular disorders. The purpose of the project was to design an adjustable system that results in mechanical components to the lower-extremity, that is, the legs. The material that was utilized in this case includes the custom molded orthotics that serve as constraints. Nevertheless, it is important to note that they require time-consuming casting as well as expensive molding fabrication [1]. Accordingly, the component is long since short-ones do not conclusively aid in the realization of the intended purpose. The location made it possible for the limb sizes to accommodate persons amid the ages of 13-75. Still, I selected the system in reference to the fact that it is easy to turn on and off. Put differently, it is desirable to note that the physical interface ought to minimize skin irritation. On the other hand, the expected performance of concept variant X with respect to a given engineering requirement under extreme conditions like temperature, time, and force. It is important to note that the foot portion must be low profile such that the normal shoes can be inserted.

6.5.3.3 Estimation of the Yield Strength

Yield strength is the point beyond which the structure gets permanently deformed. The yield strength of a carbon fiber can be estimated from the stress-strain curve. The mechanical properties of the material and the dimensions are sufficient enough for estimation of the yield strength. The structure whose yield strength has to be determined can be modeled on design software and the yield strength can be derived over few clicks on a computer. However it is essential to have information on how the yield strength is estimated. The yield strength is estimated by applying a specific force per unit area on the designed structure and estimating the strain. In the figure 1, the force is gradually increased and the strain is measured. In this regard, a curve is plotted for the obtained value . A typical stress-strain curve is as represented below. From the curve we can derive a point from where the structure enters to the plasticity region and will permanently deform. The force at which the structure enters the plasticity region is the yield strength of the structure.

1. Stress = Force/Area
2. Strain = change in length/Original Length

In all the design applications, the structure is expected to perform in the elastic region and a margin of error is given to it. The applied load ought to be lesser than the yield strength of the structure. A carbon fiber based structure is proposed for exoskeleton. The thickness and weaving pattern of the carbon fiber must be so selected to take the load of people in the age-group 13-75years. The weight carrying capacity must be 50-90kgs.

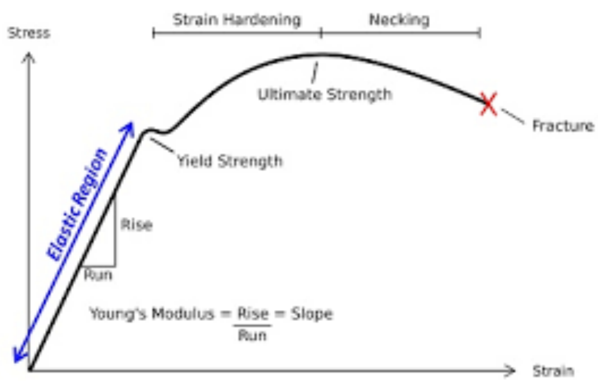

Figure 23: Stress-Strain curve depicting the yield strength

As for the torque and rpm that would result for a given power input or load, the formulae that would suffice in this case is,
HP = Torque x RPM-Formula
On the other hand, the values of X and Y will be calculated in light of the formulae.

$$\sigma^2 = \frac{\sum(x-\mu)^2}{n} --- (12)$$

Torque= 10*12
=120
Therefore RPM= HP/Torque
RPM=670/120
RPM= 5.583
From the different designs, the pressure of the X variables decreases, the energy demands increase and power loads reduces. The Y variable is more concerned by power loads. The magnitude of a complex engineering requirement for the existing and baseline for state of the art technology is that the system ought to be flexible and effective enough to make it possible for accurate measurements to be taken.
X and Y is found by the Least Squares Method. In this respect, the parameters to be considered include:
The dependent variable (modulus of elasticity)= Y
The auxiliary, also known as the independent variable (yield strength)=X
Parameters = A, B
On the other hand, the response happens to be linear with the given parameters.
By the use of the estimation value, the figures will be accrued by:

3. $y = A + BX + \varepsilon$

Where ε has a value of 0.

