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DESIGN AN AUGMENTATION EXOSKELETON TO ENHANCE LIFTING STRENGTH

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ABSTRACT

This paper describes the process of a team of mechanical engineering students in designing and simulating an easy to wear augmentation exoskeleton device. The goal of the project is to develop a fundamental technology associate with the design and control of an upper-body exoskeleton that augments human arm strength and endurance during lifting motion. The technology is intended to be used by military soldiers who are required to frequently lift more than 100 pounds objects, such as heavy machinery, tank ammunition, etc.

This proof of concept design focus on providing and supporting both arms with considerable strength to lift more than 100lb objects. A powered exoskeleton is a skeleton-like framework worn by a person and assisted by a power source that supplies the energy for limb movement. Exoskeletons can be regarded as wearable robots. This mechatronic system is designed around the shape and function of the human body, with joints corresponding to those of the person it is internally coupled with. Powered exoskeletons are primarily built to assist or protect the wearer. They could also be designed for police officers, work in rescue operations after disasters or working in toxic environments. The uses are limitless, and an exoskeleton could provide benefits in nearly any field. This paper focuses on designing and simulating a complete wearable vest with the purpose of increasing the arm strength and have a nearly full range of basic motion of the arms. Some of the features of this exoskeleton include wearable, light weight, portable, and sturdy which can be subjected to heavy load. The exoskeleton device mainly consists of two sections: one is the wearable body vest, including an enclosed structure, wearable straps, power cables and motors, and a connection mechanism of cables to the wrists; and other one is EMG sensing and Arduino control system, with EMG attached to bicep muscles on one of the upper arms to actuates motors.

During the service period, military soldiers must lift heavy objects many times a day, which requires high energy consumption and high strength of the arms. The constant lift heavy objects cause injuries and low efficiency. With this wearable exoskeleton device, the soldier's injuries will be reduced, their lifting performance will be increased, and the work efficiency is also increased.

This paper will discuss how the wearable exoskeleton device is developed and discuss how the performance and efficiency of such device are evaluated.

Keywords: Augmentation device, Exoskeleton, EMG sensor

1. INTRODUCTION

In the modern battlefield, soldiers are usually companied by mechanized equipment like tanks, and they are required to perform tasks with high arm strength to load the tank with munition. In the real battlefield, for example, an AT-6 spiral anti-tank missile has an approximate weight of 70 pounds. Soldiers need to load them frequently. With all strategic equipment on soldiers, they will need to carry over 100 pounds weapons through their arms daily. Such extensive use of arm to lift or carry heavy objects results in injuries on soldiers. It also reduces the efficiency of the work. The purpose of the human augmentation skeleton project is to develop an easy to wear vest that can help military soldiers to lift 100 pounds objects and significantly reduce muscle fatigue. The feasibility of the project is demonstrated by using light-weight materials, effective motorized structure and EMG sensors attached to human biceps. The potential market for this type of device is huge. Now, the exoskeleton has been given increasing attention from 2010. According to ABI research [1] which predicts the robotic exoskeleton market, the anticipated total market will reach to $1.9 billion in 2025.

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Note that this project also served to meet the authors' undergraduate senior design project requirements, including the stipulation that it be completed within two academic semesters.

2. PRELIMINARY RESEARCH

Several industrial and military companies have developed some devices to relieve people's arms. Ford [2] has an exoskeleton device called "EksoVest" that can support the weight of worker's arms and shoulders when workers are performing overhead tasks. Their schematic drawing is shown in Figure 1.

Figure 1: Ford "EksoVest"

GE [3] designed a whole-body suit for soldiers called "Hardiman". It can amplify human strength by a factor of 25. Neural controlled powered exoskeleton [4] utilizes genetic algorithms to predict human action and offer support to people's arms. Upper-Limb powered exoskeleton [5] design proposed by Washington University has 7 degree of freedoms which has high flexibilities and capable of performing complex tasks. Portable arm exoskeleton for shoulder rehabilitation [6] proposed by US army has rigid supporting structure which is super durable. The general structure can be seen in Fig. 2.

Figure 2: Portable Arm Exoskeleton by GE

This portable exoskeleton consists of five separate motors fixed on shoulder, elbow and back to magnify human strength. The total weight of this vest is over 20lbs and additional battery pack needed to power five motors.

