B. TECH. PROJECT REPORT

On

Design and Development of Automated SMA-actuated CPR Device

BY

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DISCIPLINE OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Design and Development of Automated SMA-actuated CPR Device

A PROJECT REPORT

Submitted in partial fulfilment of the
Requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

Submitted by:
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Guided By:
Dr. I. A. Palani

INDIAN INSTITUTE OF TECHNOLOGY INDORE
November 2018

CANDIDATES’ DECLARATION

We hereby declare that the project entitled “**Design and Development of Automated SMA-actuated CPR device**” submitted in partial fulfilment for the award of the degree of Bachelor of Technology in ‘Mechanical Engineering’ completed under the supervision of **Dr. I. A. Palani, Associate Professor, Mechanical Engineering, IIT Indore** is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Harsh Nigam

Gagan Chawara

CERTIFICATE BY BTP GUIDE

It is certified that the above statement made by the students is correct to the best of my knowledge.

Dr. I. A. Palani
Associate Professor
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IIT Indore

PREFACE

This report on **"Design and Development of Automated SMA-actuated CPR device"** is prepared under the guidance of **Dr. I. A. Palani.**

Through this report we have tried to give detailed description and design for SMA-actuated CPR device and fabrication of a prototype model. We performed different experiments to understand the behaviour of SMA springs and checkedit's suitability fora CPR device. We made the set-up and performed the experiments successfully which shows that the design is technically sound and feasible, and that SMA can be used to develop a CPR device.

We have tried to the best of our abilities and knowledge to explain the content in a lucid manner. We have also added flow charts, figures and tables to make it more illustrative.

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Acknowledgements

We would like to thank **Dr. I. A. Palani** for his support and valuable guidance. This work has been done in framework of the IIT Indore project that is funded by the **PRIUS** (Promotion of Research & Innovation for Undergraduate Student). We would like to acknowledge Mr. Sachin Bhirodkar, Mechatronics & Instrumentation lab, Metrology lab and Central Workshop of IIT Indore for providing hissincere cooperation and essential componentsthat helped us carry out this research.

It is their help and support, due to which we were able to complete the design and technical report. Without their support this report would not have been possible.

We would like to extend our sincere regards to **Mr. K. Akash** and **Mr. Suhel Khan** for helping in the lab activities. We are thankful to get constant encouragement, support and guidance from B.Tech project evaluation committee. It is their help and support, due to which we are able to complete the project.

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Abstract

This report shows the findings and highlights the idea of providing mechanical CPR with the help of Shape Memory Alloy (Nickel-Titanium – NiTi) springs with high fatigue strength.

The device will have a longer life, lighter weight and a lower cost as compared to its already existing mechanical CPR counterparts making it a worthy substitute in the coming future. The device would be capable of providing regular chest compressions using a net force of up to 60N with a frequency of nearly 20 compressions per minute to the compression depth of around 2.5cms. SMA springs provide the controlled compressions, whereas, normal steel springs provide the expansion and the cycle goes on. We have used a polycarbonate sheet with a smooth notch, which would be concentrating the load on the lower portion of the patient's sternum.

The load on the patient's thorax is measured with the help of a load cell placed on a base board and the signal is fed back to the system and the actuating current value may be adjusted accordingly so that the required force is maintained.

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Chapter I: INTRODUCTION

1.1 What is CPR?

Cardiopulmonary resuscitation (CPR) is an emergency procedure to support and maintain breathing and circulation for an infant, child, or adolescent who has stopped breathing (respiratory arrest) and/or whose heart has stopped (cardiac arrest). CPR is performed to restore and maintain breathing and circulation and to provide oxygen and blood flow to the heart, brain, and other vital organs.

There are two commonly known versions of CPR:

1. For healthcare providers and those trained: conventional CPR using chest compressions and mouth-to-mouth breathing at a ratio of 30:2 compressions-to-breaths. In adult victims of cardiac arrest, it is reasonable for rescuers to perform chest compressions with force of around 200N, at a rate of 100 compressions/min and to a depth of 2 inches (5 cm) for an average adult, while avoiding excessive chest compression depths (greater than 2.4 inches). **[1]**
2. For the general public or bystanders who witness an adult suddenly collapse: compression-only CPR, or Hands-Only CPR. Hands-Only CPR is CPR without mouth-to-mouth breaths. It is recommended for use by people who see a teen or adult suddenly collapse in an out-of-hospital setting (such as at home, at work, or in a park). **[1]**

Figure 1: CPR on an adult dummy

Figure 2: CPR on a baby dummy

1.2 Motivation

More than 3,50,000 people suffer an out of hospital cardiac arrest every year. Even when medical providers have adequate training, it can still be difficult to carry out an effective resuscitation due to suboptimal CPR, multiple interventions needing to be done simultaneously, and many other less than ideal conditions. According to AHA`s 2015 Heart and Stroke Statistics. New report suggests the incidence of out-of-hospital cardiac arrest is 326,200. The average survival rate is 10.6% and survival with good neurologic function is 8.3%. Nearly one in three victims survives when the arrest is witnessed by a bystander. The death rate due to cardiovascular diseases (CVD) increased by a significant 34 per cent from 155.7 to 209.1 deaths per one lakh population in India between 1990 and 2016.

Due to these reasons we decided to design and develop an automated CPR device. So that precise and effective CPR can be provided. We considered SMA springs to provide force because it can produce high force per unit volume and have high fatigue strength and the device thus made is light-weight.

Chapter II: SHAPE MEMORY ALLOYS

2.1 What is SMA?

SMAs (Shape Memory Alloys) are metallic alloys with the ability to return to a predetermined shape when heated. After a plastic deformation, the SMAs undergo a thermo-elastic change in crystal structure when heated above its transformation temperature range, resulting in a recovery of the deformation. This effect is known as Shape Memory Effect. SMAs can exist in two different phases, with three different crystal structures (i.e. twinned martensite, detwinned martensite and austenite). **[2]**

There are four characteristic temperatures to define Shape Memory Effect; the martensite start temperature M_s, at which martensite first appears in the austenite. The transformation proceeds with further cooling and is complete at the martensite finish temperature, M_f. Below M_f, the entire body is in the martensite phase. With heating, the austenite start temperature A_s, is the temperature at which austenite first appears in the martensite. With further heating, more and more of the body transforms back into austenite, and this reverse transformation is complete at the austenite finish temperature, A_f. Above A_f, the specimen is in the original undistorted state.