Figure 24: An Illustration of the Modulus of Elasticity

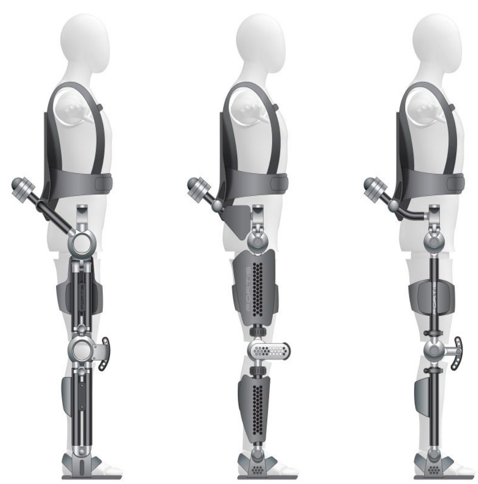

Figure 25: An Illustration of the Modulus of Elasticity

As seen in Figure 24 and 25 above, the strength of the materials to be used in this project is very important. All the materials used in this work must have sufficient yield strength of 12 psi. In this regard, the yield strength is direction dependent. For example, the straight metal rod for the limb between the knee and the toe is expected to take the axial load of the human and must not bend [2] ,and the high of the load is 700g for each leg. Its yield strength must be sufficiently high to take the axial loads. Whereas, the lateral loads on the rod will be comparatively lesser. The reason for the lower lateral loads because it is experiencing no much lateral force.

6.5.4 Must be Quantified

6.5.4.1 Introduction

There are countless engineering teams worldwide that are and have been working on development of complex robotic exoskeleton for the lower extremities. Normally these teams of professionals work in labs across the world. Some of the notable institutions in this field are: Raytheon Sarcos' exoskeleton, Berkeley Bionics' BLEEX, and Cyberdyne's HAL. In retrospect, there are a number of goals in the development of exoskeletons; and that is, offer assistance for the disabled, learn more about the workings of the human physiology, and augment the human performance. The augmenting part is perhaps the most important reason for this technology in that it aims to assist the less disabled individuals to be close to a "normal" person as possible.

The exoskeleton has many components that work together with the human physiology. Sensors and control systems are integrated to the system to help mimic the "will" of the wearer. The study of human physiology in this field is necessary; factors like neutral control, energy expelled during movement, and the biomechanics are considered.

6.5.4.2 Discussions

The design of the exoskeleton is a team work and each of the team members is assigned with an individual responsibility. My individual work is to make the system quantifiable. The idea here is to assess the performance of the systems in terms of some numerical values. These numerical values can be compared with the standard values and the actual performance can be evaluated. The performance of the systems can be derived in terms of various characteristics. The characteristics and the corresponding formula are as mentioned.

$$Mechanical\ Advantage = \frac{Output\ force}{Input\ force} - - - - - - - - - - - (13)$$

The mechanical advantage is used to find the amount of the input energy that is converted into effective output. It basically gives the amount of losses. This value is useful in analyzing the sources of losses and to reduce them.

Factor of safety

The factor of safety is the margin that is provided in the design with respect to the ultimate failure of the system. All the designs have some factor of safety to take care of the unexpected loads on the system. The factor of safety does not have any unit and is presented in some numbers. Factor of safety is given by

$$Factor\ of\ safety = \frac{ultimate\ stress}{actual\ stress} - - - - - - - - - - - (14)$$

Reliability

The reliability is another quantifiable property and it deals with reducing the frequency of failures. It is used to estimate the problem free operation of the system. The reliability if a system is calculated as

$$R(t) = e^{\left(-\frac{t}{MTBF}\right)} = e^{-\lambda t} - - - - - - - - - - - - - (15)$$

MTBF is the mean time between the failures and λ is the failure rate. The reliability of the system decreases with time. The reliability at the start of the system must be considerably high.

Maintainability

It is the property that tells the maintenance requirement of the system. The maintenance requirement increases with time because of the ageing and the wear and tear. The maintainability of the system is given as

$$M(t) = 1 - e^{\left(-\frac{t}{MTTR}\right)} = 1 - e^{-\mu t} - - - - - - - - - - - (16)$$

MTTR is the mean time to repair and μ is the maintenance rate. The maintainability of the system decreases with time. The maintainability at the start of the system must be considerably high.

Efficiency

The efficiency of the system is the ratio of the output to the input and is expressed in terms of the percentage.

It is in a way similar to the mechanical advantage but is carried out for the overall system. It is not effective in estimating the system individual component loss.

6.5.4.3 Design

Expandable internal tubing enclosed in a braided shell made of polyester are used to make the artificial pneumatic muscles. In the event that the internal tubing is inflated with pressurized air, there is a tension created due to the presence of the braided polyester shell. Perhaps the most advantageous thing about using artificial pneumatic muscle is the fact that they are very light and their power output is high. Further study into the artificial muscle reveals a linear relationship between force and length. The amount of force required to stretch an artificial pneumatic muscle is equal to the force used when shortening the length. It is for this reason that they are ideal since there is no need for extra power for locomotion. The forces produced by these muscles have a direct correlation to their cross-section. Therefore increasing the size of the muscle increases the total force.
Activation dynamics can be integrated to the artificial muscles. The force bandwidth of a an artificial muscle is 2.4 Hz; on comparison, the human muscle has a bandwidth of 2.2 Hz. The artificial muscle and the human one have identical twitch mechanics coupled with an electromechanical delay.