Among those developed exoskeleton devices, Ford is the only organization putting their product into large manufacturing. Workers are indeed gained support from this type of vest. However, without motors integrated in the vest, it can only provide 15 pounds passive lift supports for labors' arms and shoulders. Most importantly, according to the article published on the Telegraph in 2019, each device will cost Ford around 5000 dollars which is impossible for large implementation in active labors. When looking at US army's portable exoskeleton, five bulky motors significantly increase the total weight of the device and make it hard to wear. None of the above exoskeleton devices is cheap or capable to provide sufficient force. It is the hope that this project can provide soldiers a light weight, durable, wearable, affordable and versatile device that can replace heavy lifting machinery in harmful working environment condition.

3. MECHANICAL DESIGN AND ANALYSIS OF EXOSKELETON DEVICE

3.1 Design Features

Based on the research conducted and the challenges observed, a method of using cable driven device to lift heavy object is developed. The device includes the following features:

1) The exoskeleton should easy to wear. This is necessary for the soldiers to wear the exoskeleton easily in the battlefield where time is precious, and even size of the exoskeleton is inconsistent with the holding user, it can be adjusted quickly.
2) The exoskeleton should be comfortable for long-time wearing. This ensures that the exoskeleton will not make the soldiers under long-running tasks uncomfortable. To aid this, it must be light weight, portable and sturdy which can be subjected to heavy load, and it should also be ergonomic.
3) The exoskeleton also has to ensure the maximum range of basic motion of the arms. The device is used in the battlefield, then the range of basic motion of arms would accelerate the mission and make multitasking feasible.

Once the features were incorporated in the design, the overall design of the exoskeleton consists of four modules: wearable module, structure module, power module and connection module, as shown in Fig. 3. And detailed discussion in each module will be described in section 3.2.

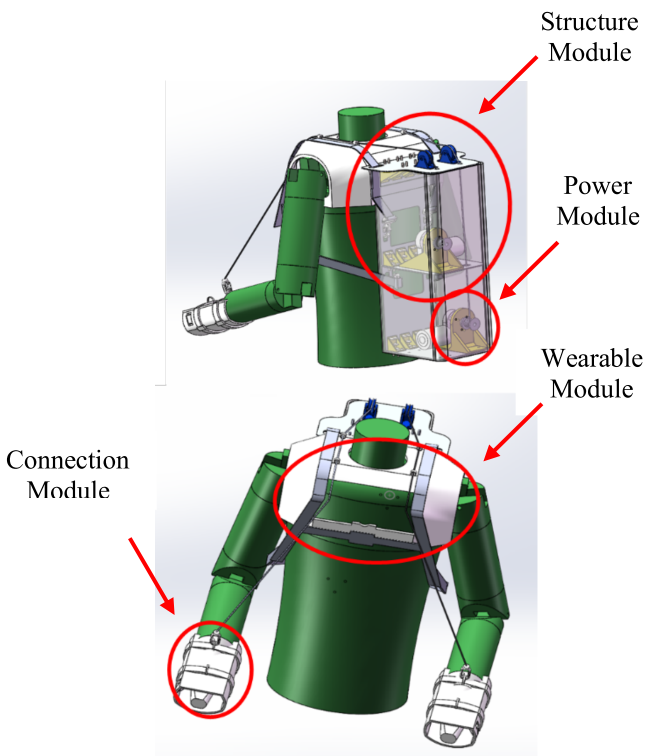

Figure 3: Exoskeleton Device Design Overview

3.2 Design Description

The mechanical design of the exoskeleton consists of four modules: wearable module, structure module, power module and connection module. The wearable module includes the X suspender and the shoulder patch. The structure module is the aluminum frame and the connectors. The power module contains the motor, motor base, pulley, and power supply. The connection module involves the cable, the wrist protector and the aluminum rings attached to it.

The exoskeleton is cable driven. The cable will pull with the rotation of the motor and lift the users' arms. The cable was attached to the carabiner, when the device is not in use, the cable can be simply removed. When the device is in use, users can buckle the carabiner to the rings, which was fixed on the wrist protector. The X suspender and the aluminum frame were connected through the carabiner that is easy for assembly and disassembly. General speaking, the motion of lifting the load by using the device contains six steps. First, the user will pick up the object he or she want to move, then the control system turns on and detect whether the user is taking the heavy stuff, if yes then the control system will transmit the signal into motor module and the motor will rotate and drive the cable. The motor rotates counterclockwise, the cable will tighten and lift the stuff upwards, as shown in Fig. 4-step 1 for the motion of the cable.

