Implementation of the control system on a robotic spine
&
Validation of the benchtop model

By:
Siril Teja Dukkipati

Supervisor:
Prof. Mark Driscoll

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McGill University
Musculoskeletal Biomechanics Research Lab

817 Sherbrooke Street West,
Macdonald Eng. Bldg. office #357
Montreal, QC, H3A 0C3, Canada.

Cover Letter

To whom it may concern,

I, Siril Teja Dukkipati, am writing this letter with regards to this project taken up by me on June 10, 2019.

This project is a part of “Summer Undergraduate Research in Engineering Program” shortly known as SURE Program by the Faculty of Engineering of McGill university. The SURE program is meant to provide exposure to the research experience as well as opportunities to learn more about the graduate school experience and about careers in research.

The present project is titled as “Implementation of the control system on a robotic spine & Validation of the benchtop model” which focused on developing a benchtop robotic spine model consisting of artificial muscles and it’s validation so that,after validation, it can be used as a training tool. It is an absolute pleasure being a part of this project and the work culture. This project has shown me the biological side of the spine and our human body. I can confidently say that I have learned some software and hardware tools that I never could have learned. The knowledge of Biomechanics of our own system is very important as it helps in tackling daily life problems with technique and without damage to our system.

I conclude by urging my peers to indulge in research activities which gives an overall perspective of our own and our surrounding systems. Research only progresses when there is curiosity. Let the curiosity never die.

Thank You.

Siril Teja Dukkipati.

Declaration

I, Siril Teja Dukkipati, declare that this work titled, “Implementation of the control system on a robotic spine & Validation of the benchtop model” and the work presented in it are my own. I confirm that:

1. This work was done in the context of the SURE program at McGill University in Canada, while completing B.Tech in Mechanical Engineering at the Manipal Institute of Technology, Manipal, India.
2. no part of this work has previously been submitted for review or any other qualification at this University or any other institution.
3. I have acknowledged all main sources of help.

15 July 2019

Date

Signature

Acknowledgements

I would like to express my gratitude and warmest thanks, first and foremost, to my supervisor, Professor Mark Driscoll for his friendly support and valuable guidance throughout the project. He gave me the opportunity to experience McGill and its profound culture, to be a part of a wonderful research group and gain experience in a purposeful field of work.
I would like to extend my gratitude to Prof. James Forbes for his technical expertise and thanks to his amazing lecture on Control systems-101 when I needed.

My thanks extend to Brittany Stott for her willingness to help and give advice during the entire period of the project. I thank Emily Newell, for her encouraging and kind words and helping me in the literature study. And to all the other members of the Musculoskeletal Biomechanics Research Lab that welcomed me and motivated me every day. I am privileged to be a part of that work culture. Finally, I would like to thank my family, without whom I would not be the person who I am, and where I am today.

Contents

1. Introduction

Spinal cord is one of the major components of the human body which plays a role in the human stability and dexterity. Many studies have been carried out on human and animal cadavers which shines light on the internal mechanisms and spinal response to different load scenarios. But it is trivial that a cadaver cannot be used for everytime. Thus, a benchtop model of the spine consisting of ribcage, erector spinae and an abdomen is built. A system like this would be helpful in evaluating parameters like intradiscal pressure (IDP), Intramuscular pressure (IMP), Intra-abdominal pressure (IAP) and the deflection of the spine under different loading scenarios.

The robotic spine in this work is named TIM which stands for “Testing of Inflatable Muscles”. The ultimate aim behind this spinal model is to establish a validated benchtop model of the spinal cord with active muscles. The model then can be used for verifying different theories and any finite element analysis results.

This work is a part of SURE program and is the continuation of the work done by the first two groups who worked on modelling McKibben muscles and procuring the Spine and the components needed for the implementation of the control system.
The analogous spinal cord is equipped with McKibben muscles, pressure sensors for the intramuscular pressure, force sensors for capturing intradiscal pressure, and position trackers for the movement of the spinal cord under loading conditions.

2. Problem Statement

The valves are controlled manually to adjust the pressure in the muscles. This is very laborious and time consuming. Also, the benchtop model itself is not validated. The response of the spine is not mapped to any in vivo observations.

The aim of 2019 SURE program is to tackle these two problems : “Develop a control system for muscle pressure, position data, IDP measurements and Validation of the benchtop model of the robotic spine.”