a) Ankle Exoskeleton

The ankle exoskeleton is very important because this is where positive mechanical work takes place. The ankle is responsible for the stance the individual takes when walking. There were improvements in the ankle exoskeleton; a bivalve design coupled with buckles made of plastic is used to ease donning and doffing. Figure 26 shows artificial exoskeletons with pneumatic muscles

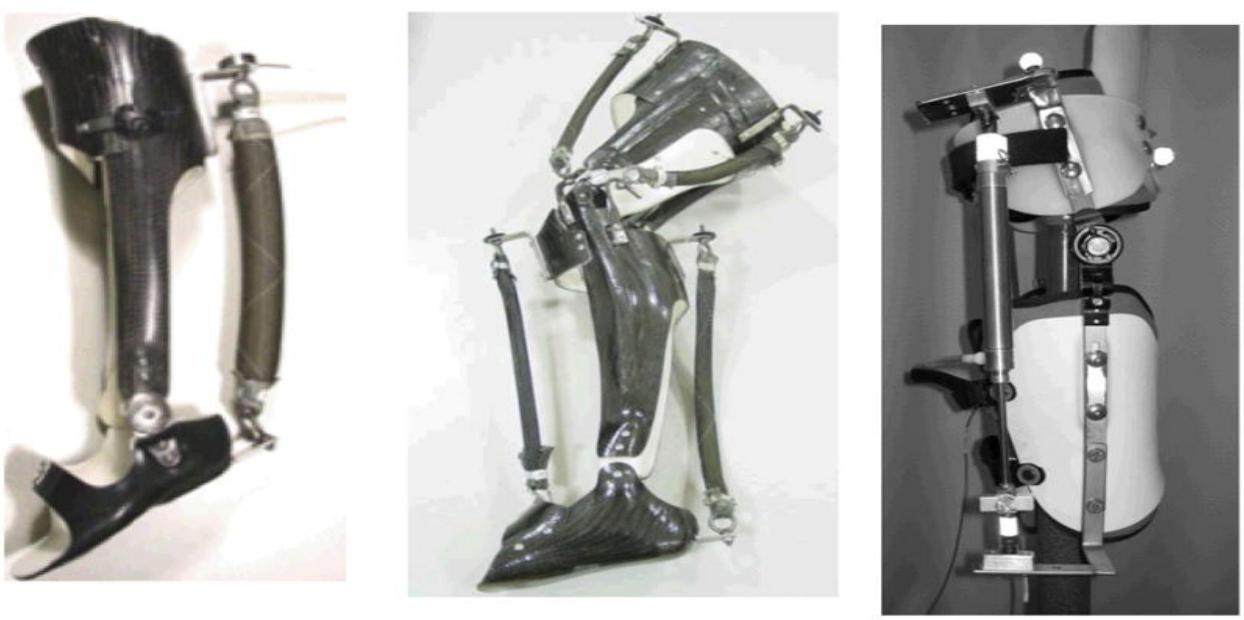

Figure 26 artificial exoskeletons with pneumatic muscles

The materials used to construct the different components of the artificial exoskeleton were taken into consideration based on their characteristics. For instance, the shank part of the design is made of carbon granted the tough nature of the substance; this brings stability and dependability. The foot part of the design is made of polypropylene, this attributes to the flexibility and comfort of the design. The dorsiflexion together with plantar flexion of the ankle is handled by a steel hinge joint that acts as a conduit between the shank and the foot part of the design. The foot and the shank had steel brackets attached to them that are helpful when connecting multiple artificial pneumatic muscles. This connection supplies the plantar torque required. During human walking, the ankle skeleton was able to provide 60 Nm plantar flexor torque or 57% of the same (Moromugi 56).

6.5.4.4 Modeling and Analysis

Modeling and analysis can be carried out to estimate the system efficiency and output. Each of the individual component of the exoskeleton can be analyzed to find the individual performance and the loads that it can handle. Thus, making the exoskeleton quantifiable. Finite element analysis has to be carried out to estimate such values.

