Design Report 1

Biomedical Device Design

MECH 4013

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Automated Chest Compression System

Introduction

The medical condition that is the topic for this design project is called a Cardiac Arrest or CA. This is a condition where the heart, the primary pumping/ blood supply organ in any living organism, suddenly stops beating/pumping blood[1]. This causes the person to lose bodily functions as disruption in the flow of blood to the brain may cause the person to lose consciousness[2]. This condition can be serious as, without swift attendance, organs might fail due to oxygen deprivation[2]. According to the Heart and Stroke Foundation, symptoms include irregular breathing, making a gasping sound, and being unresponsive to touch, among many more[2].
Also, according to the Heart and Stroke Foundation, 60,000[2] cases of cardiac arrest happen in Canada each year outside of a hospital, and the survival rate for an outside-of-hospital case is 1 in 10[2].

Immediate care like performing Cardiopulmonary resuscitation (CPR) or using an Automated External Defibrillator (AED) to shock the heart can save a life as they are an excellent first aid measure until professional help can arrive. AEDs are now being implemented to be accessible in public settings, but they are still not common[3]. As a result, CPR stands to be the only viable and quick method that is used by medical personnel or anyone trained to perform it.

Cardiopulmonary resuscitation or CPR is a procedure where the patient's chest is compressed by a bystander in order to keep blood flowing to vital organs as the heart is unable to beat/pump[4]. As professional help can take some time to arrive, CPR is performed to keep the blood supply going.

But there are cases where there are no people available nearby to perform CPR or to call emergency services, and vulnerable populations like the elderly and people with heart conditions need constant supervision but, due to socioeconomic factors, are unable to have someone supervise them 24/7 and even if there are people nearby, they are unable to properly perform CPR due to lack of training and education.

In cases like this, an automated contraption that can perform rhythmic chest compressions and also sound an alarm to alert nearby people and notify emergency services can save someone's life. This automated system is intended to work in conjunction with any type/brand of smartwatch, which can monitor vital signs, and the system itself will also have a built-in accelerometer that will be able to detect a fall, that can happen as the patient has a high possibility of collapsing when a cardiac arrest is underway. When the device detects signs of cardiac arrest, it will turn on and perform CPR with the help of three inflatable pouches that will compress the entire chest cavity in a rhythmic pattern and will be pulled on both sides with the help of elastic straps connected to a power unit strapped at the back of the patient. The patient is to wear this device with the help of shoulder and chest straps, like a backpack.

Design Inputs

For a device like an automated chest compression system, design inputs need to be considered based on what this device is trying to achieve. In our case, the device is looking to perform chest compressions in a rhythmic manner. Among many considerations, four major design considerations/design inputs/functions can be narrowed down to,

- Amount of force needed for compression
- Sensors and monitoring subsystems
- Mechanical design and material selection
- Safety and ease of use

The four design inputs mentioned are among many other considerations, but the four mentioned can be deemed to be the most important ones based on the primary objectives of this design project. Now, going into detail about the design inputs,

Amount of force needed for compression

The process of performing CPR needs to be done in a precise manner as too much force application can cause other problems like shattering a rib, and too little force application will not displace enough blood to make a meaningful difference.

According to sources, compressions should be performed at a pace of 100-120 compressions per minute[5], and the device is designed to perform exactly 120 compressions or cycles per minute, with 2 cycles being performed every second. The chest needs to be depressed no less than 2 inches and no more than 2.4 inches[5], and according to the American Heart Association (AHA) guidelines, to compress the chest 1.5-2 inches[4], around 100-125 lbs of force[4] is required and in this device, the amount of applied force is will be limited to 130 lbs.

To exert this amount of force, two brushless DC servo actuators will be needed on both sides, pulling on the elastic straps.

Sensors and Monitoring Subsystems

In order for the chest compression process to start, it will need to detect physical signs of cardiac arrest, which, according to the National Heart Lung and Blood Institute of America, are collapse due to lack of oxygen, shortness of breath or gasping for air, loss of pulse and decrease in cardiac activity [4].
The device designed in this report will look for sudden falls or collapses via an accelerometer embedded into the power unit, loss of pulse detected via a smartwatch, and irregular expansion and compression of the chest detected by an integrated pressure sensor, something which is offered by the company Adinstrument[6] as the patient will most likely be gasping for air during a cardiac arrest.