This is done by developing a control system for the muscle pressures and integration all the sensors to a user friendly LabView based GUI. Further, different loading scenarios are to be simulated and the spinal response is to be captured.

3. Past Works

This work is the third addition to the robotic spine project. The first two groups laid the foundations for the present work.

Thomas Jansen worked on the characterization of the McKibben muscles and conducted experiments to quantify the pressure-force characteristics of the different types of muscles. This work showed that there is a linear relation between the pressure in the pneumatic muscle and the pulling force generated by the muscle. This data is used in the present work to adjust the muscle pressures in order to stabilize the spine under loading.

Brittany Stott, Laura Fasanella, Benjamin Francolini, Jody Haig sourced and procured all the necessary parts and worked on the assembly required for the functioning of the robotic spine.

The current edition involves the development of the control systems for the muscles, force and position data acquisition and validation of the benchtop model.

4. Muscle Control

To respond to external stimulus, human muscles compress by pumping the muscle fluid into the and pull the bones attached to them thus causing them to move. The spinal cord reacts in the same way by activating a specific set of muscles for the different kinds of movements. In order to replicate this mechanism, McKibben muscles are chosen as they have predictable force-pressure relation and significant contraction characteristics.
The assembly of the McKibben muscle on the spinal cord is shown below.

Fig.1 Arrangement of Artificial muscles on the spinal cord - Erector Spinae

The source of pressurized air is the air compressor that delivers air to all the valves. The inlet pressure is restricted to 40PSI because of the problems associated with the air compressor size and the muscle strength. The air compressor used is small and can only hold upto 22.7 Lit. Also, if the pressure is too high, the pressure sensors will pop out of the muscles.Due to this, the bleed rate is restricted at 40 PSI. To pull the spinal cord, the muscle is fed with pressurized air. So a pressure controller is developed based on PID algorithm in LabView using the Autotuning PID Virtual Instrument.

4.1. Hardware

4.1.1. Valves

The valve used for the pressure control is a solenoid type switch valve from Burkert. It is a plunger type valve, 2/2 way direct-acting, Type 6011. These valves are fitted and sealed on the manifold for distribution. The air supply from the compressor is directly plugged into the manifold. With the help of the valve switching, the pressure distribution in the muscles is controlled.

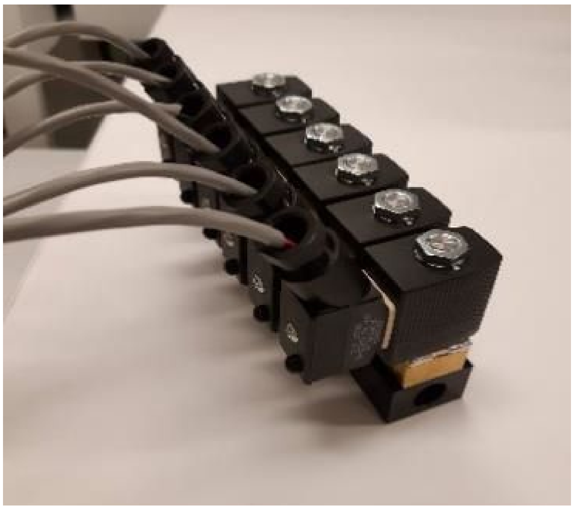

Fig.2 Solenoid valves and the manifold for pressurized air distribution

4.1.2. Data Acquisition System

National Instruments Compact data acquisition system (NI cDAQ-9178) is used to acquire and transmit the data from the computer to the benchtop model and vice versa. 4 NI-9485 8-Channel Solid state relay digital output modules are used to send commands to all the valves and NI-9205 analog card is used to acquire data from the pressure sensors.

Fig.3 From left to right -NI-cDAQ-9178, NI-9485, NI-9205

4.1.3. McKibben Muscle

The artificial muscles are McKibben muscles which exhibit linear force-pressure and force-contraction relationships. These characteristics of the muscles result in building a simple kinematic model of the spine.