6.5.4.5 Controllers

The load conditioning is a factor that attributes `to the performance of the sensor.

a) Materials and methods

The LOPES gait is an exoskeleton that has 8 degrees of freedom. A series of elastic actuators power the joints in LOPES. They can be controlled in two ways: via a virtual mode impedance control or the torque mode. There are three attachment points situated in individual legs that are strapped to the user. There is a single attachment point on the upper leg the other two belong to the lower leg. Cuffs made of robust carbon fiber are linked directly to the robot via a steel bar. A belt is also strapped to the subject's leg. Figure 2 shows LOPES gait exoskeleton. Sensory system in upper leg cuff

(a)

(b)

Figure 27. shows LOPES gait exoskeleton

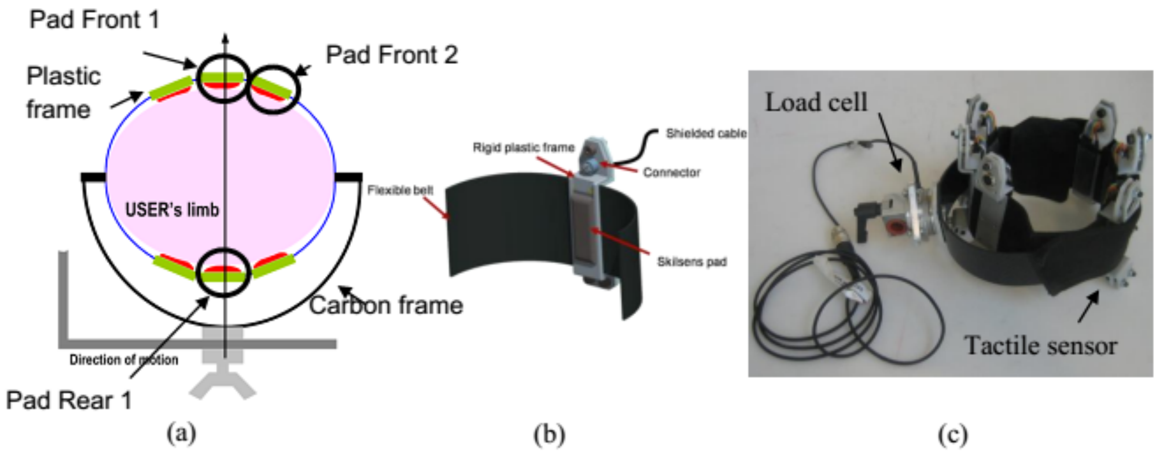

Figure 28 (a) the cross section of the sensor belt (c) an actual belt sensor

b) Calibrations- static loading

The precision and accuracy is assessed through calibrations of the sensors while in contact with the user. Since the sensors were used in, actual walking/ working conditions the following alterations were considered:

- ➢ The pressure distribution coupled with deformation profile loaded on the sensor differs from the controlled loading conditions.
- ➢ The sensors are custom made to adequately attach them to the thighs of the user.
- ➢ Where the sensors are situated, determine the manner in which the distribution of the force is done on the belt.
- ➢ There is a possible shift in the position of the sensor belt though it is unclear how this affects the final outcome.

Load cells measure the existing interaction between the point of contact with and the force produced (Racine 78).

6.5.5 No Dimension Outside of the Knee of 10cm (size)

6.5.5.1 Introduction

Exoskeletons are designed to help people with disabilities to recover control over their limbs, help increase the mobility of the persons with disability. In a broad perspective, an exoskeleton is the augmentation of human physical performance such as walking by applying bio mechatronics and robotics. It is achieved by introducing an external wearable framework to the body. Other terms used to refer to exoskeletons include Exo suit, robotic suit, exo-frame or powered armor [1].

Exoskeletons are designed to suit the body requirements of the patient. They are built using materials such as carbon fiber or metal. Some parts of the exoskeleton are made out of soft and elastic parts. Sensors and actuators are used to power these devices. However, some exoskeletons are completely passive and do not need any external force to power them [2]. Depending on its application the system can cover just the lower or upper limbs, the whole body or even particular body parts such as the hip or the knee.

This work presents the design of an exoskeleton to meet various different objectives. My individual responsibility in this work was to ensure that the dimension does not come out of the knee. Figure 1 shows the normal projections of the exoskeleton surface outside of the knee.

6.5.5.2 Discussion

The exoskeletons are wearable type and have projections outside the human body. The projection is one of the important criteria in the design of the exoskeleton. The projections must not be too high as it can become uncomfortable to the user as well as the surrounding people. These projections however cannot be completely avoided and has to limited to a particular value. One of the design criteria for our group is that the dimension outside the knee should not cross 10cm.