Activation of the compressions by the device is designed to trigger when it detects feedback from at least two of the three integrated feedback systems as though common, a sudden fall in not always guaranteed as the patient might be on a wheelchair.
The deploy time for the chest compressions is set to 10 seconds after detection, and additional sensors include network modules to send notifications to an assigned phone number and also a siren, which will alert nearby people.

Mechanical Design and Material Selection

The system can be divided into two separate parts. The first part is the three interconnected inflatable pouches, which are connected by lightweight stainless steel type 304 in accordance with ASTM A240 specifications for a stainless steel plate[8] that goes onto the chest of the patient and a primary housing unit that will contain the mechanical and electric components like the servo actuators, power supply and the accelerometer.
The housing is designed to be ergonomic with the shape of the back and will house the critical sensors mentioned before.

The inflatable pouches are made from flexible material similar to what is found in life jackets, and a carbon dioxide container will be housed in the back housing to inflate the pouches. Specific material properties will be discussed in the Preliminary Design/Design Output section.

Safety and ease of use

Since medical devices regarding cardiovascular health and sensitive to false alarms and triggers, safety mechanisms like a kill switch are built into the right side strap connecting the power unit to the pouches.

One more safety feature to avoid a false alarm is the fact that the device will activate and start compressions only if it detects input from two of the three integrated sensors mentioned, the pressure sensor and the heart rate sensor on the smart watch as mentioned before, the accelerometer might be triggered by other factors like during transportation, hard braking on the road might be registered as a fall.

Besides, all the materials used in the construction of this device are certified to be used in medical devices according to international standards.

This device is meant to be certified as Class 1 biomedical electrical equipment[9], which implies that the device has its own insulation/grounding built in as all of the electrical equipment will be housed inside of the protective hard shell in the form of the power unit at the back.

Preliminary Design

In this section, the detailed engineering Drawings and materials used in the construction of this device are shown.

- **Inflatable Pouch**

Fig 1: CAD model of singular inflated pouch

The material used in the construction of these pouches is the same type of material used in life jackets, which is a nylon-based material with a yield strength of 140Kpa [10], and the standard followed by life-jacket manufacturers is ISO 12402[11]. This is a high strength material that is also wear and tear resistant.

The dimensional specifications of the pouches are shown below with the detailed drawing.

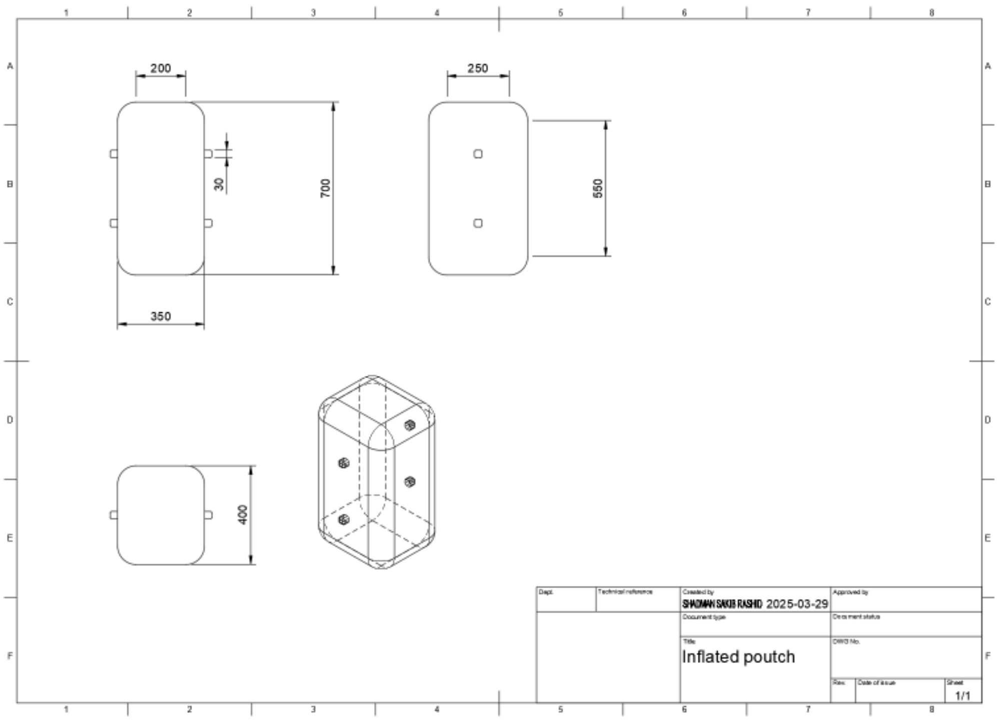

Fig 2: Dimensional drawing for inflated pouch

- **Power supply housing unit**

Fig 3: Power supply unit

The power supply unit will house mechanical components like the DC servo motors, the geartrain, power unit, accelerometer sensor, and a cellular communication module.