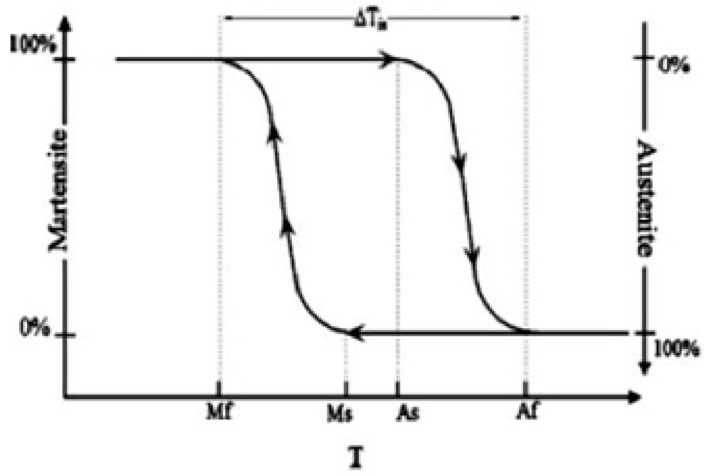


Figure 3: SMA material transformation process

When SMA is at lower temperatures and is not deformed than it`s crystal structure is twinned martensite. It can be easily deformed into any shape. After deformation it`s crystal structure changes to detwinned martensite. Phase for both of these crystal structures is martensite. When the alloy is heated, it goes through transformation from martensite to austenite. In the austenite phase, it remembers the shape it had before it was deformed and resists deformation.

The most effective and widely used shape memory alloys include NiTi (Nickel - Titanium), CuZnAl, and CuAlNi.

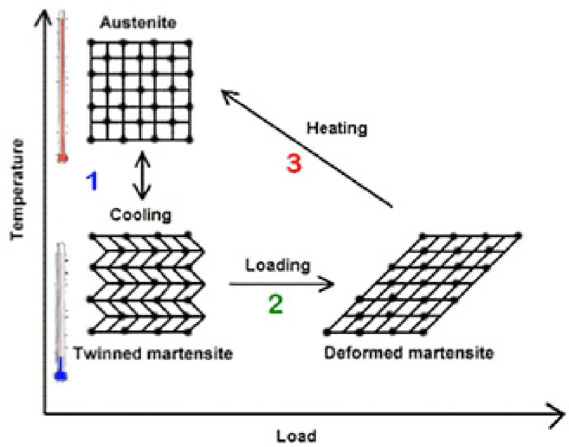


Figure 4: Schematic illustration of deformation and shape recovery of an SMA

2.2 One-way vs. two-way shape memory

One-way memory effect- When a shape memory alloy is in its cold state (below A_s), the metal can be bent or stretched into a variety of new shapes and will hold that shape until it is heated above the transition temperature. Upon heating, the shape changes back to its original shape, regardless of the shape it was when cold. When the metal cools again it will remain in the hot shape, until deformed again. With the one-way effect, cooling from high temperatures does not cause a macroscopic shape change. A deformation is necessary to create the low-temperature shape.

Two-way memory effect- the material remembers two different shapes: one at low temperatures, and one at the high temperature shape. A material that shows a shape memory effect during both heating and cooling is called two-way shape memory. This can also be obtained without the application of an external force (intrinsic two-way effect). The reason the material behaves so differently in these situations lies in training.

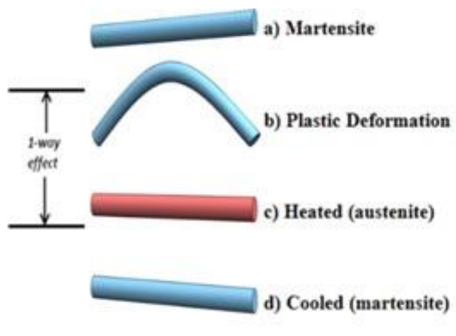


Figure 5: One-way shape memory effect

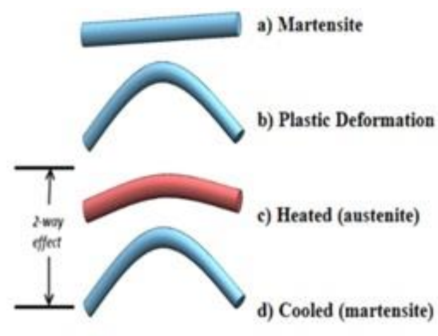


Figure 6: Two-way shape memory effect

2.3 Choice of SMA component

SMA springs were used for obtaining the actuation. We conducted experiments on two of the available SMA products, namely SMA springs and SMA wires. Experiments were done on both and former came out as the preferred choice. Since the actuation in wire was too miniscule to have even a considerable effect. The SMA springs, on the other hand proved to be a better alternative.

Table 1: SMA wire vs SMA spring

Property	SMA wire	SMA springs
Actuation (Relative Displacement)	Very Small	Adjustable(as per requirement)
Restoring force Required	Low	Very Low
Implementation in Design	Clumsy	Easy

Hence we decided to work with the SMA springs.

The springs that we used were made of processed Ni-Ti wires known as Flexinol, which are low-cost and one-way.

NiTi general properties for bio-medical devices.

NiTi is among those shape memory alloys which have excellent manufacturability and workability during its martensite phase. It has a good corrosion resistance and high fatigue strength.

Table 2: Properties of materials for bio-medical applications **[3]**

Material	Density (g/cm3)	Young's Modulus (GPa)
Nitinol	6.45	Austenite = 53.5; Martensite = 29.2
Stainless Steel (316L)	7.95	193
Titanium (Ti) **Ti-6Al-4V**	4.43	113.8
Bone	1.7-2	0.2-19.4

NiTi shape memory alloy is used in various medical areas, namely, orthodontics, orthopedics, general surgery, neurosurgery, urology and physiotherapy.

Coronary artery disease is one of the major hazards to human health. This occurs due to development of plague in-growth developed in the artery reducing its cross section. A stent made up of SMA which is made to travel through the artery where it expands depending on the thermal actuation and reinstate the blood flow. Temperature dependence, in such an emergency situation, becomes an important factor to consider. Many devices made out of shape memory allows are manufactured and fabricated and are currently in use. Some of them are shown in Figure below:-

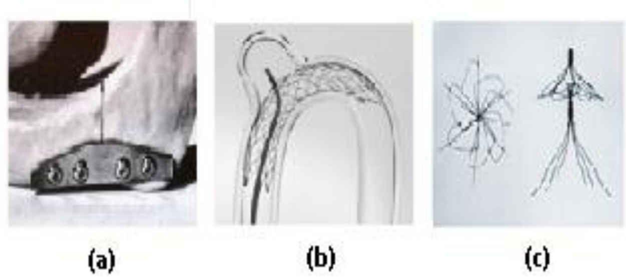


Figure 7: (a) NiTi plate for mandible fracture

(b)NiTi self-expandable neurosurgical stent (Enterprise Vascular Reconstruction Device; Cordis Corp., Miami Lakes, FL).