Second, as shown in Fig. 4-step 2, the motor rotates to the certain place, then it will stop and lock in that position, and the length of the cable will not change when the motor is locking there. In this step, the object is holding in the certain position due to the motor lock and the user can take the stuff away to the unloading place. Third, the user walks close to the unloading place with the stuff holding. Then, the user places the stuff to the unloading zone, and the control system senses the user is no longer holding the heavy stuff anymore, thus, the control system output the signal that let the motor rotates clockwise, which may loosen the cable and the user's arm will gradually lower until the motor reset to the original position. After those steps, the user will back to the loading zone and start the loop again.

In conclusion, the skeleton can reduce the muscle energy a human needed when lifting or holding the heavy stuff and make the process of lifting much easier so the user can repeat the process with less energy consuming.

Figure 4: Cable Assisted Arms Movement Diagram

3.3 Power Module

There were two ways to provide mechanical power to the arms. One is to use motors. The motor driven method required the users attach the motor to their arms directly that will increase the burden of the users and also limit the movement range of arms. Other one is to use cable to drive the motion of both arms. This method will reduce the burden for their arms, rather add the burden on the back of the users. Another good thing is that the cable can be easily removed when the device is not used, and the process of releasing is simple and easy.

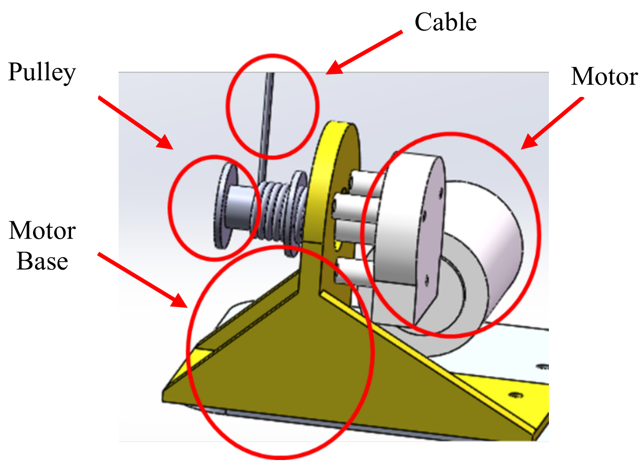

Figure 5: Cable Driven by Motor

The motor and cable are two major components of the power module, as shown in Fig. 5. The motor is selected based on the calculation of required torque and speed to lift a 100 lb object. The final selection is a DC high torque gear motor.

The energy supply of the device was considered. The main idea of the exoskeleton is to design an efficient device and the application is battlefield missions. Thus, the energy supply should last for a long time or it can be replenished quickly. Instead of using other forms of energy supply, the 12 Volt rechargeable battery will serve as power supply and it is attached to the aluminum frame through the Velcro. Again, the battery pack can be assembled and disassembled quickly.

3.4 Wearable Module

With wrapping the X suspender to user's body, the aluminum frame can be considered as a backpack. The alterable suspender makes the device suit for users in any body types and sizes. Both X suspender and the shoulder patch are made of soft materials that will reduce the force of the whole device acting on the users. Meanwhile, the X suspender provides an alterable surface, which is changeable according to user's body type. It also serves as slideway to restrict the cable from slipping away. Moreover, the suspender is connected to the aluminum frame through the carabiner that is convenient to maintain process.

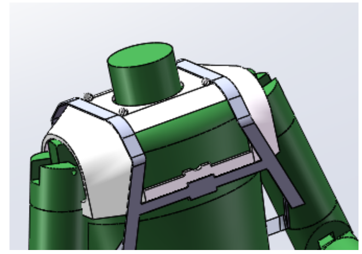

Figure 6a: Model of Wearable Module

Figure 7b: Real Product of Wearable Module

3.5 Structure Module

The aluminum frame is consisting of three aluminum plates and fixed by the 3D printing ABS connectors. Two types of the structure were designed and analyzed based on the design features, as shown in Fig. 7.