The construction material used in the housing is a high-grade polycarbonate material by SABIC's LEXAN healthcare resins, in particular, the product offered by them called HPS9NEU[12], which is a biocompatible polycarbonate material adhering to ISO10993 or UPS Class VI for medical devices which are safe in limited contact with the skin and offer excellent durability[12].

The dimensional characteristics of the power unit housing are given below.

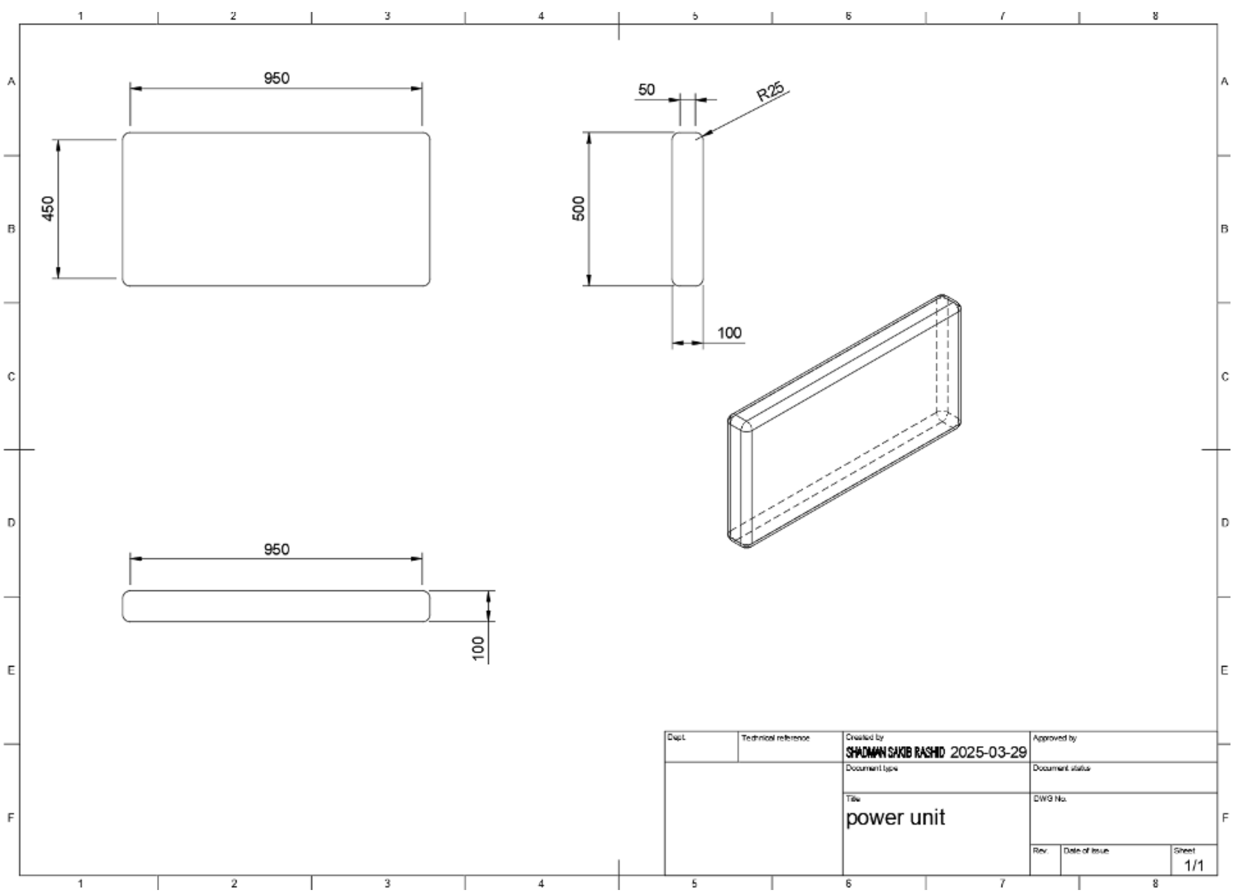

Fig 4: Detained engineering drawing of the power supply unit

- **Stainless steel linkage**