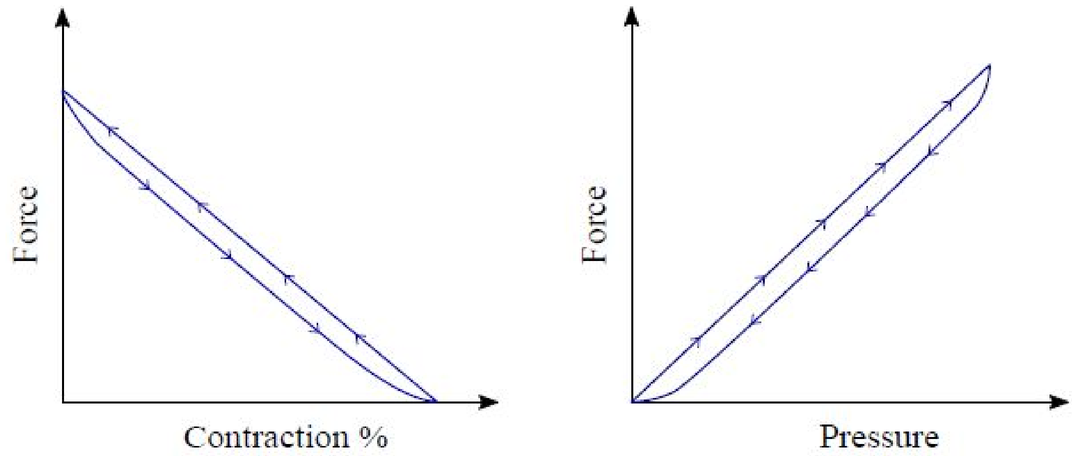

Fig.4 Force-Contraction and Force-Pressure correlation. Taken from the work of Thomas Jansen.

Given that the force output is linear in response to the pressure in the muscle, to manipulate the force, a pressure controller is built and pressure is adjusted according to the force requirements.

4.2. Software

Matlab and Labview are two options to choose from as they both can be used for data acquisition and control. Matlab is best for complex simulations and operations involving higher level functions. Labview is focused on data acquisition and processing. Both the softwares are user friendly.

The position tracking system i.e. Polhemus has Labview libraries that enable the serial communication between the tracking console and the computer which makes it very easy to interpret and record the Position data. The force sensor has a USB 2.0 output. NI Visa is used for the communication between the device and the computer.
Thus Labview is chosen as the development environment after considering all its merits.

4.3. Pressure Sensor

The pressure sensor gives a voltage output depending upon the pressure applied and is acquired from Omega serial numbered PX26-100GV.

Fig.5 Omega PX26-100GV Analog Pressure sensor

First, the raw data from the sensor is amplified by a factor of 1000 as the sensor output is in millivolts. Then these values are mapped to the actual pressure value in the muscle through manually controlling the pressure. The values are tabulated for all the sensors and graphs [Misc. Section] are plotted. Polynomial fit is selected based on the best R^2 value.

Pressure (PSI)	Muscle 1	Muscle 4	Muscle 2	Muscle 7	Muscle 6	Muscle 11
0	89.45	96.3	100.9	-1.5	91.1	92.73
5	90.6	97.3	101.9	-8.4	92	94.05
10	91.6	98.3	102.9	-15.5	92.9	95.21
15	92.6	99.5	103.9	-22.4	93.7	96.24
20	93.75	100.35	104.9	-29.8	94.9	97.18
25	94.75	101.3	105.9	-35.5	95.8	98.05
30	95.8	102.4	106.7	-42	96.7	98.87

Table.1 Pressure sensor calibration data

4.4. PID Definition and Working

A **P**roportional–**I**ntegral–**D**erivative controller or Three-term controller shortly called as a PID Controller is chosen because of the simplicity of its application. The gains can be estimated using simple tests even for a complicated system. Labview offers a package for PID controller design. The Mathematical form of the controller is represented as below.

$$u(t) = K_{\text{p}}\left(e(t) + \frac{1}{T_{\text{i}}}\int_0^t e(t')\,dt' + T_{\text{d}}\frac{de(t)}{dt}\right)$$

The coefficients Kp, Ti, Td in the above equation are called the PID gains. The PID controller takes the feedback from the system and imposes it on the next output thus by minimizing the distance between the setpoint and the process variable i.e. pressure in this case.

An autotuning PID controller based on the major tuning principles has been developed. The tuning rules include Ziegler-Nichols, Cohen-Coon, Chien-Hrones-Reswick, Internal Model Control. The Zigler-Nicholas rules are tested and proven to be effective in this particular setup.The pressure transducer is a voltage varying type transducer. The data from this transducer is fed to the controller which gives the output. Based on this output, a PWM signal is generated which is used to control the exhaust valve. For the sake of simplicity, only the exhaust valve is actively controlled - [*discussed in section-4.7*]. The inlet valve is left open and can be closed from the GUI incase of any mishap.