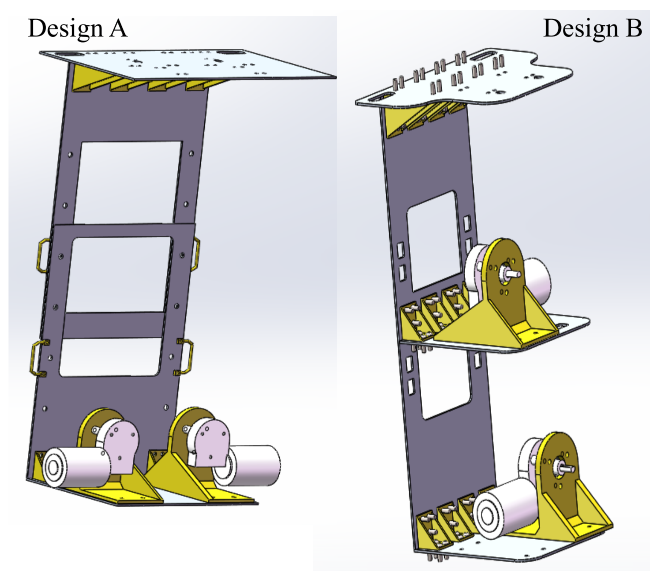

Figure 8: Two Structure Module Designs without Housing

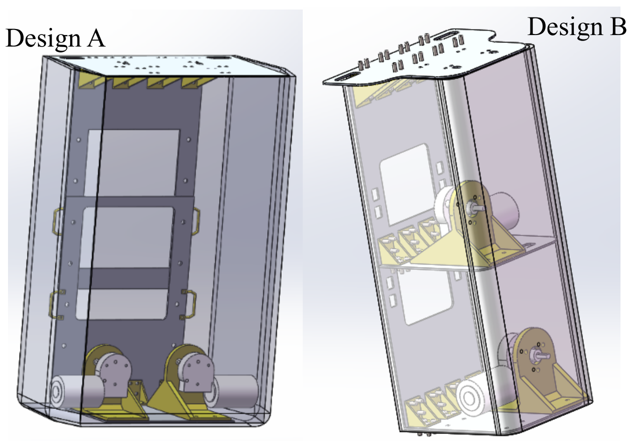

Figure 9: Two Structure Module Designs with Housing

The main difference between two types of design is the mounting location of the motors. Design A places two motors at the same level at the bottom frame, while design B places them in two different levels. The relative design feature of the aluminum frame is the second feature that the exoskeleton should be comfortable for long-time wearing. Design A aims to concentrate the weight at the bottom plate of the frame so using of material will be minimum, but it brings a problem that the width of the frame is bigger. However, the design should fit to 95th percentile male's dimensions [7]. Due to limited width of the exoskeleton, so the length of two motors will be larger than the width of the plate. As for design B, one of the motors is moved to middle level of the frame. Although it may increase the use of material, but the size of the frame in width can be decreased. Meanwhile, design B balances the weight and increases the space utilization. Comparing these two designs, deign B is more compact, decreases the width of the frame, and therefore makes the design more portable and closer to the design feature. So design B is chosen for future development.

The strength of the structure was analyzed by using ANSYS. Applying the 50 lb force on the upper frame, the deformation and stress of the supporting bracket and connecting bolt as shown in Fig. 9a and 9b. The simulated maximum stress is under the Young's Modulus of the material. Diameter for bolt is 5/16 inch (7.94mm) and it have shear strength 3.6GPa. The normal force needed to support objects is 50 pounds (222.264N). From the simulation, the bolts can provide sufficient support for the frame, and the structure design is feasible.

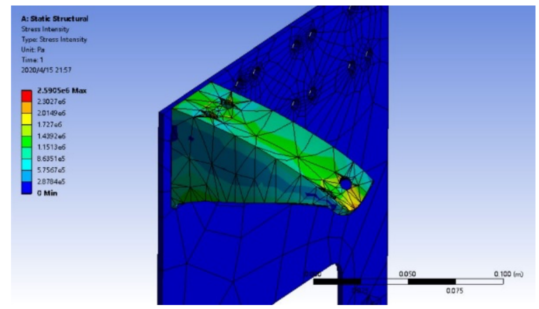

Figure 9a: Stress Distribution of a Supporting Bracket

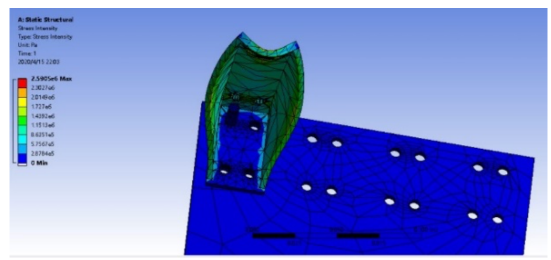

Figure 9b: Stress Distribution of a Connecting Bolt

3.6 Connection Module

The key to the connection module is the connection method of the cable. As the third design feature, the exoskeleton should ensure the maximum range of basic motion of arms, if the cable attached to the arms all the time, the friction will restrict the motion of arms and the cable may be damaged accidentally. Thus, the cable should not be attached to the arms all the time, so the connection method should able to tie or untie. However, the carabiners satisfied the requirement perfectly, the carabiners used in hiking, so they can be taken on or off easily and the loading capacity is large enough for the frames or shell. Therefore, the carabiner can serve as the good connection. As shown in Fig. 10a and 10b, the wrist protector is the perfect choice for the components attached to arms. For one thing, the fixed support is strong enough to protect the wrists and arms when lifting the heavy stuffs. For another thing, it provides the carabiner a place to fix the hook. Moreover, the fixed supporter can be adjusted easily that makes user in any body types can wear the device. Finally, the rings to the wrist protector was tightened by the cable, and the carabiners can attach to the rings when the device is used. Then, when the device is off, the carabiners can be taken off and the cables will not bother the user when the device is off.