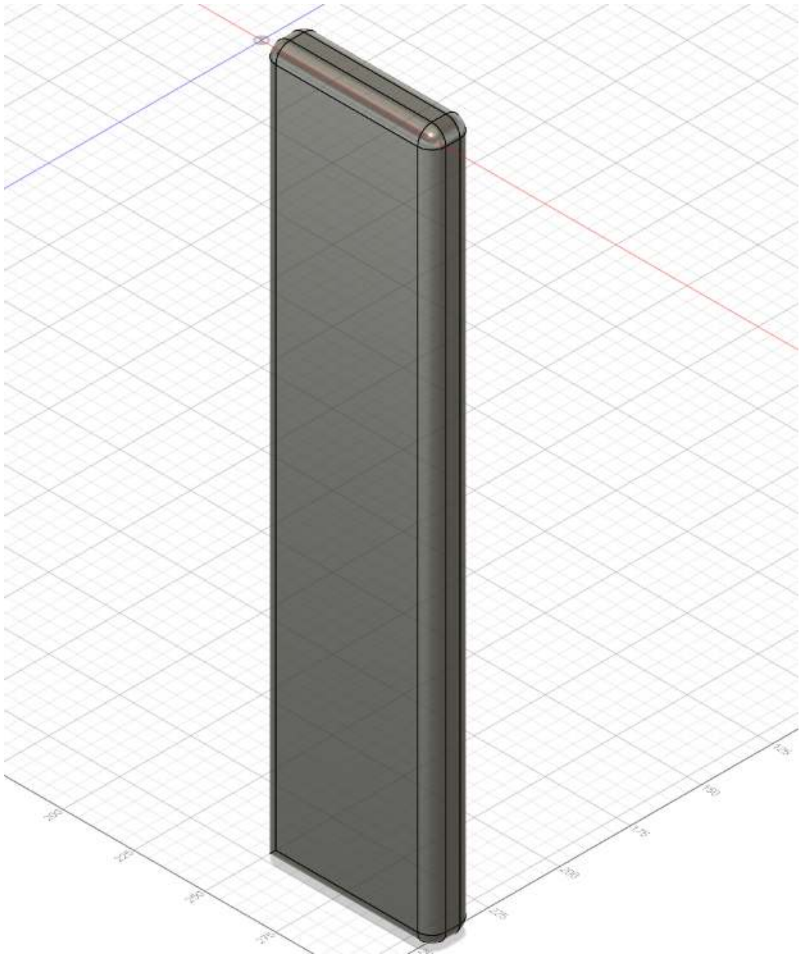

Fig 5: CAD of Stainless steel linkage

Figure 5 depicts a singular linkage, which is used to hold the three pouches together. This part makes all of the pouches rigidly lock in place so the pressure distribution is even all across the chest. To handle the amount of load that will be exerted by the device, the material chosen is stainless steel, more specifically, lightweight stainless steel type 304 in accordance with ASTM A240 specifications for a stainless steel plate[8].
The dimensional drawing in detail is presented below in figure 6,

