Lerner Exoskeleton I

Preliminary Report

03/24/2017

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

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, for adults between (13-75) ages old. 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 knee joints [1]. The goal of our exoskeleton is to design an adjustable system that 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 to design a system as well as ensuring that it is able to function as required, because the client already offers the motor. 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. Because the team is willing to adjust different sizes of users' limbs as well as accommodate people of different ages between (13-75) ages, make it easy to doff/don, minimize on the skin irritation by the physical interface, low profile foot portion, make it lightweight and strong material. By attaining these specifications and client's requirements, the team will have accomplished its mission in improving the exoskeleton design.

1.2 Project Description

Haptics 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 [1]. 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.

Figure 1 Adjustable Human-Exoskeleton Mounting Interface

1.3 Original System

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.

1.3.1 Original System Structure

The original structures for the robotic exoskeleton made for purposes of suiting people from different age groups. Walsh and Massachusetts Inst of Tech Cambridge Media Lab 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 others are designed to be bigger, for use by adults [2]. 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 aimed at ensuring that the users are comfortable and that the designs serve their intended purposes.

1.3.2 Original System Operation

According to Walsh and Massachusetts Inst of Tech Cambridge Media Lab state that the original systems come in different forms, where there were those that controlled by the users and those that controlled by another party other than the users [2]. The design is fitted with sensors and operating systems that allow 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 designs served their purposes in an effective way despite the different forms of challenges that are experienced [3].

1.3.3 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 strength 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.

1.3.4 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 upon. 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 needs 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 viable. 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 customer needs, the team weighted these requirements from 0 (less important) to 5 (most important) as shown in the Table1.

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

Between the requirements that were obtained from our clients, the top weighted are providing a rigid mounting points and making the design lightweight (<0.75kg/limb). Both of these requirements have weighted 5 out of 5, since the team discussed them with the client and he mentioned that they are the most important requirements in this design. Toward achieving success for this design is to make sure that the team is meeting the most significant requirements as mentioned in the Table1.

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. Certain 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.

Table 2. Engineering Requirements

Customer Requirements	**Corresponding Engineering Requirements**
Providing rigid mounting points to foot shank and the thigh	Yield strength of X and Modulus of Elasticity X
To allow the design to be Adjustable.	Adjustable from 6” – X” on dimension from ankle to knee
To make the design easy to don/doff	Must take less than X 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 cm/in
Make the design lightweight	Weight of 0.75kg/limb or less
Strong	Volume constraint of X

2.5 House of Quality (HoQ)

The House of Quality 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 get 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 it 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 works 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 as described in Table3 :

Table 3. House of Quality

Customer Requirement	Weight	Engineering Requirement	Yield strength of X and Modulus of Elasticity X	Adjustable from 6" – X" on dimension fro[m] ankle to knee	Must take less than X seconds to dON/ dOff	All hypoallergic materials that touches the skin	No dimension outside off knee of x in/cm (size)	Weight of X lb/kg or less	Volume constraint of X
Providing rigid mounting points to foot shank and the thigh	5		5	5	4	5	3	4	4
Adjustable	3		5	4	4	4	4	3	4
Easy to doff/don	2		3	2	1	2	4	5	2
Minimize skin irritation by the physical interface	4		3	4	4	4	3	4	4
Allow the foot portion to be low profile and insert into normal shoes	4		5	3	4	3	2	4	4
Lightweight	5		4	5	5	5	4	3	5
Strong	5		4	5	4	3	5	2	4
Absolute Technical Importance (ATI)									
Relative Technical Importance (RTI)									
Target(s), with Tolerance(s)			Max +1	+/-1	0	0	0	+/-2	+/-1
Testing Procedure (TP#)									
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 stated by Haruhisa, Ueki, Ito, and Mouri, 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 [5]. Haruhisa adds that the latter was focused on developing technology that was assistive in nature for the physically challenged individuals [5]. 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 viable 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

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 advancements 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

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

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 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 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 Depth of Focus hip, as explained by Mankala, 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 Functional Decomposition

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. Therefore, for all the limb movement a control signal has to come from the brain. Thus, 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.