6.5.5.3 Design & Analysis

The design has to be in accordance with the design criteria. For keeping the projections lesser than 10cm the design must include certain factors and can be described as follows

Cross Members with lesser dimensions

The cross members used in the exoskeleton has to be made thicker and shorter. The By making it thicker the stiffness will increase and it will take more loads. Figure 2 shows the schematics of a normal beam to take vertical loads. The deflection of the cross member can be estimated using the formula

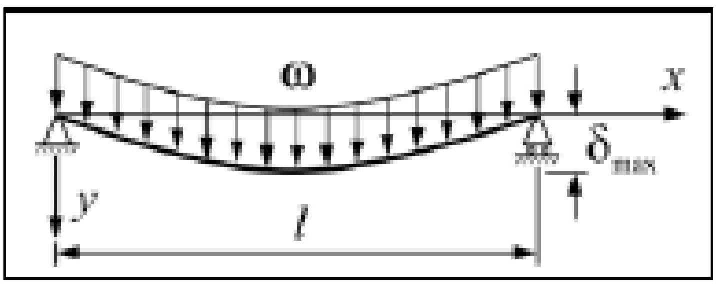

Figure 29. Schematics of a Beam supported at Ends [26]

The deflection of the beam is beam is given by

$$y = \frac{\omega x}{24EI}\left(l^3 - 2lx^2 + x^3\right) ------(17)$$

For the designed exoskeleton the projections can be taken as

l = 0.06m

x = 0.1m

ω = 10 rad/sec

E = 665Ksi

I = 400 mm^4

$$y = \frac{10 \times 0.1}{24 \times 665E3 \times 0.4}\left(0.06^3 - 2 \times 0.06 \times 0.1^2 + 0.1^3\right) = 0.00045m = 0.045mm$$

It can be assumed that the cross member is taking the load above. The deflection can be evaluated and the deflection has to be a very less value.

Component Material

The carbon fiber based material used for the exoskeleton. This material will be accompanied by certain metallic parts. The metallic parts must be light weight and strong. The weight of the designed exoskeleton will be 800 grams and the ultimate stress will be 665Ksi. Carbon fiber based material is the best option for the exoskeleton.

Axial Loading

The projection also depends upon the axial loads. The Figure 3 below shows the areas where the axial loads will occur. These areas must be stiffer so that the projection is not required.

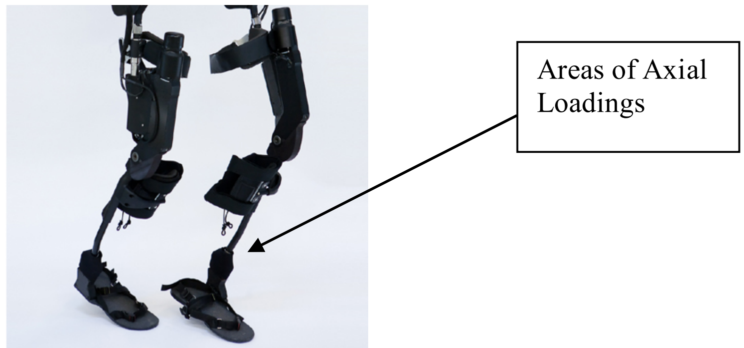

Figure 30 Exoskeleton With Areas of Axial Loading [27]

The loads at the specified areas can be large and can be considered as a beam that may buckle when experiences a large load. The strength of the beam will also account for the dimension of the exoskeleton outside the knee. The deflection load of the beam can be calculated as

$$Deflection\ load = \frac{\pi^2 EI}{L^2} - - - - - - - - -(18)$$

In the above formula E is the Young's modulus, I is moment of area and L is the length of the limb

The deflection load can be calculated using the values

L = 0.06m

E = 665Ksi

I = 400 mm^4

$$Deflection\ load = \frac{\pi^2 \times 665E3 \times 400}{0.06^2} = 7292E6\ N$$

The obtained deflection load is very large and will be able to take the desired load.

d) Adjustable Components

The exoskeleton is expected to be used by 13-75years age group. The dimension outside the knee is different for a 13-year-old boy and a 50-year-old adult. For accommodating both the requirements, we can introduce certain adaptive and adjustable components. The kneecap and the components coming in the area around the knee can be made adjustable.

6.5.5.4 Description of the System

The robotic exoskeleton will specifically be designed to improve the walking biomechanics of different individuals with the need of improving their walking. It will be designed in such a way that it will be able to serve a large group irrespective of the age. For this reason, the parts of the exoskeleton will be in such a way that they will not protrude too much. In particular, the system will include powerful motors as well as transmission systems that will be specifically responsible for helping the wearer at the ankle and knee joints [2]. For this reason, it will be important to design a system that can effectively adjust the exoskeleton's mechanical properties. This system will specifically involve the development of an exoskeleton that can assist individuals of all ages to walk. It will include the exploration of different elastic actuators and how they can be used to control the different surroundings.