(c)Venous filter: Simon filter **[4]**

Chapter III: Modelling and Component selection

3.1 Model

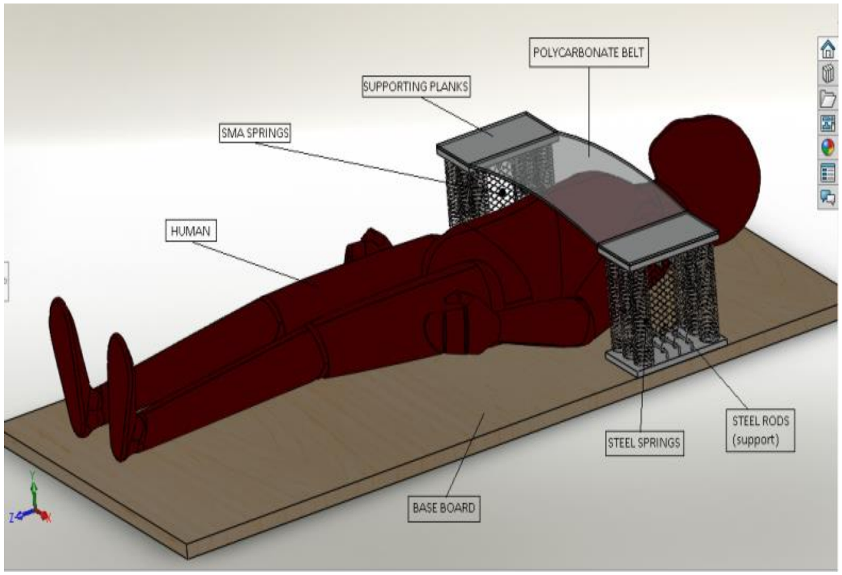


Figure 8: CAD model of SMA-actuated CPR device

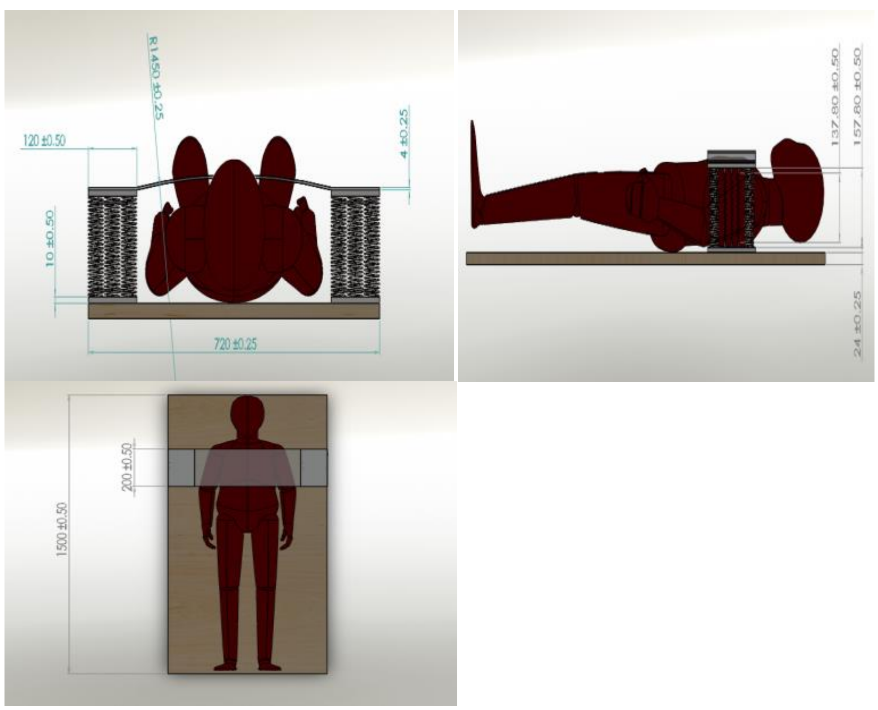


Figure 9: Different views of CPR device

3.2 Specifications of various components

SMA Springs: We are using SMA springs to provide force for compression. We chose 3-642 NiTi Spring (Tension) for our purpose. It works on 5V and 3 amps.

Figure 10: NiTi SMA springs (deformed and undeformed)

Helical Compression Steel Springs: We are using steel springs to provide force so that system can return to its original position. We are using Helical compression spring with spring constant 0.75 N/cm, length 180 mm, wire diameter 1.7mm, outer diameter 37mm and 25 active coils for our design calculations.

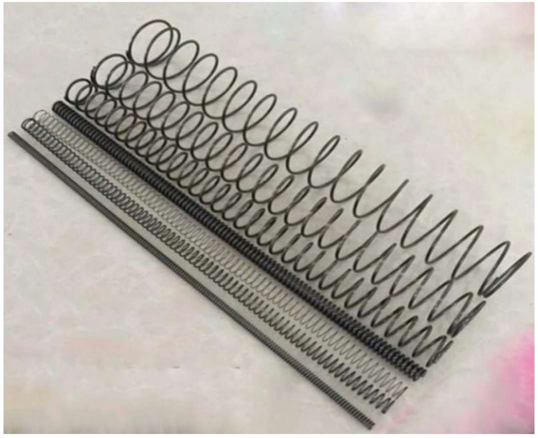


Figure 11: Helical compression steel springs

Arduino: We are using Arduino to systematically control all the components of the device. We have selected Arduino UNO for our purpose. Arduino Uno is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button.

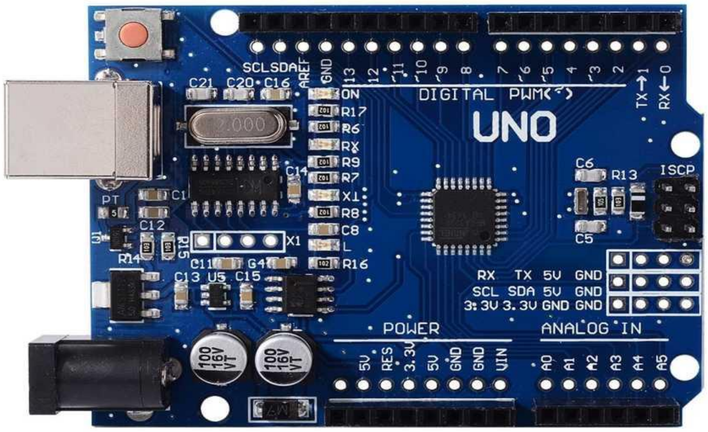


Figure 12: Arduino UNO

Load cell: We will be using Load cell to measure force on patient's Thorax. We have selected FX1901-0001-0200-L COMPRESSION LOAD CELL, 5VDCfor our purpose. It`s specifications are as follows:

Sensor Type: OEM Compression Load Cells

Full Scale Range (lbf): 200 – 200

Operating Temperature: 0 – 50 °C [32 – 122 °F]

Zero Shift in CTR (% of FS): ±.05

Sensitivity Shift (% of FS): ±.05

Figure 13: FX1901-0001-0200-L COMPRESSION LOAD CELL

Instrumentation amplifier: We are using Instrumentation amplifier to amplify the signal sent by load cell so that arduino can sense it. We have selected INA125P for our purpose.The INA125 is laser-trimmed for low offset voltage (250µV), low offset drift (2µV/°C), and high common-mode rejection (100dB at G = 100). It operates on single (+2.7V to +36V) or dual (±1.35V to ±18V) supplies.

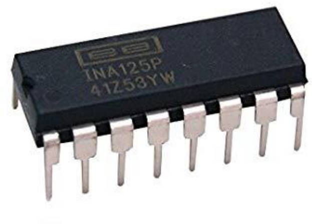


Figure 14: INA125P

Polycarbonate Plastic Sheet: We are using Polycarbonate sheet as the belt (60x20x1 cm3) which will be in contact with patient`s thorax and as the base board (100x50x2 cm3).Polycarbonate (PC) plastics are a naturally transparent amorphous thermoplastic. It`s Glass transition temperature is 145^0C and its melting point is 225^0C. It has high impact strength and thermo-formability.