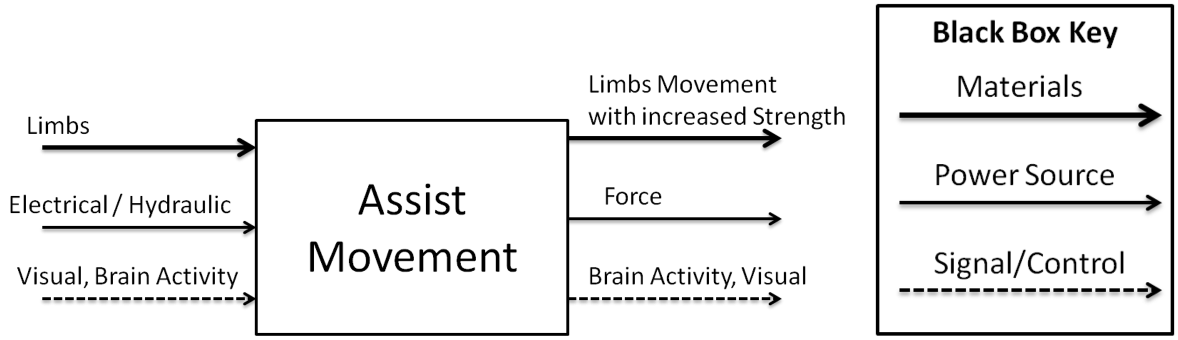

Figure 5. Blackbox Model

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

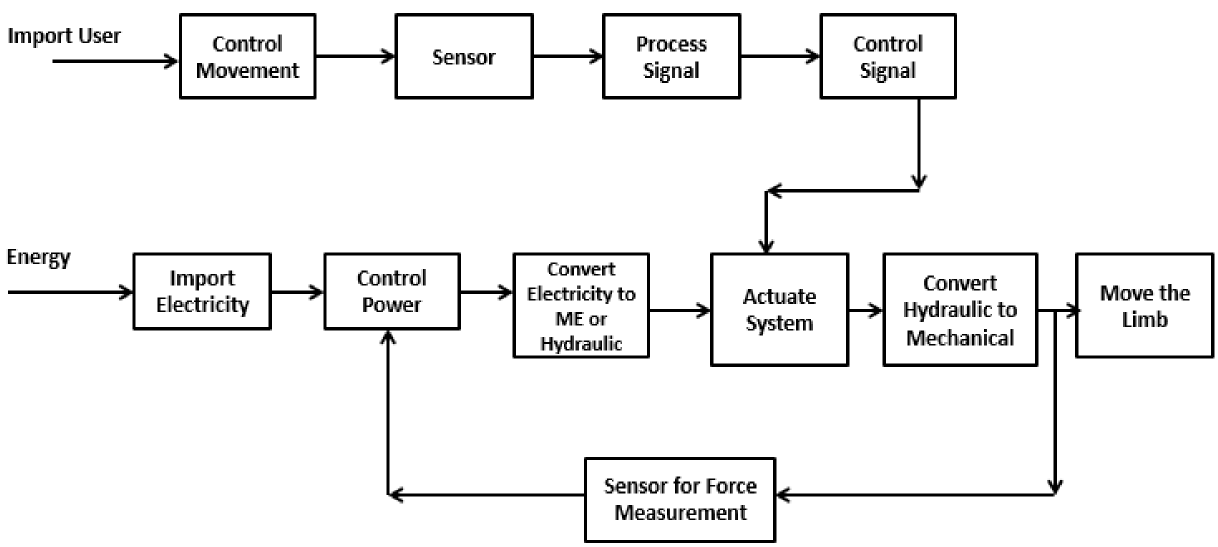

Figure 6. Functional Model

4 DESIGNS CONSIDERED

8 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. All of these designs will be demonstrated 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.

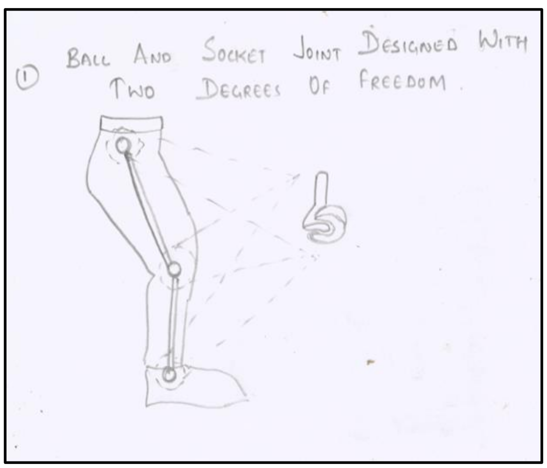

Figure 7. Joint with Two DOF Exoskeleton

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.