4.5. Implementation with PWM

PWM stands for **P**ulse **W**idth **M**odulation. The solenoid valve in usage is a DC valve with the voltage rating of 24V. So there are only 2 states that the valve can be in - Open or Close. There are no intermediate positions.

The PID controller gives an analog output based on the setpoint and the feedback from the pressure sensor. But a digital signal is needed to activate the valve. This is achieved by creating a PWM signal depending on the output of the PID.

The gradient of the process variable is assessed -whether it is increasing or decreasing. If it is increasing, the PWM is set to the ON position. If the process variable is decreasing, PWM is set to OFF position. This method enables to interpret the analog data from the controller in a digital format. This digital information then used to control the valve through the solid state relay module.

4.6. Gains

Based on the above step response test results, the system is modelled considering that it is a Simple 1st order model. This contains 5 essential steps.

1. Inspection

   It is important to first check the system for any unnecessary elements that can hinder the control. The pressure valve is a solenoid valve which is in closed position by default. It is in open state when energized with 24V DC. Cross check the voltage supplied to the valve and the pressure sensor. The pressure sensor readings can sometimes be affected by the cleanliness of the supply i.e. there should not be any noise and fluctuations in the power supply to the system. Also check the pneumatic connections and the air supply pressure for any irregularities.

2. Manual Bump Test

   To determine the PID gains, the step response data of the sensor is necessary. From the results obtained, the plant parameters are determined and accordingly the gains are set in the model section. 10 trails in total have been performed. 5 trails with a step of 20 psi and 5 with a step of 30 psi. The sensor response has been plotted against time.

   At t=0 sec, plotting is started, valve is in the off position.
   At t=5 sec, Valve is turned ON (0 to 20 psi) (0 to 30 psi)
   At t=15 sec, Valve is turned OFF (20 psi to 0) (30 psi to 0)
   At t=20 sec, plotting is stopped (for 20 psi category)
   At t=20 sec, plotting is stopped (for 30 psi category).