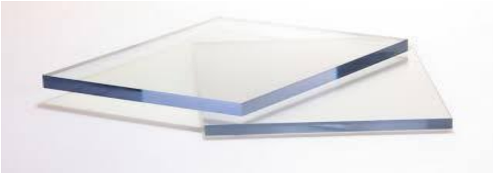
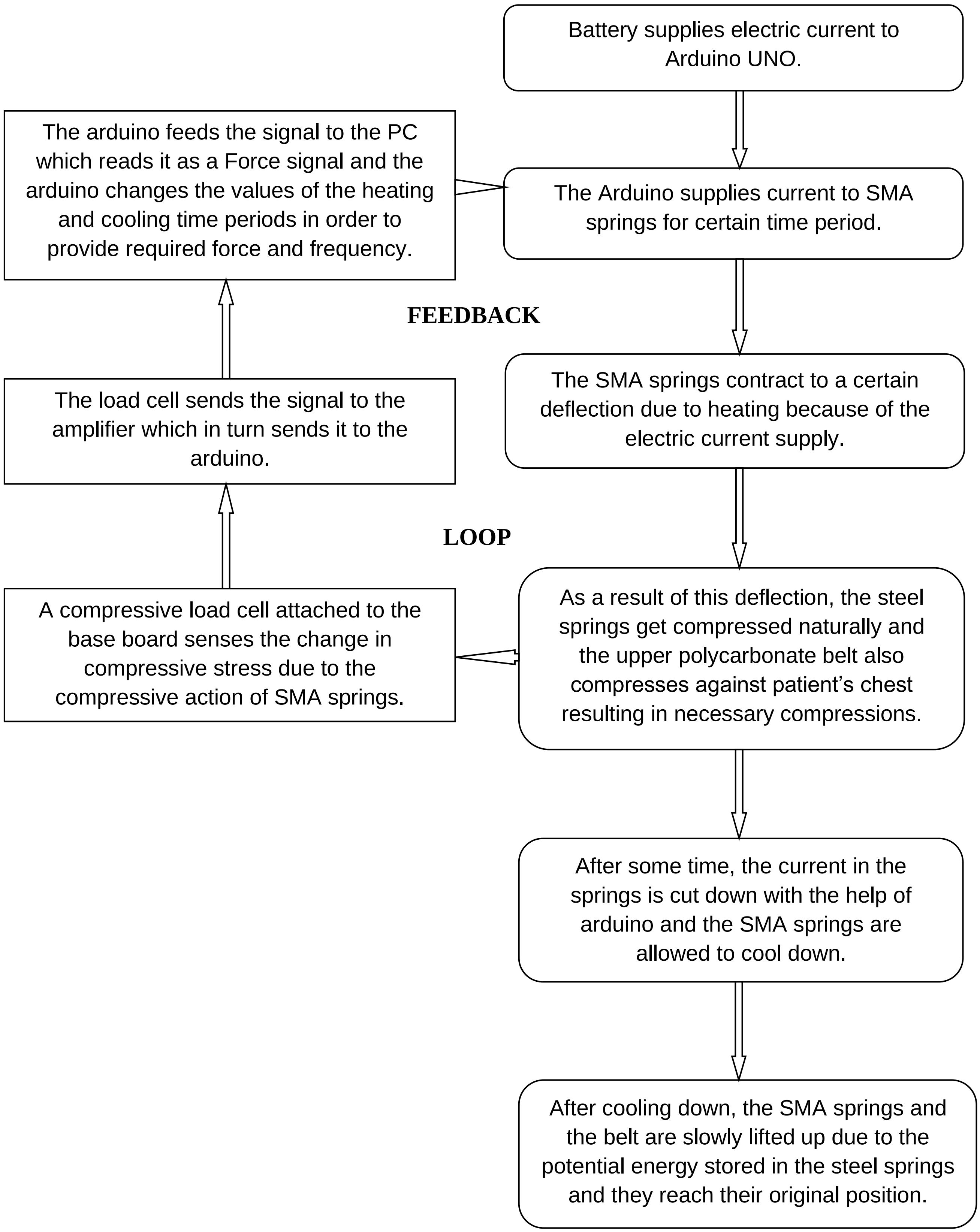


Figure 15: Polycarbonate sheet

Supporting Planks: We needed a high temperature resistant material to connect SMA springs with belt and base board. We decided to use Four PEEK boards of size 20x6x1 cm3.PEEK is a unique, semi-crystalline, high temperature engineering thermoplastic. It has a tensile strength of 90 to 100 MPa. It melts at around 343°C. It is highly resistant to thermal degradation as well as attack by both organic and aqueous environments.

Figure 16: PEEK sheet

3.3 Flowchart



3.4 Control System

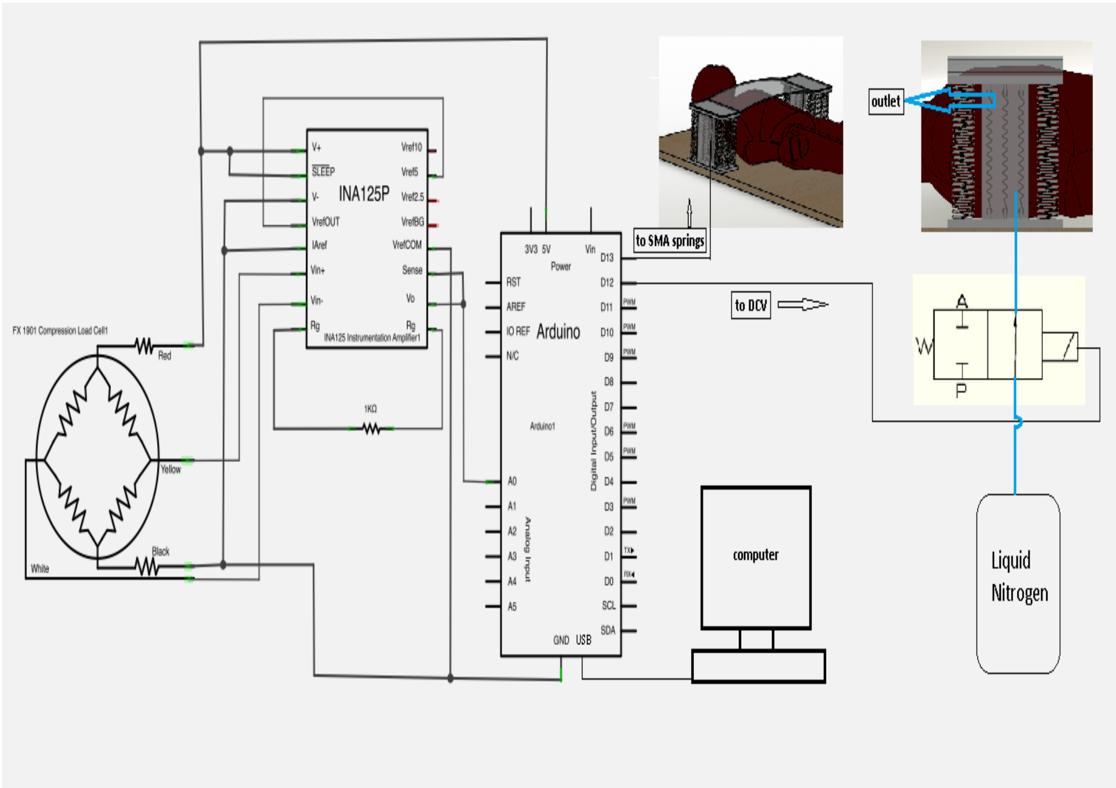


Figure 17: Control System

The circuit consists of a power supply battery to power the Arduino, a Load cell, a Personal Computer (PC), INA125P Instrumentation Amplifier. Arduino works as a moderator unit and provides signal to SMA Springs as well as reads signal received from the load-cell. Arduino is to be connected to a PC.