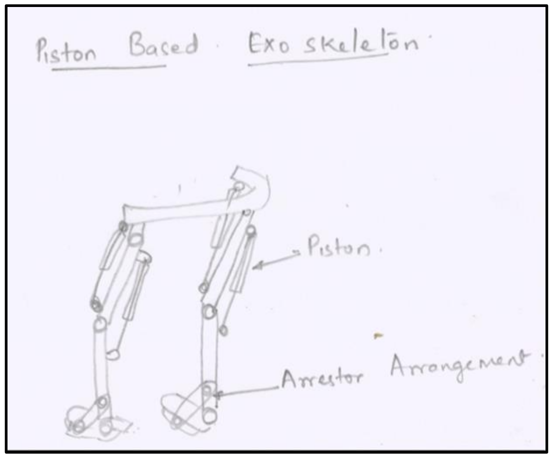

Figure 8. Piston Based exoskeleton

4.3 *Design #3: Battery Powered 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.

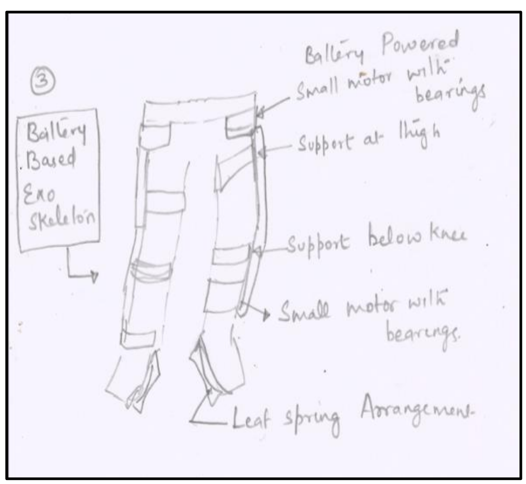

Figure 9. Battery Powered Exoskeleton

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.

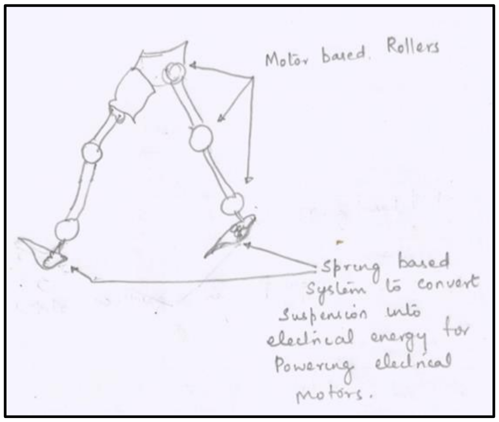

Figure 10. Motor based Rollers for exoskeleton

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.

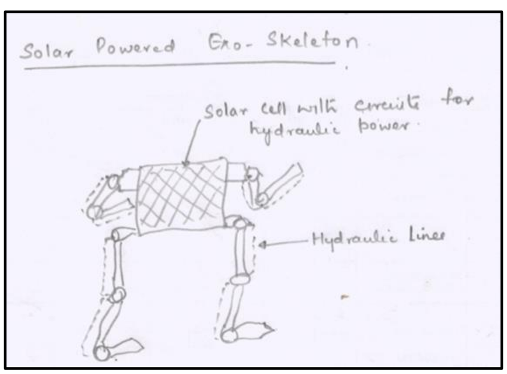

Figure 11. Solar Powered Exoskeleton

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.

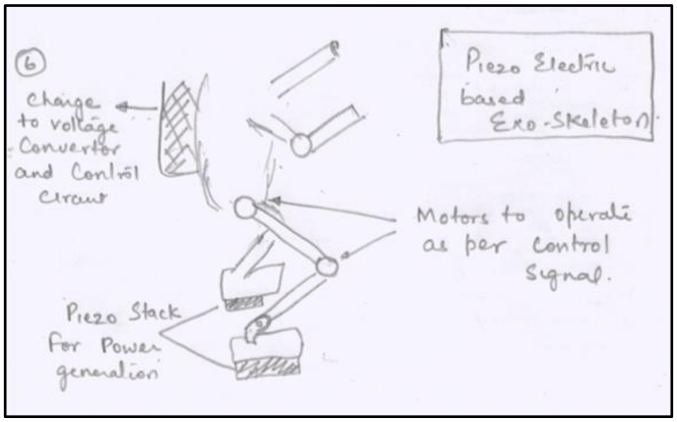

Figure 12. Piezoelectric Based Exoskeleton

4.7 Design #7: Exoskeleton with spring load mechanism

The spring load mechanism will be typically as if a wristwatch 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.