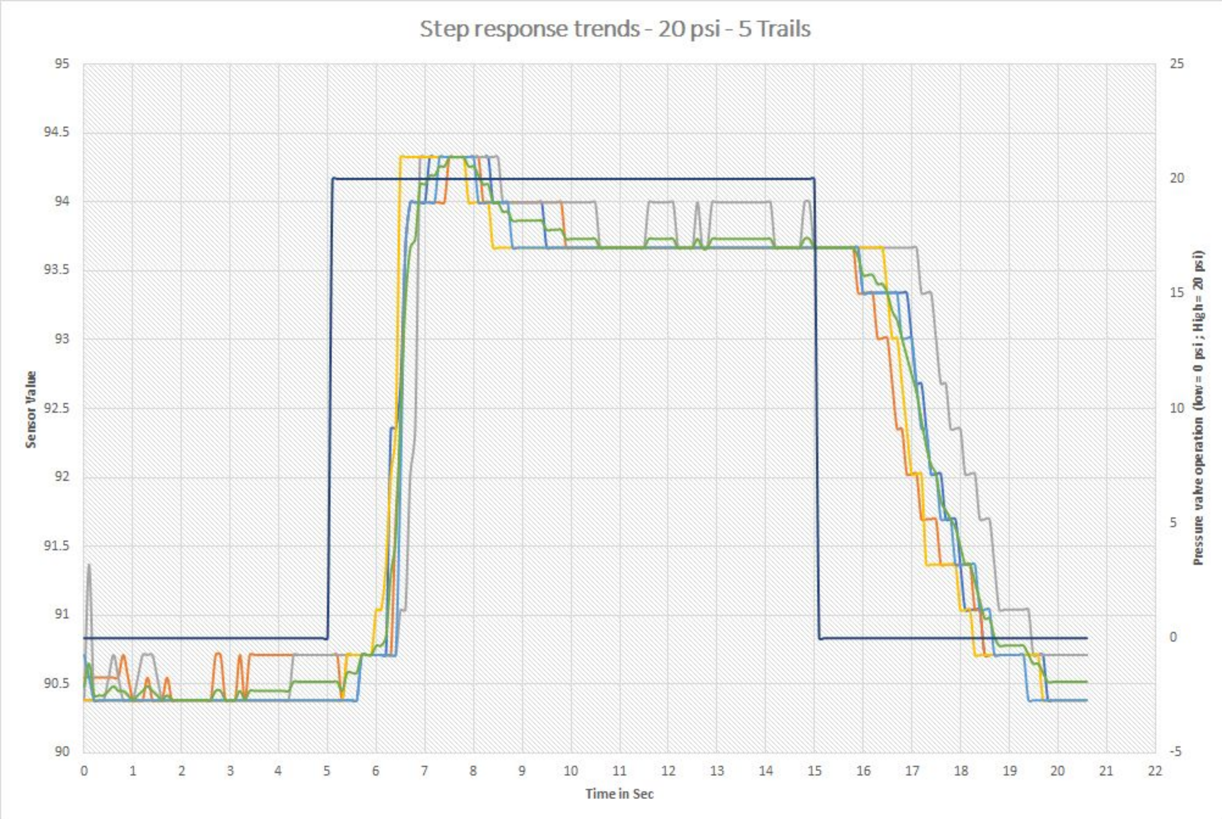

Fig.6 Step response test - 20 PSI

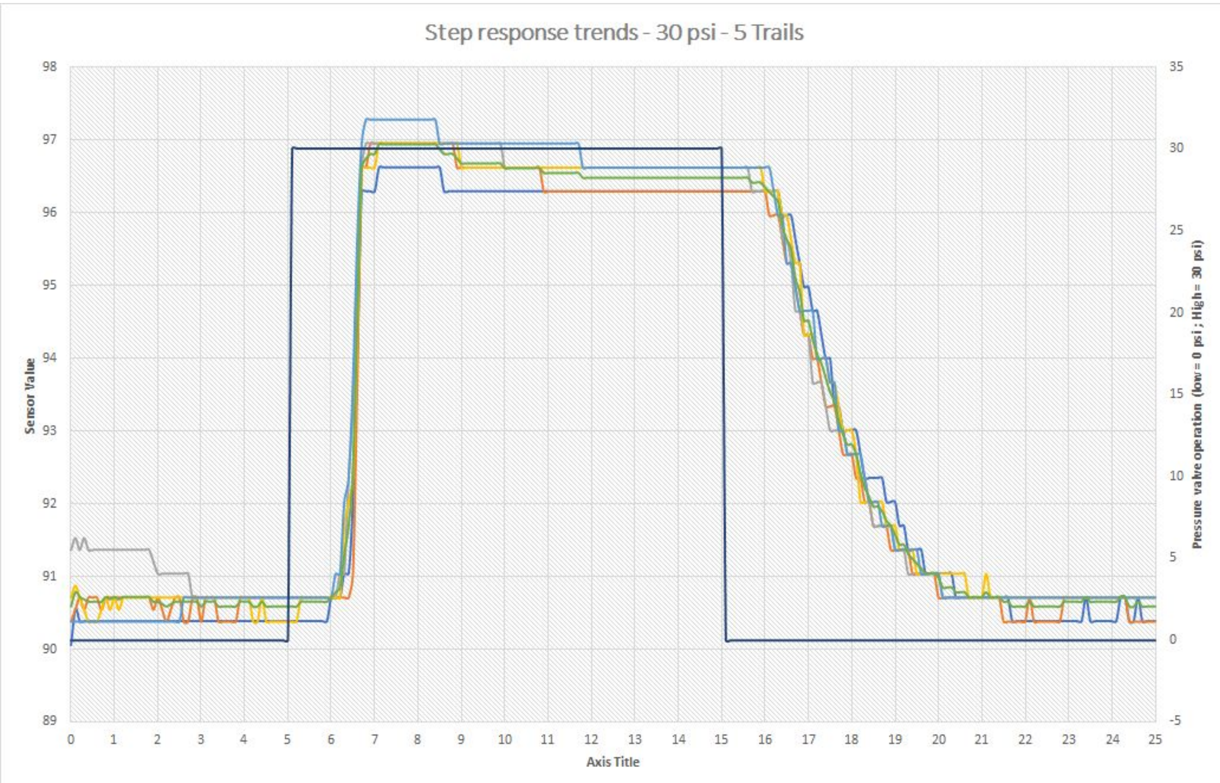

Fig.7 Step response test - 30 PSI

3. Model

Terminology:

A. <u>Process Variable (P.V):</u>

A process variable, process value or process parameter is the current measured value of a particular part of a process which is being monitored or controlled. In this scenario, it is the sensor data.

B. <u>Output:</u>

It is the actual parameter change in the system. In this case, it is the pressure. As mentioned earlier, the change in the output is the step value of the test i.e. 20 PSI and 30 PSI.