The system is expected to be comfortable, lightweight, and safe as well as can be adapted by several users. For the purposes of achieving all this, carbon Fiber based material will be used for building the mechanical structure because it is light and has an appropriate resistance level. Again, it will be helpful in reducing skin irritation. The system also included components such as bilateral uprights, articulated footplates, a hinged hip and a support for the waist [1]. Additionally, it will incorporate an adjustment to the range of limb sizes so that individuals of all ages can be accommodated. The expected maximal walking speed of the system will be 0.8m/s and the extension of the knee should not exceed 1.5 degrees for purposes of preventing hyperextension. However, this can only happen if there is a misalignment between the exoskeleton and the person wearing it.

6.5.5.5 Design Specifications

For human use, it is important to ensure that the range of motion and the degrees of freedom are well specified to allow the wearer to be able to stand, sit and walk comfortably. Again, there will be a need to power the hip flexion, the knee flexion hip ab/adduction, the sagittal and frontal planes so that the wearer can use the exoskeleton comfortably and in balance. The sagittal and frontal planes are the human body movements in the front and traverse directions. Therefore, to effectively design the system, the peak torque should be set at 100Nm and the peak power more than 150W. Using these values, the spring should be having a stiffness of 800Nm/rad and an update frequency of 1000Hz. If the stiffness is set at that level, it will be possible for the wearer to move at a speed of 0.8m/s. however, it is also vital to have a spring stiffness that is higher so that it can be easier to control the closed-loop control bandwidth. Again, these high levels of stiffness will simply mean the deformations will be lower.

For complex exoskeleton systems, there will be a need to involve networked architecture in the design. In this way, the whole system uses EtherCAT E-Bus as the medium of connection while the medium of communication as the EtherCAT Fieldbus. These are important components aiding the communication between the computer and the networked slaves. For such a system, the sampling frequency should be more than 2000Hz. Again it requires Analogue-to-digital channels which are interfaced with the joint, spring and motor encoders [29]. These components make the system more effective and can work with respect to gravity.

6.5.6 Must Take Less Than 20 seconds to don/off

6.5.6.1 Introduction

Disability can occur during birth, accidents and many other reasons. A person with disability finds it very difficult to walk or move from one location to another. Many different systems are available to support the person with disability and to assist him/her to move from one location to another. These systems are designed after considering the extent of disability. The systems are designed in such a manner that it suits the person in requirement. Exoskeleton is a system that is used to assist the person with disability to move. The exoskeleton has an external frame that is attached to the body of the person with disability. The person with disability can instruct it through operation of some switches. The exoskeleton will move the person as per the instructions. The design of the exoskeleton is carried out in two main aspects. Mechanical aspects will analyze the design and the load carrying capacity of the structure whereas the electrical aspects will analyze the control system, dynamics, motors, wiring, ergonomic control on switches and others.

It need to ensure that the D_{on} and D_{off} for the designed system has to be lesser than 20seconds. For ensuring this condition it need to concentrate on the components used and the control system part of the designed exoskeleton. The mechanical counterparts in my group have to work upon designing the system that is in line with all the requirements. The Don and Doff time of the system will depend upon the mechanical design of the system.

6.5.6.2 Design Description

The final design of the exoskeleton is represented in Figure 1. A carbon fiber based material is used of the construction and all the required accessories and fittings are provided. The top and bottom portion of the knee will be covered with the structure as shown in the left side of the figure. The movement will be based on the motor as supplied by the supplier.

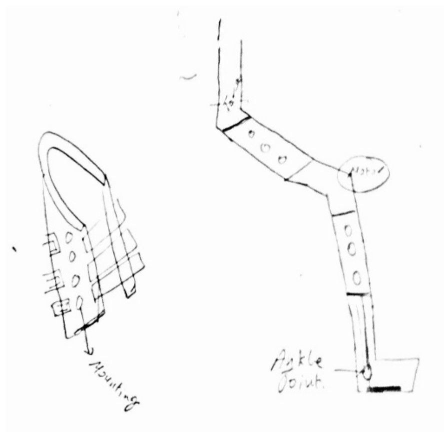

Figure 31. Final design of the Carbon fiber based Exoskeleton

The control of the device will be dependent upon the mechanical design, the motor used and the human weight.

6.5.6.3 Design Considerations

For maintaining the D_{on} and D_{off} below 20 seconds it has to look for certain design considerations and to inform the counterparts about the requirements which looks in the exoskeleton to get the required D_{on} and D_{off}. An analytical model will be first generated and the mechanical properties fulfilling the required criteria will be extracted from the model. Those criteria will be provided to other team members for proper design.