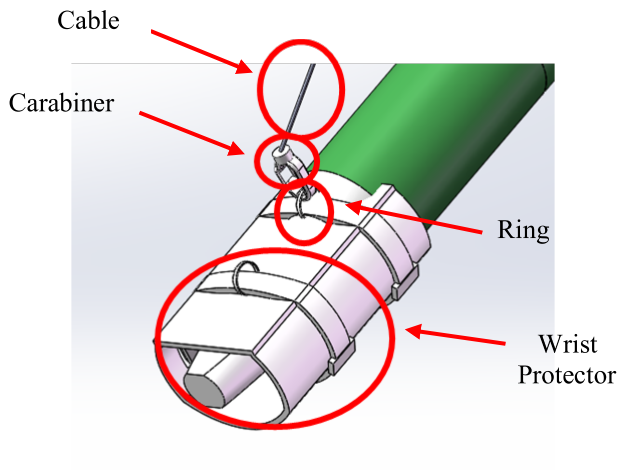

Figure 10a Model of Connection Module

Figure 10b: Real Product of Connection Module

In this project, four above mentioned modules are designed to achieve the functionality of the device. Power module verifies the torsional forces generated by motors, they are sufficient to provide 100 pounds lifting force. For wearable module, X suspender makes sure proposed project is easy to use and easy to adjust for any user. In structure module, a comprehensive stress analysis for exoskeleton is performed by using ANSYS. In order to maintain structural integrity while decreasing the total weight, a corrosion-resistant 3003 aluminum plate is used as the back support. Compared to stainless steel, aluminum has sufficient yield strength around 17,000 psi and low density around 173 lb/ft^3. Moreover, the back support of the exoskeleton can be manufactured using waterjet from a single plate. To further reduce the cost of the proposed device, all non-standard components were 3D printed in digital lab. In connection module, cables transfer torque into support force onto human wrists. Considering the potential harm to human wrists, a wrist protector is wrapped around lower arm. When the cable starts to give lifting force, the force will be distributed to larger area on human arm. Since wrist protectors and cables are always available on market, the cost and time to get them are very reasonable.

4. CONTROL SYSTEM DESIGN

Two control systems are considered to be applied in exoskeleton at the beginning of the design. The first one was to use motor to directly connect to elbow, as shown in Fig. 2. The other one is to use electronic motor with cable-driven mechanism, as shown in Fig. 3. Based on the research on ergonomic and considered comfort, price and portability, the cable-driven system is chosen and is more suitable for soldiers.

The motor with cable-driven system is controlled by pulse width modulation (PWM). The PWM signals are generated by an Arduino microcontroller by processing the input from certain pressure sensor. Therefore, it is important to choose a proper sensor to actuate motor in the control system

4.1 Sensor Selection

In the beginning of the design, three sensors were considered to actuate the exoskeleton device: (1) Direct switch, (2) Strain gage, and (3) EMG sensor. The brief introductions of these three sensors are below.

4.1.1 Direct Switch

A switch is fixed between thumb and index finger, as illustrated in Fig. 11a. The switch will connect to the microcontroller directly. Using preset several PWM values in microcontroller and gear adjustment of the switch control the speed of electronic motor in exoskeleton. However, in the actual situation, it is difficult for soldiers to operate the exoskeleton switch shown in Fig. 11b. And the operating speed is fixed by the preset PWM value, which will cause soldiers to feel uncomfortable during the moving process.

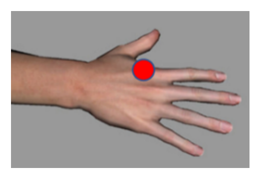

Figure 11a: Direct switch position

4.1.2 Strain Gage

The strain gauges [8] are supposed to place in the dense muscles area on the arms to measure the changes in the pressure during the arm moving process, so as to transmit the signal to the single-chip microcomputer, and control the operation and speed of the motor through the single-chip microcomputer processing signals. However, the difficulty of applying strain gage limits accurately detecting muscle changes. During the movement of the human body, the changes of muscles are very complicated, especially the dense parts of muscle groups. It is very difficult to detect such change with strain gages. Besides, in the process of soldier handling, the working environment of the sensor is poor.