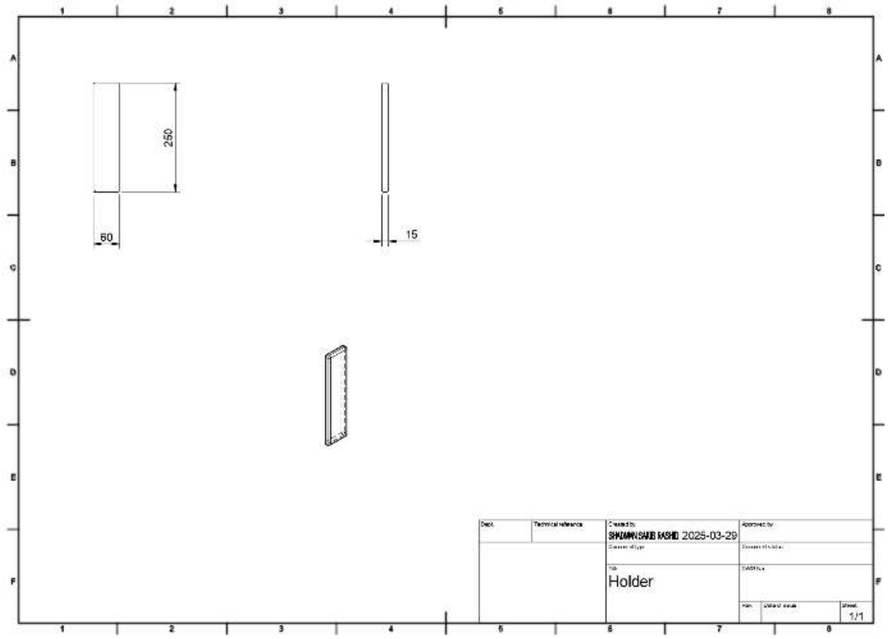

Fig 6: Detailed dimensional CAD drawing for stainless steel linkage

- **Full assembly of the Automated Cardiopulmonary resuscitation device**

As mentioned before, the fully assembled chest compression device is comprised of two major assemblies: the front inflated pouches, as seen in Figure 7 and 8, which stays in contact with the chest, and the back plate, called the power unit housing, which will house the geartrain, motors, and other integrated sensors.

Fig 7: Full assembly of the chest compression device

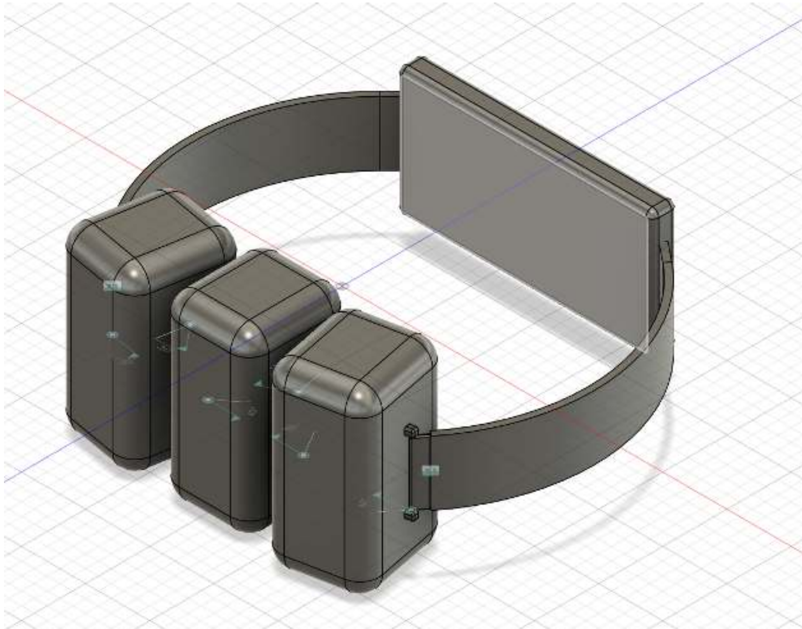

Fig 8: Full assembly of the chest compression device

- **Integrated Accelerometer**

This is the sensor responsible for detecting a fall, and this is one of the sensors that are integrated into the device to alert the system to start administering CPR. The specific model used in this device is the BOSCH Accelaration sensor BMA400[13] adhering to RoHS- Directive 2011/65/EU including 2015/863/EU [13] in the use and restrictions of hazardous substances in electronoc equipments.

Fig 9: BMA 400 Accelerometer[13]

- **Integrated respiratory pressure sensor**

This integrated sensor will detect any changes in the circumference of the thoracic cavity, and this is able to detect when a person is gasping for air, which is also one of the signs of an ongoing cardiac arrest. The specific one used for this application is the TN1132/ST Respiratory Belt from Ad instruments[6], which adheres to ISO 9001:2008[7].

Fig 10: Respiratory pressure belt sensor TN/1132/ST[6]

- **Servo Motors in use**

The specific type of servo motor used in this device is the AKM2F-23F from Kollmorgen[14], which has a continuous stall torque of 1.5 N.M[14]. This was chosen because of its light weight of 1.7 kg[14] and small dimensions. A mechanical analysis of this type of motor is shown in the next section, which is the analysis section. The spec sheet can be found within link[14].

Fig 11: AKM2G-23F servo motor[14]

Preliminary Design Verification [Analysis]

For the **amount of force needed for compression,**

In this section, calculations justifying the torque and force requirements of the motor and other components will be shown

The motor selected for this application is the AKM2G-23F from Kollmorgen with a continuous stall torque of 1.5 N.m or 13.3 lb. in [14].
As mentioned in the design input section, the expected force output for the device will be 130 lbs, so each motor needs to support a force of 65 lbs.