6.5.6.4 Model Generation and Analysis

The free body diagram of the system is shown in Figure 2. The force equation of this system has to be derived and various other parameters such as the time constant, damping and other properties can be estimated.

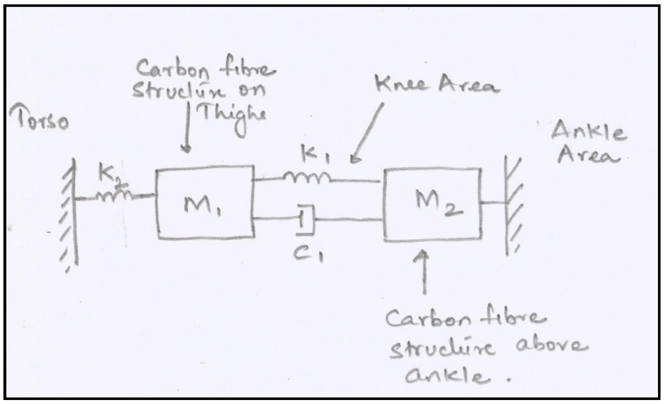

Figure 32. Free body diagram of the exoskeleton

The masses M1 and M2 are the carbon fiber structure that is attached above and below the knee. The movement at the knee will have both the spring and the damper movement. The system has two associated masses and the obtained transfer function may be of the fourth order. The analysis has to be thus performed through some software. MATLAB Simulink is can be used to find the total properties of the system. The damping and the frequency information can be extracted to maintain the time constant to a minimum value. The equation for a single mass second order system will be

$$Transfer\ fuunction = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \quad ----------(19)$$

This is the transfer function of the second order system.

6.5.6.5 Analysis Required:

The time constant of the system is the time taken by the system to settle within a particular value of the final steady state value. Time constant for a 2% settling time of a second order system has to be calculated using the formula

$$Time\ constant = \frac{4}{\zeta * \omega_n} --------(20)$$

ζ is the damping ration and ω_n is the natural frequency. The time constant should to be kept to a smaller value to keep the Don and Doff within the required value (< 20seconds). The system will be be kept as an under-damped system (0 – 1 damping ratio) [1]. Reason for taking the system as under damped is that in underdamped system oscillation and vibrations produced by the system reduced after some time. Whereas over damped and critical damped system produce the no oscillations and need external force to operate the system. For this machine if we need to apply the external force then the system is useless. Person with disabilities don't have the force that's why they cannot stand or walk. If they have the force then why they will use such system. So if the critical damped system or over damped system this machine is useless because the damping ratio will overcome only through the external force which is not possible here. So the system has to be underdamped to reduce the oscillations produced by the system and make the system stable for person with disability.

The rise time of the system also has to be evaluated and has maintained lesser than then Doff time. The rise time is the time taken by the system to reach the 90% of the maximum value for the very first time upon switch on. The peak overshoot of the system has to be evaluated through the analysis of the model. The combination of the time constant, rise time and the peak overshoot will decide upon the Don and Doff of the system. The rise time is give as

$$Rise\ time = \frac{\pi - \emptyset}{\omega_n\sqrt{1 - \zeta^2}} ---------(21)$$

$Rise\ time \leq 10\ seconds$ to make the system $D_{on}\ and\ D_{off}$ in less than 20 seconds.

$$\zeta = 0$$

$$w_n = \frac{pi}{10} = 0.314\frac{rad}{sec}$$

$$\zeta = 1$$

$$Time\ constant \leq 10$$

$$w_n = \frac{4}{10} = 0.4\frac{rad}{sec}$$

$$w_n = 2\pi f$$

$$f = \frac{w_n}{2\pi} = \frac{0.314}{2\pi}$$

$$f = 0.05\ Hz$$

$$w_n = 0.4$$

$$f = \frac{0.4}{2\pi}$$

$$f = 0.0637\ Hz$$

So the frequency of system would be between 0.05 Hz to 0.063 Hz for $D_{on}\ and\ D_{off} \leq 20\ seconds$

6.5.6.6 Material for the control and actuation activities

The material used for the control and actuation has to have quick response. In addition to the quick response the system must not load heavily in the structure in which it is mounted. The actuation mechanisms have to be designed to take quick control with a less lag [2]. The torque supplied by the motor has to be within the specified limit and it must be able to attain the required torque in a very small time.

6.5.6.7 Mathematical Calculations

The system has to D_{on} and D_{off} in less than 20 seconds and this value will depend upon the performance of the components in the exoskeleton. The performance of the motor and the torque generated must be within the limits.

$$Torque = \frac{Horse\ Power}{RPM} ---------(22)$$

The RPM requirement for the exoskeleton is very less thus the torque can be set at a considerably high value.