Different control buttons are provided for RUN and STOP functions. Liquid nitrogen could be used as a cooling medium and thus increase the frequency of the system.

3.5 Features of Project

Table 3: Features of Project

Force	Depth of Compression	Frequency
60N	2.5cm	20 compressions/min

Chapter IV: Analysis of SMA Springs

4.1 Why?

As the source of force in our device is SMA springs and the movement of system is completely dependent on it, we required in-depth detail of SMA spring`s behaviour. That is why we decided to do experiment on SMA springs.

4.2 Experimental setup

Since the system is driven by SMA springs, so some objective-oriented tests were performed on the springs. For all the experiments explained henceforth, we have used NI Compact DAQ for Data Acquisition. For the measurement of Load Displacement, Laser Aperture Sensor by Panasonic Electric Works SUNX Co. Ltd was employed. The Force was measured using Load (Load Cell Name), Thermocouple was used to record Temperature. The SMA NiTi spring was actuated with a Programmable power supply (RIGOL DP1308A by LXI). SMA was actuated using a potential difference of 5Volts and using a current of 3Amps. All the graphs were obtained in LabVIEW software (version). The power supply was programmed in such a way that the spring is allowed to compress fully. All the experiments were performed while keeping weights on the other side of the system to provide a constant load. and the different graphs for different loads are obtained and analysed. Each graph represents repetitive heating-and-cooling cycles of SMA. A little noise is incorporated in the system due to friction and manual errors. So, error bars are put to get a range of results. The results of force and displacement were scaled from current amplitude to their respective units by considering a linear relation.

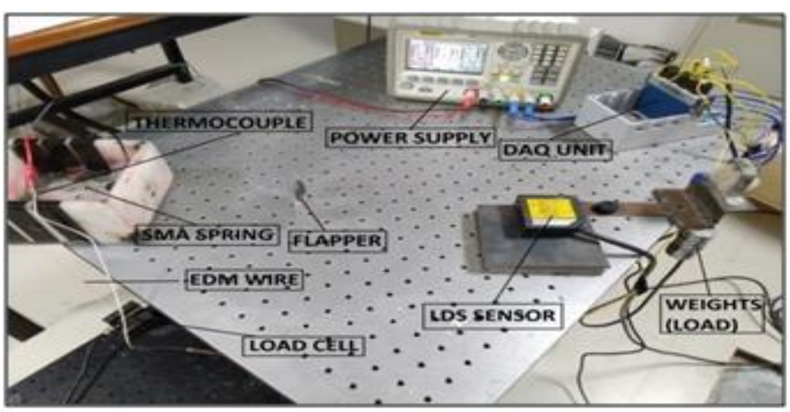


Figure 18: Experimental setup

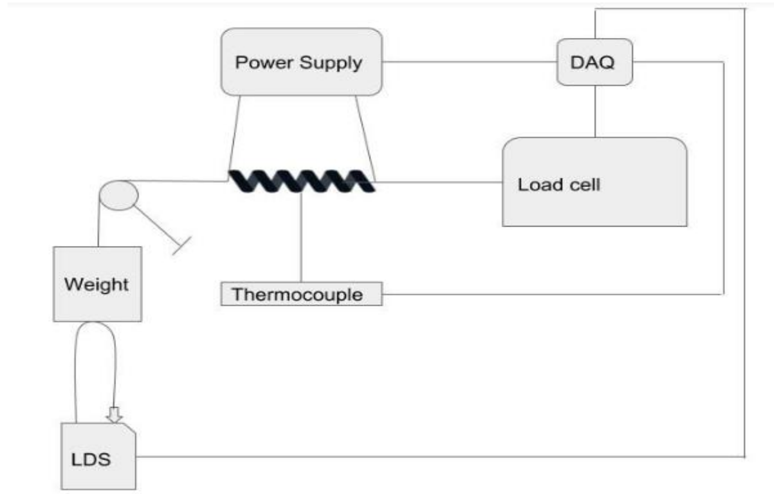


Figure 19: Block diagram

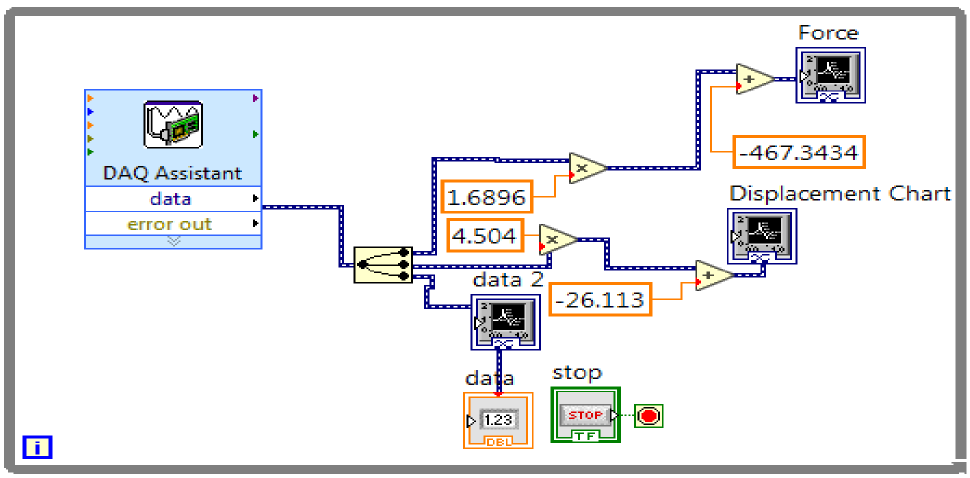


Figure 20: Block Diagram Design in LabVIEW

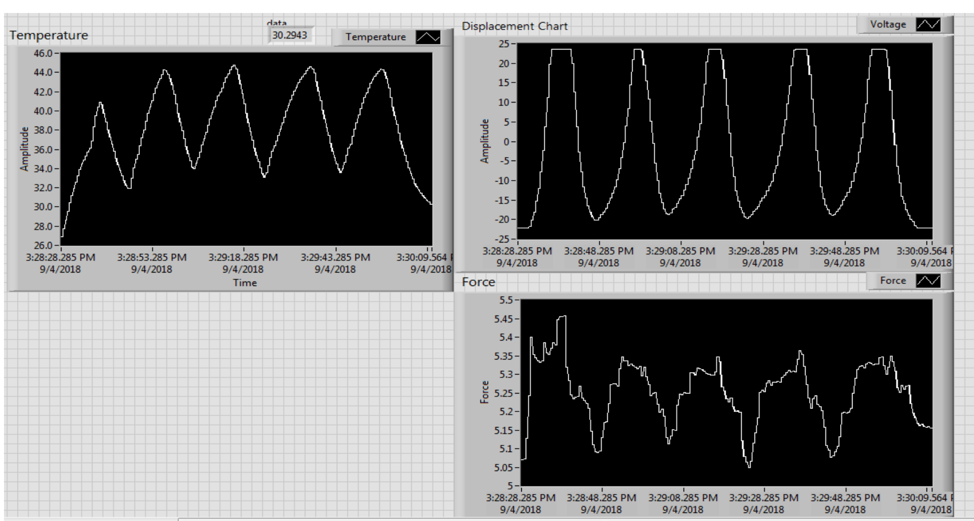


Figure 21: LabVIEW results for 3.92N load

4.3 Temperature Analysis

Since temperature is the main parameter for the actuation of the SMA, so we needed to make sure that the power supply is enough to actuate the spring so that the desired frequency is obtained. Temperature is also a critical parameter when we are dealing with an emergency medical situation.