Dust, sweat, jitter and other factors will affect the accuracy of the strain gauge.

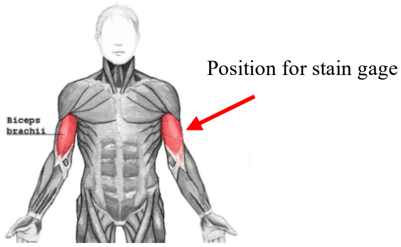

Figure 11b: Strain gage position

4.1.3 EMG Sensor

EMG sensor shown in Fig. 11c, electromyography (EMG) is the detection and recording of the electrical signal produced by muscle tissue as its contracts [9]. An electromyograph detects the electric potential generated by muscle cells, when these cells are electrically or neurologically activated [10]. In this way, during the process of soldiers carrying heavy objects, sensor can be used to collect EMG signals to determine the real situation of the solider. By processing the signal, the microcontroller can determine whether the electronic motor should be turned on or the proper time to turn off the motor. Compare to the former two methods, the advantages of EMG sensor are obvious. Using EMG to collect human body movement data, especially the data of human arm during movement is more reliable and accurate. At the same time, the EMG signal can conveniently determine the state of the human muscles, and the signal can be better fed back to the single-chip microcomputer, so as to make more intelligent and practical instructions. The disadvantage of EMG is that it is more difficult to learn and more complicated to control.

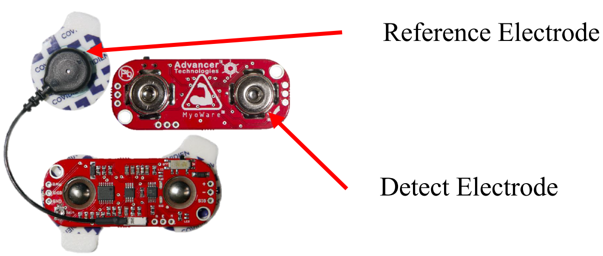

Figure 11c: MyoWare EMG Sensor [12]

Considering all the pros and cons of the three methods, EMG sensor is the best choice for our control system.

4.2 Using EMG sensor

Below are the instruction steps to use EMG sensor to sense the bicep muscle's tension changes.

1) Connect electrodes to the sensor's snap connectors
2) Place the sensor on the target muscle area, ie bicep [13]

a. Clean the target area thoroughly
b. Place the electrodes in the middle of the desired muscle. The other electrode should line up in the direction of the muscle length
c. Peel off the backs of the electrodes to expose the adhesive and apply them to the skin
d. Place the reference electrode on a bony or nonadjacent muscular part near the targeted area on your body.

3) Connect to a microcontroller. The final setup should be look like in Fig. 13.

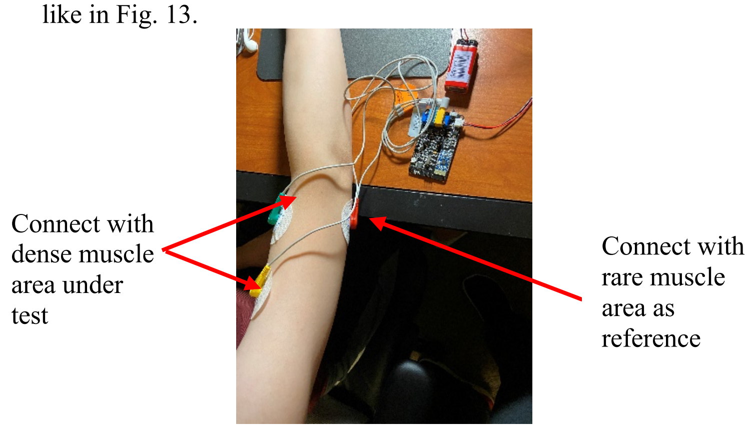

Figure 13: EMG Connection Instruction

4.3 Control Algorithm

4.3.1 Control Description

The control algorithm determines the movement of the exoskeleton corresponding to the certain input value (EMG measurement). The readings of EMG sensor are related to the level of soldiers' biceps movement. The output of the control system is the speed and torque of the motor. Due to the different type and sensitivity of EMG sensor, several values are needed to be determined by experiments before applying control algorithm in exoskeleton.

In this case, users can adjust according to their actual situation to determine the several certain values.