Horse power taken for such motors is high. Horse power for the motor is 2

$$2\ horse\ power = 1491\ watts$$

$$RPM\ for\ the\ motor = 5$$

$$Torque = \frac{1491}{5}$$

$$Torque = 298\ Nm$$

So this is torque which we need for the design of this project. This is a very high torque and it can easily bear the load of person and can hold the person. So for the design of this project we need two things to estimate, one is torque which we have determined is around 300 Nm. And the second thing about the system is we need to keep the zeta in between 0 and 1 to make the system under damped.

7 IMPLEMENTATION

The design as finalized for the implementation had some issues with the practical implementation. The main issue was with respect to the cost. Composite carbon fiber is an excellent material in terms of the strength and weight. It can take sufficient load and is light weight; however, the associated cost was too high. It was thus decided to replace the composite fiber material with other similar material having almost equal strength. After a detailed market survey, it was found that thermoplastic material is having similar properties as that of the composite fiber. We had to compromise slightly with respect to the strength of the newly selected material. The thermoplastic is a polymer based material that is having sufficient strength at the room temperature. This material loses its strength when subjected to high temperature. Except for the material change no other design changes were made.

7.1 Analytical Analysis

The present study analyzed the normal gait and the slow gait in healthy subjects belonging to a sample of young adults, which could limit the transfer of the results to other population groups with ages or different sociocultural context. As for the evaluation of the gait with the Hybrid device, as a consequence of the little availability of the exoskeleton and the prolonged time necessary for the collection of data with each subject could be analyzed a reduced number of subjects carrying the device [35]. This fact could limit the acquired knowledge regarding the functioning of the device, as well as the adaptations and modifications in the interaction with the subjects. . We analyzed the inclusion criteria of these subjects and planned their analysis in the laboratory during the investigation. However, the difficulty of contacting a sample with a spinal cord injury that met the established inclusion criteria, as well as the availability of the Hybrid device, made it impossible to evaluate the system with these patients. In this research, the parameters of the gait and the variables of the lower limb that will be fundamental to develop the exoskeleton in the physical part as in the mechanical part were analyzed [35]. In addition, the flexion/extension angles of each of the joints were obtained, which can be used to control the mechanism.

The design will include the use of Aluminum 6061 t-651 for the structure. This will allow for the design to be able to support weight of up to 50kgs. In addition, the design will include use of thermoplastic material to cover the legs for purposes of improving on the strength of the material, allow for comfort of use, as well as improve on the covering of the legs while in use [36].

The information below shows the properties of the material selected for the structure, Aluminum, for purposes of working effectively.

Wt% - 95.8 to 98.6

Density – 2.7 g/cc

Tensile strength – 310 Mpa

Tensile yield strength – 276 Mpa

Fracture toughness – 29 Mpa-m1/2

Elasticity resistivity 3.99 – 006 ohm-cm

Melting point 586 – 652 ^{o}C

Based on the design, the team seeks to improve ensure that the structure of the design is hard enough to be able to carry a load weight of maximum 50kgs. In addition, the structure toughness and elasticity should be in such a manner that the design remains effective for use and also be long lasting. For the team to attain these properties, Aluminum provides the best results compared to other materials, such as steel.

7.2 Design Change

Design changes is the part that help the team to improve the design to achieve the goal of the project. These changes started at the beginning of the first semester. Design changes have already made some problems for the team such as finding the best material and this problem happened due to the cost of the materials. The team has faced problem with building the design to make it adjustable by following the customer requirements. Moreover, thermoplastic materials are fairly hard and can resist wear. In Hardware review1 where the team had done completing 50% of the project as it is shown in figure 33. At the same time, the team planned to finish the rest of requirements of the projects. First, building a few different sizes of feet plate and change the plate's material due to heaviness of the design. Also, attaching thermoplastic materials to the project has a benefit, since they have good resistance to chemicals and can take sufficient amount of load.

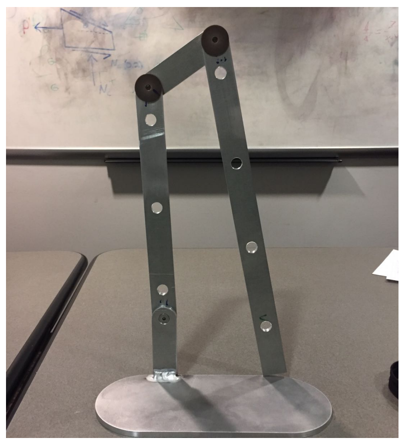

Figure 33. 50% of the Project

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