We used thermocouple to measure temperature. But as tip of thermocouple was not in contact with SMA springs at all times, we got the value of temperature of air near the SMA spring`s surface.

For a more conspicuous analysis of the temperature change, Thermal photos of the spring in cooled state and in fully heated state were taken with FLIR ONE thermal imaging camera.

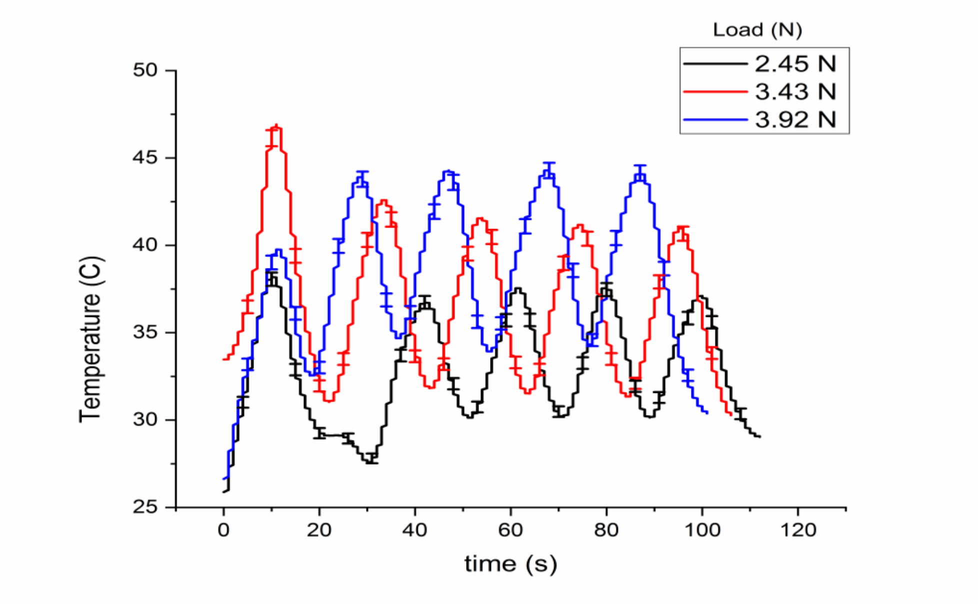


Figure 22: Temperature vs Time

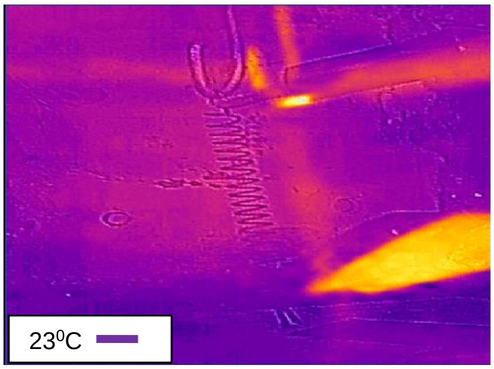


Figure 23: Thermal image of SMA spring at low temperature

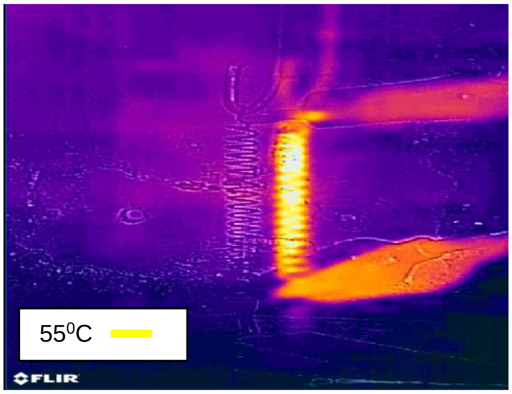


Figure 24: Thermal image of SMA spring at high temperature

4.4 Displacement Analysis

The Linear Displacement Sensor projects the LASER on a flapper that moves along with the spring and the displacement is measured with a DAQ and viewed on LabVIEW. The following results were obtained at different loads:

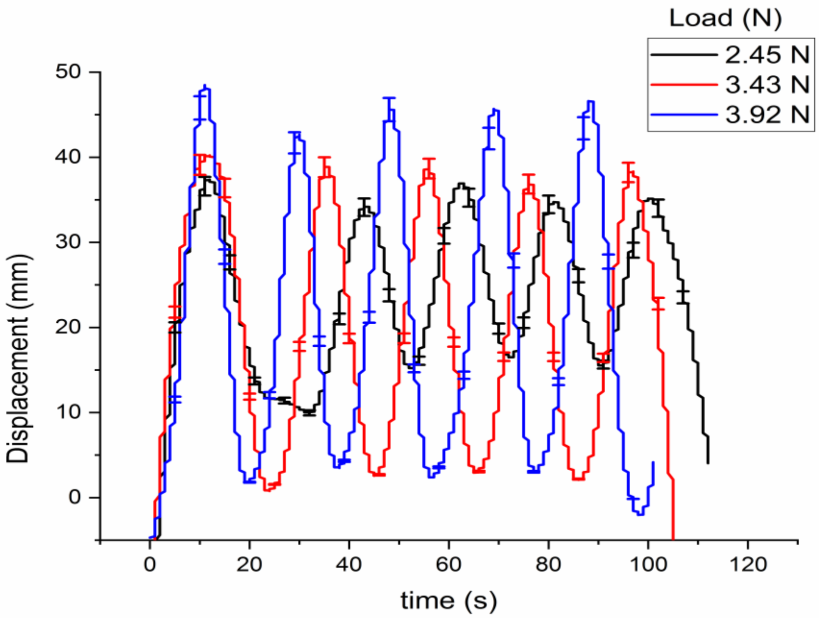


Figure 25: Displacement vs time

Table 4: Frequency and maximum displacement at different loads

Load(N)	Maximum Displacement(mm)	Frequency(Hz)
2.45	37.39	0.05
3.43	37.75	0.055
3.92	45.69	0.067

4.5 Force Analysis

The force that an SMA spring produces due to compression is recorded with the help of a load cell and its curve with respect to time is plotted and results analysed.