We know the relation between force and torque,

T = F * r, where F is the force, T is the torque, and r is the moment arm.

So the force needed per motor will be

F= T/r, An assumption is made that the moment arm is 1 inch. so,

F= 65 lbs of force per motor.

As the required torque is way more than the produced torque per motor, we need to have a geartrain to increase the torque output

The gear ratio can be calculated by the following formula,

Gear ratio, G = Required Torque/Motor torque = output torque/input torque [15]

The required torque is 65 lb.in, and the motor torque is 13.3 lb.in. So the required gear ratio is
G= 65/13.3
G= 4.88:1

This gear ratio can be implemented with just one gear train on each side for each of the motors, and stock spur gears will be used.

As for obtaining the required compression on the chest, a target chest compression is assumed to be 2.2 inches, which is within the range of safe chest compression amount specified by the American Heart Institute[4].

The output shaft, which is attached to the gear train, has a radius of 1 inch; the total linear travel from the output shaft will be,
C= 2* 3.1416* 1

C= 6.283 inch, which is more than what is required.

So, to achieve a linear stroke length of 2.2 inches, 2.2/6.283 = 0.350 revolutions are required from the output shaft.

Now, since the target is 120 chest compressions per minute, or 2 compressions per second, the motor needs to be reciprocating between forward and backward strokes. So to produce 2 chest compressions per second, the forward stroke length travelled by the output shaft will be 2* 0.350 inch or 0.7 inch per half second or 1.4 inch per second,
Which gives the shaft an output speed of,
= 1.4* 60
= 84 RMP

So, since the necessary gear ratio for the gear train is calculated to be 4.88:1, the required motor RPM will be,
Motor speed = 84*4.88 = 409 RPM[15]

So since the motor RPM is 409, which is well below the maximum for this motor, it will be able to perform a total of 120 compressions per minute with a force of 65 lb when paired with a gear ration of 4.88:1 on each side for each motor.

For the **sensors and the monitoring subsystems,**

A popular type of accelerometer used in wearable devices is the BOSCH acceleration sensor BMA400[13], since this is very popular for use in the wearable industry, this will be a suitable choice for our application in this medical device due to its compact and lightweight nature.

For detecting abnormal breathing, the respiratory belt sensor from AD instruments [6] is the perfect solution for this device as it can sense when the patient is hyperventilating, which is a critical system to detect during a cardiac arrest

For the inflatable pouches, a **material property analysis** is shown

The required 130 lbs of force required for the chest compression will be divided by three inflatable pouches, so each inflatable pouch will bear a total of 130/3, 43.33 lb of force.

To verify the material strength of the fabric, we will compare the yield strength of the material to the **hoop stress** in the pouch material.

The area of the pouch, which will be in contact with the patient's chest, is **0.11 m^{2}**, and the force exerted on each pouch is 43.33 lb or 193 newtons.

So the pressure on the pouch is,

P= F/A
P= 193/0.11
P= 1754.54 Pascals

Now, to measure the tensile or the hoop stress in the pouch material, we will make an assumption that the pouch is a thin-walled pressure vessel of thickness t and radius r, which is cylindrical in shape due to when it is inflated.

We know that the expression to calculate the tensile/hoop stress in a thin-walled cylindrical pressure vessel is,

$\sigma = \frac{Pr}{2t}$[16]

The radius in this case will be assumed to be the minimum distance from the center of the pouch to the nearest wall,
Which is r = 175 mm, and the thickness is assumed to be t = 25 mm

Putting in the values,

$$\sigma = \frac{1754.54\ pa * 0.175\ m}{2 * 0.025\ m}$$

σ = **6140.89 pa or 6.14 Kpa**

Here, the material used for this pouch will be the same type of material which is used to make inflated life jackets, which is a Nylon-based fabric with a PVC coating. This material was chosen for its high durability and water resistance, and this type of material is rated with a yield strength of 140 kPa, which means that the use of this type of material in our biomedical device is justified.

For **power consumption**,

Energy required for this system can be provided by high density lithium ion batteries which adhere to IEC 62133 standard[17]

Verifying the power consumption can be done by adding the power consumed from the servo motors, the integrated sensors.

References

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