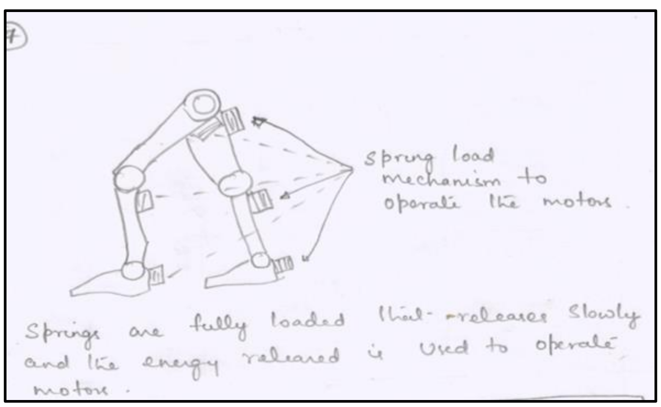

Figure 13. Exoskeleton with spring load mechanism

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.

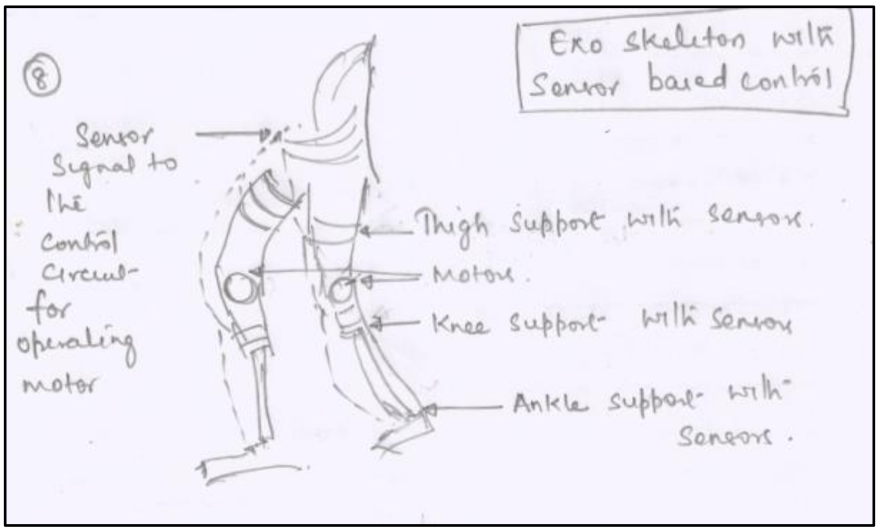

Figure 14. Exoskeleton with sensor based controls

5 DESIGN SELECTED

All the proposed 8 designs were thoroughly analyzed and the design criterions were considered

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

to converge at top three. The best among the three were considered for the design was design 3.

5.1 *Rationale for Design Selection*

The final selected design was design 3 as shown in Table4. 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 Table4 below:

Table4: 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	+	-	+		-	-	+	-
$\sum +$	5	2	6		3	3	4	0
$\sum -$	2	5	1		4	4	3	7

The Pugh chart in Table4 shows that designs 1, 3 and 7 are good in terms of design criteria. Design 3 is on the top and seems to be perfect for the customer requirements. The selected designs were further confirmed using the decision matrix as shown Table5:

Table5: Decision Matrix

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.

5.2 Design Description

The proposed design 3 is a battery powered exoskeleton design that uses chargeable batteries. The battery and its circuit will be positioned at both ends on the waist. Two batteries will be used for uniform mass distribution and proper positioning.

5.2.1 Components Involved

The main components involved in this design will be:

- Battery and the associated circuits.
- Motor for driving the exoskeleton.
- Mechanisms to transfer the power from Motor to the exoskeleton.

Apart from these three main components, the proposed design will also have many other sub components such as frames, bearings, cushions, connecting buckles and many others.

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. The design to small sized high power output batteries circuit will be a challenge. However, modern Lithium-ion (Li-ion) batteries have smaller size and can deliver large power. The usage of Li-ion for the proposed design can be considered.

The motor must be small and capable to deliver high torque. Servomotors can be used for this application. These are DC motors with high flux density to supply maximum power. These motors have long life and high torque to inertia ratio.

The mechanisms for power transfer also have to be looked into. Gear and pinion arrangement is the best option for power transfer mechanism. The gear can be adjusted as per the load requirement. The gear design has to be modeled in some modeling software and checked for its capability to handle the required load.

Other accessories such as frames, cushions and connecting buckles have to be appropriately chosen to withstand the load and to provide maximum comfort to the users.

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.

Electrical analysis is required to access the power output capability of the battery, characterization of the servomotor and the power output capability.

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.

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