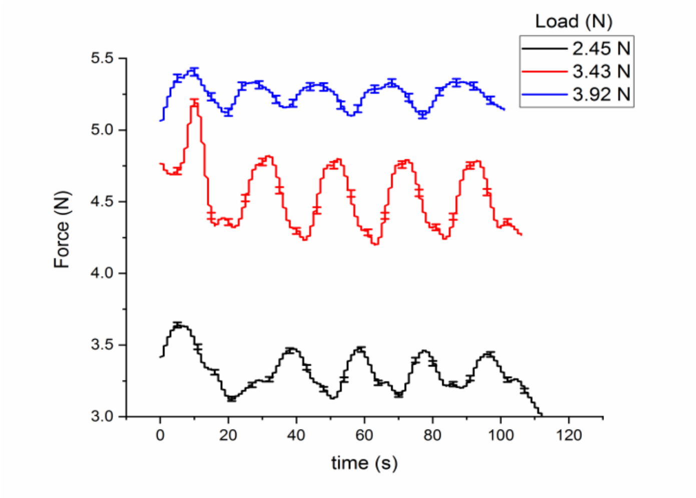


Figure 26: Force vs time

We also did analysis of variation of force with displacement of the SMA spring. Here, we have taken the graph with 3.43N of weight.

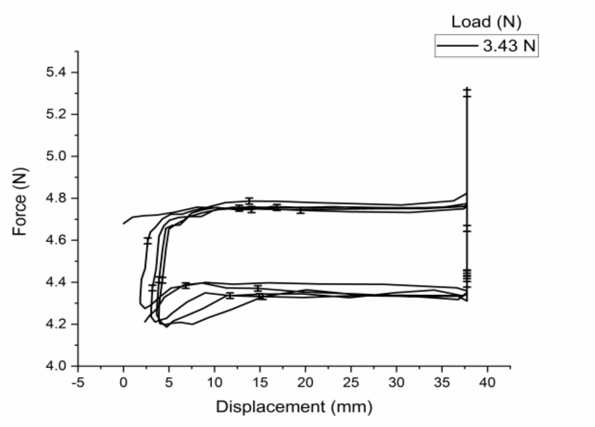


Figure 27: Force vs displacement

The graph shows the psuedoelastic effect of NiTi spring and the associated energy dissipation in the hysteresis loop.

Maximum force analysis of SMA under restrained condition

In this experiment, we measured the maximum force that an NiTi spring can generate at different initial lengths. The setup had two fixed supports between which the spring was mounted. Then a current of 3A and voltage of 5V was applied to SMA spring and the SMA was allowed to heat up between the supports until it was dislodged from the hooks due to the stresses developed within and regains its natural length of around 2.2cm.

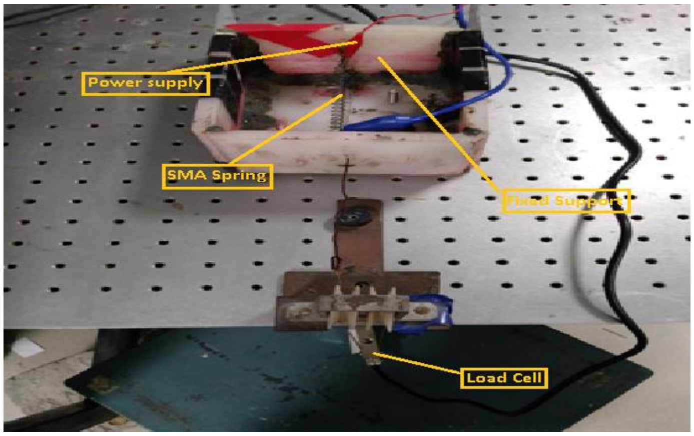


Figure 28: Experimental setup

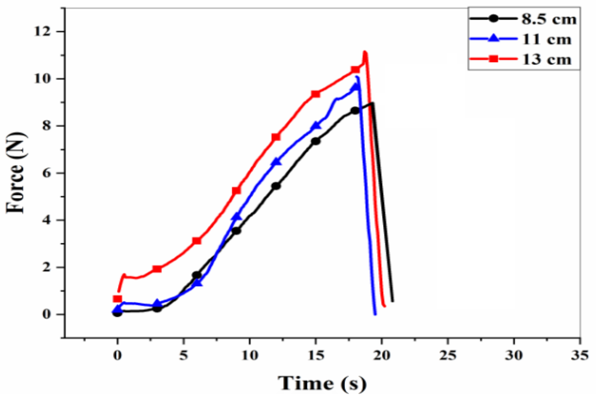


Figure 29: Force vs Time with different initial lengths of SMA springs

Chapter V: Prototype Analysis

5.1 Design of prototype and Frequency analysis

For making the prototype, two 3D printed plates were utilized. We attached the first one to a vertical support held fixed and the other to the normal steel springs (k = 1.22 N/cm) by using Araldite standard epoxy adhesive. The other ends of normal steel springs are, in turn, attached to another fixed support directly opposite to the first support. All the SMA springs are actuated with a power supply (5V, 12A) and the middle plate starts to move to the right. We placed a 2.5cm market on the fixing board. We stop the current when the plate reaches the marker and the springs starts to cool and expand under the action of the force developed in the steel spring. The current is again passed when the plate passes through the left line of the marker and the time was noted.We were using forced convection for cooling.