- Threshold: The input (EMG measurement) of one certain weight, such as 15 lb. This value is used to determine the minimum starting weight of the exoskeleton.
- Preset value: the preset value is used to compare with the average number by calculating difference between the threshold and the input data (real time). This value is used to measure the relationship between the current weight and the minimum weight to determine whether the exoskeleton needs to be shut down
- Preset degree: The angle at which the motor turns when the arm is bent from 140° to 75°, based on the research on ergonomics, this degree varies according to the radius of the motor.

4.3.2 Control Flow Chart

The general control sequence is described in Fig. 14. First step is to equip with exoskeleton and turn it on, then start carrying objects, the EMG sensor will detect related values and send it to microcontroller. If the input exceeds the threshold, the microcontroller will process the input and generate corresponding PWM to control the speed and torque of the motor. During the working process of the motor, the EMG sensor will be keeping detecting muscle situation to provide data to microcontroller in order to adjust electronic motor. Once the motor turns over the preset degree, the motor will be locked. After unloading the weight, the EMG will change rapidly. If the EMG changes exceed preset value, which means the soldier does not need the assistance of the exoskeleton, the exoskeleton will stop. However, the EMG sensor will be keeping working unless soldier turn off the exoskeleton.

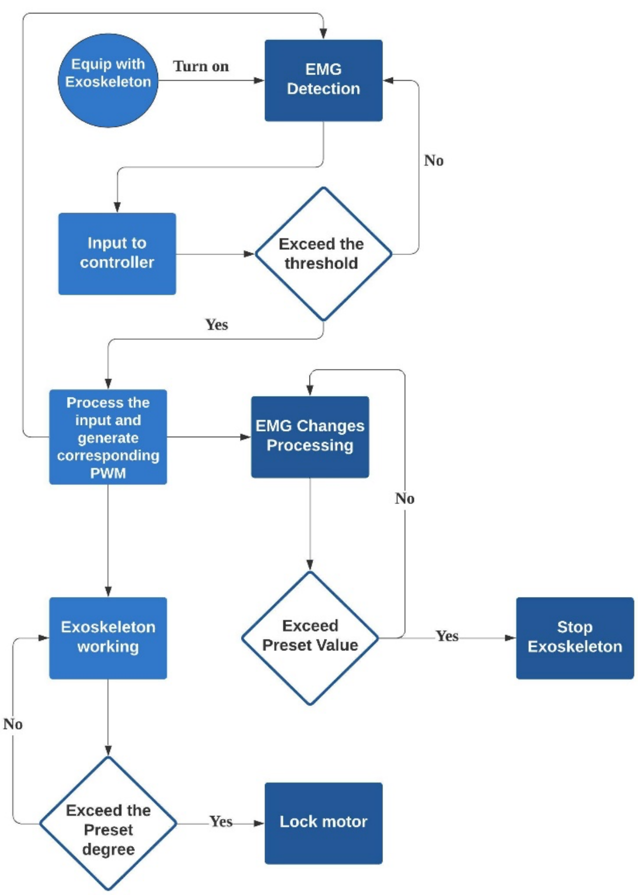

Figure 14: Control Flow Chart

4.4 Limitation

EMG sensors connected to Arduino board are equipped to closely monitor the biological voltage difference through human biceps. Based on the empirical relationship between voltage and activation limits, the proposed exoskeleton can activate motor when people use their muscle. Knowing the general size of human, the overall structure is flexible and suitable for majority of users based on ergonomic consideration. [11]

5. PROPOSED ASSEMBLY AND TESTING

5.1. Assemble Device

Components are either fabricated in machine shop or 3D printed in digital 3D printing lab. The assembly sequence should be clearly followed in order to have an ideal performance. As shown in Fig. 15a, vertical aluminum plate serves as a central board to support motors and straps. Both sides of the aluminum plate are cut to install straps which is wrapped around human's shoulders. Other three horizontal aluminum plates are fixed onto the central plate using 3D printed connection brackets.

Motor will be installed on the motor base first using standardized bolts. Then two motors with 3D printed motor bases are mounted to the middle and bottom plates, respectively. Two motors will face opposite directions to balance the weight. To ensure the strength of the connection between central plate and three other plates, via calculations, three separate printed connection brackets are needed to hold the motor and motor base. Fig. 15b shows the scheme of finished back structure. Each component is mounted by two pair of bolts.