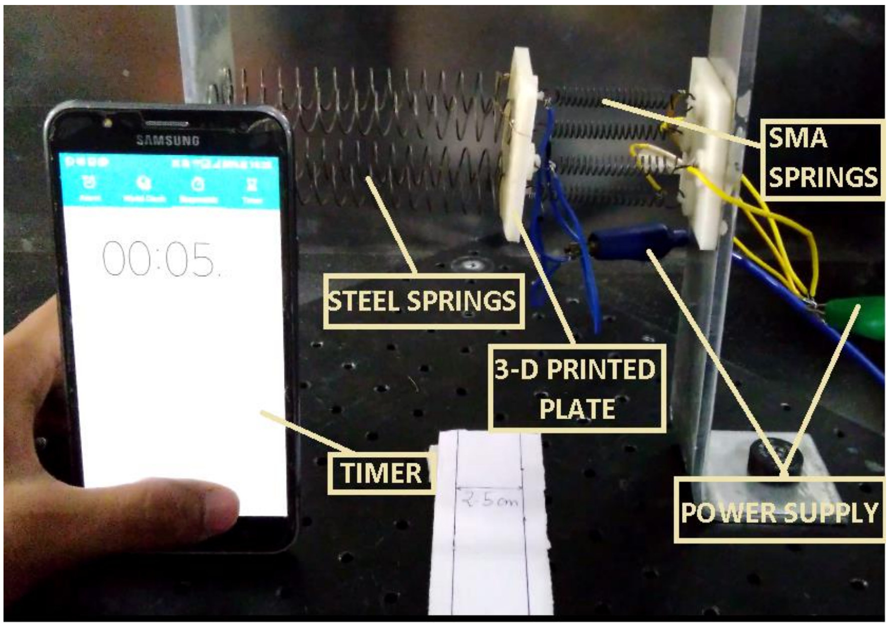


Figure 30: Prototype with timer

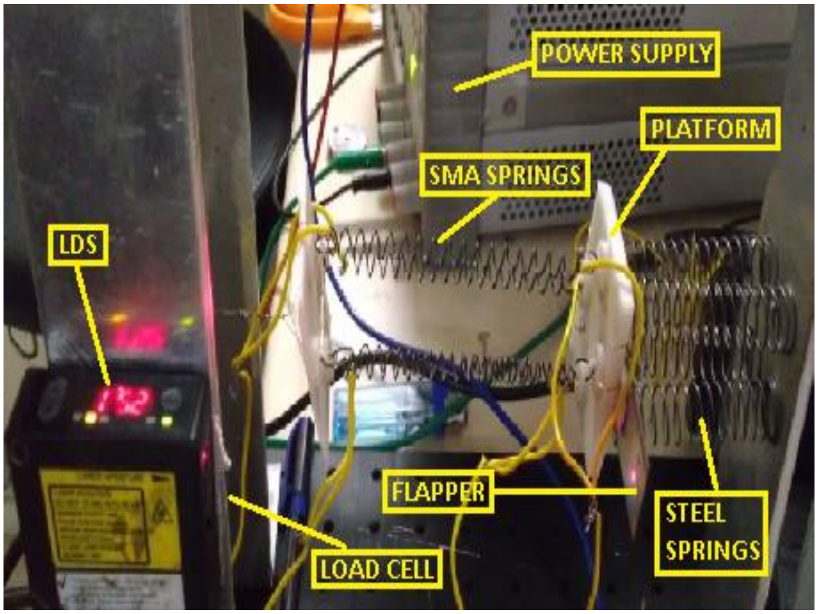


Figure 31: Prototype equipped with LDS and load cell

5.2 Force Analysis (prototype)

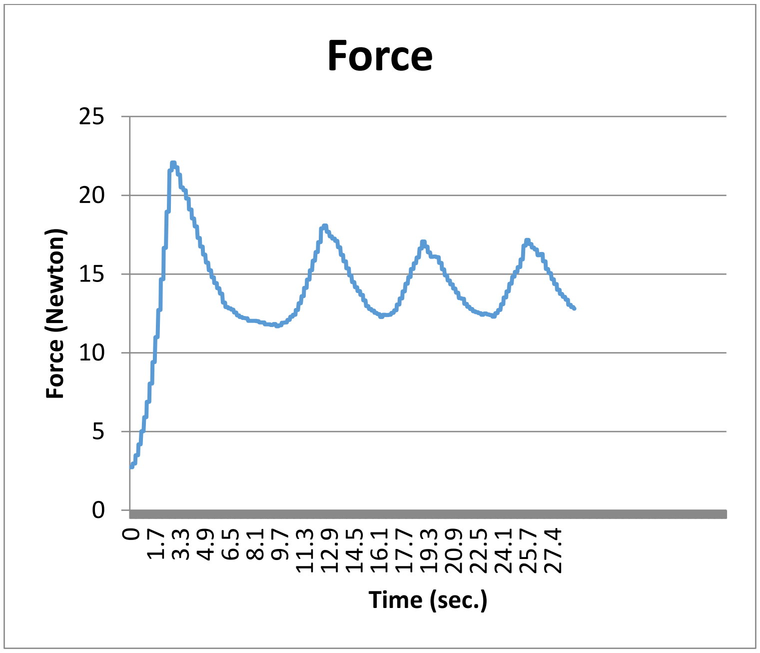


Figure 32: Force vs time(prototype)

5.3 Displacement Analysis (prototype)

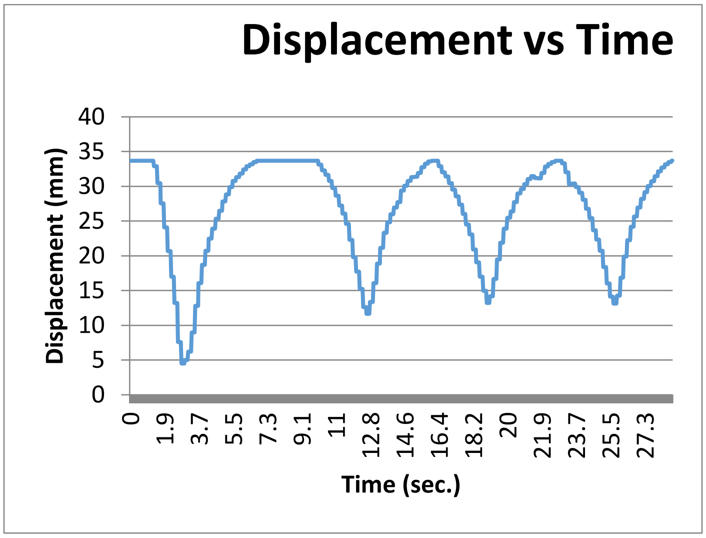


Figure 33: Displacement vs time(prototype)

Chapter VI: Results and Discussion

1. **Temperature Analysis** - From Fig. 22 we can notice that the maximum temperature is nearly, 460C, at 3.92N load. Therefore, proper thermal insulation is required so that the temperature rise would not affect the patient.

   It takes around 10 seconds for the heating cycle to get completed and around 9 seconds for the cooling cycle.

2. **Displacement Analysis** - It is noteworthy from Fig. 25 that the frequency increases as the load increases. This happens because a larger load helps the spring to expand when it is cooling. Therefore, the important parameter to increase the frequency is to increase the load.

   The maximum deflection observed was 45.69 mm for 3.92N load.

3. **Force Analysis**–From Fig. 26, we can see that to cover the same distance the force is increasing as the load increases. The maximum force generated by the SMA spring is 5.46N at a load of 3.92N.

4. **Maximum force analysis of SMA under restrained condition**–We can see from Fig. 29 thatas the initial extension of SMA spring increases the force provided at any instant also increases. The maximum force obtained is around 10.7N for initial length of 13cm.

5. **Frequency analysis of flat platform actuated by SMA springs under the influence of bias mechanism** - The frequency was found to be 10 compressions per minute. The average heating time was 3.5 seconds and average cooling time was 2.5 seconds.

Chapter VII: Conclusion and Scope

This idea of providing automated CPR with the help of SMA springs is noble and reliable. It has many advantages when compared to other mechanical CPR devices.

Available mechanical CPR machines are currently very costly in the market. The developed system is precise and uses SMA springs with high fatigue strengths, whereas, the already available techniques use a motor which drives the whole system and thus the system's life is shorter as the motor would wear out eventually after a certain time and you would need a new motor to run the system all over again, which thus increases the overall maintenance cost. Further the system is coupled with open source software's which can be modified easily. It may be noted that in earlier models, pistons of light plastic bag-type belts are used to provide compressions which required excessive care and lubrication. We, on the other hand, have used SMA springs which have a high fatigue strength and higher life. Many designs used pneumatic system for actuation. There is always a problem of leakage in such systems and it has to be dealt with.

Other advantages with using shape memory alloys:-

- High force per unit volume/weight
- Light weight and compact
- Robust
- Frictionless
- Low maintenance
- Low energy requirements
- It eliminates extraneous system like, hydraulic, pneumatic, mechanical

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