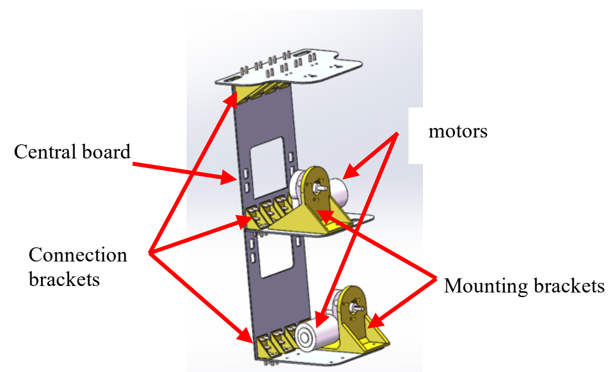

Figure 15a: Exoskeleton back structure

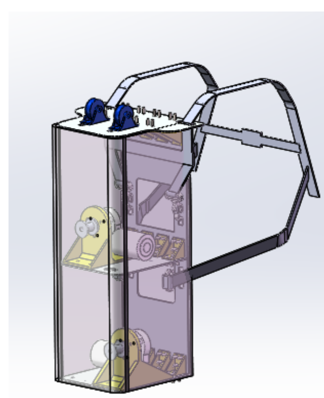

Figure 15*b*: Exoskeleton finished assembly

After mounting the pulleys and motors on the aluminum plate, the rope, straps and shield can be installed. Ropes are connected between wrists and motors. When EMG sensors detect sufficient voltage differences, the motors will be activated and generate torque on two cables. Two cables will transmit the tensions from torque into the normal forces acting on human's wrists.

5.2 Prototype Wearing Instruction

This section is to demonstrate a safe way to wear prototype. To wear the device properly, certain steps need to be followed. First, a user should put on the wrist protector by slip in, and adjust the hook and loop of the protector based on the size of their wrists. Then, the user will put on the exoskeleton device like putting on a backpack, adjust the suspenders until the suspenders hardly slip and adjust the shoulder straps to make sure the central board closely attached to the back. Next, the user will wrap the chest strap around the body and buckle it firmly. The carabiners should not be buckled to the wrist protector until the user wants to start the lifting task. When performing the lifting task, the user should pull the carabiner to the ring which is attached to the wrist protector on each wrist, then turn on the device. After the lifting task is finished, the user should turn off the device, then released the carabiners and buckle them to the shoulder straps on each side of the suspender.

5.3 Proposed Testing

The proposed testing is to reveal the relationship between EMG voltage difference and the weight of the object, therefore determine the threshold or the minimum starting weight for the device and the preset value to measure the relationship between the current weight and the minimum weight to determine whether the exoskeleton needs to be shut down. After successfully wearing the device, the relaxed voltage difference should be recorded first. Then, testers should start with 20 pounds object and monitoring the voltage change on biceps. Comparing to the relax value, testers should determine how much voltage is raised. Then higher weight may be lifted to obtain the empirical relationship between the weight and voltage raise. In order to get better resolution, the increment of weight should be as small as possible. The objective for this project is to lift a 100-pound object, so the data is collected within 100 pounds weight. Plot all the data points from 20 pounds to 100 pounds and collect them with straight line. Therefore, the users can roughly determine the voltage corresponding to different weights and the relationship between voltage and weight, so as to better program the control system.

6. CONCLUSION AND FUTURE WORK

The proposed project can provide military soldiers an ideal device which helps them effectively lifting 100 pounds objects in the battlefield. The total cost is reduced by using aluminum plates, 3D printed parts and standardized components. After simulating the distribution of stress using ANSYS, the general structural integrity is achieved. The animation generated by SolidWorks validates its feasibilities. The main task of our next stage is the fabrication and assembly of prototype. In the previous work, most of the tasks progressed smoothly. However, there were also some difficulties encountered, such as material selection and force analysis of some key parts; structural optimization and trade-offs; and improvement and testing of control theory. The following aspects should be considered in the future work.

For fabrication, as machine shops and makerspace currently closed for students, the real prototype is difficult to build. However, with all available codes, models and drawings in place, once the school reopen, we will be ready to have the prototype build. Ground Floor Makerspace at UC provides sufficient equipment needed to produce the exoskeleton. For Testing, the testing procedure needs to be designed in more details and more comprehensive. A more comprehensive schedule means to find an accurate relationship between the lift weight and muscle relief numerically so we can justify or convince that the device is helpful to military soldiers. For EMG, the position where EMG is deployed on human's arm should be accurately determined. As biceps can have viable biological voltage flow, it is important to determine the threshold experimentally for enabling the motor. Inappropriate setting may cause serious injuries when users perform heavy lifting tasks. The purpose of the experiment is to find satisfying setting for motor rotation speed, motor strength, sensor deploying position and voltage required to trigger the motors.

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