C. <u>Time:</u>

It is the time taken by the sensor to reach a stable value.

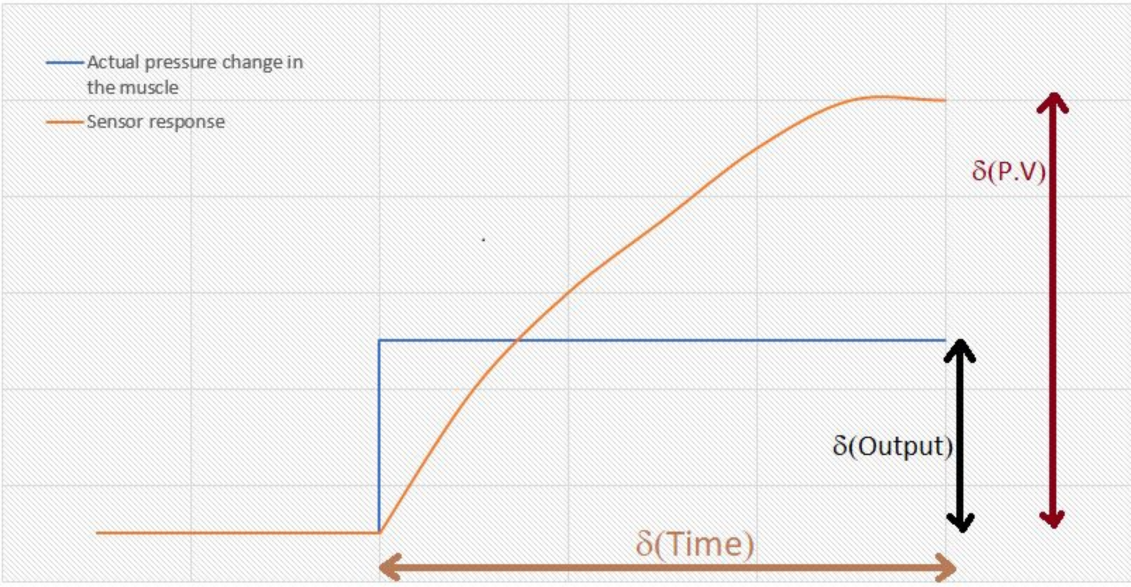

Fig.8 Model step response test defining the terminology

Open loop process gain (Kp) = $\frac{\Delta(P.V)}{\Delta(Output)}$

Open loop time constant (τp) = $\frac{\Delta(Time)}{4}$ or the approximate time taken for the process variable to reach 63.2% of the set point value.

These two parameters define the process dynamics. From the step response results, Kp and τp are calculated.

Kp= 0.1625 τp= 1.25 sec

4. Tuning

In this step, the gains are calculated based on the captured system dynamics. Assuming that the system is a simple 1st order close loop, the gains are set as:

Kc = $\frac{1}{Kp * \tau\ ratio}$ Ti = τp Td= 0

τ *ratio* is defined as the ratio between the closed loop time constant and the open loop time constant. It is a representation of the speed of the controller. In the frontend, while autotuning, this parameter can be changed under “Ziegler-Nichols tuning rule” as per the requirement.

In this way, the gains are predicted as

Kc =0.6153 Ti =0.02 min Td= 0

These values are calculated based on the response of one sensor. Assuming the characteristics are the same across all sensors, these gains are set to all the valve control systems. Note that these values are only a starting point to start the controller. These values can be updated by tuning the gains by following the instructions in the Labview file.

5. Verification

   After the gains are set, the model is verified by changing the setpoint. If the pressure reaches the setpoint and remains between the allowed error band, then the model is said to be complete. If the process variable oscillates about the setpoint, it is recommended that the loop is autotuned with the help of the instructions mentioned in the VI.

4.7. Strategy

To control the pressure in the muscle, essentially, there is a need for two valves. An inlet and an outlet. Actively controlling both inlet and outlet is very complex because of the dependency of the inlet valve state on the outlet valve state or vice versa. Such a system requires two controllers to maintain pressure in a single muscle which increases the computation power. Moreover, it is redundant of these kind of simple systems.
So, the inlet valve is always kept open and only the outlet valve is actively controlled by the PID controller.

All the configurations that are feasible are listed below.

1. Inlet - Active Control Outlet - Always open
2. Inlet - Active control Outlet - Constant high frequency PWM (which simulates a leak in the system)
3. Inlet - Always open Outlet - Active Control

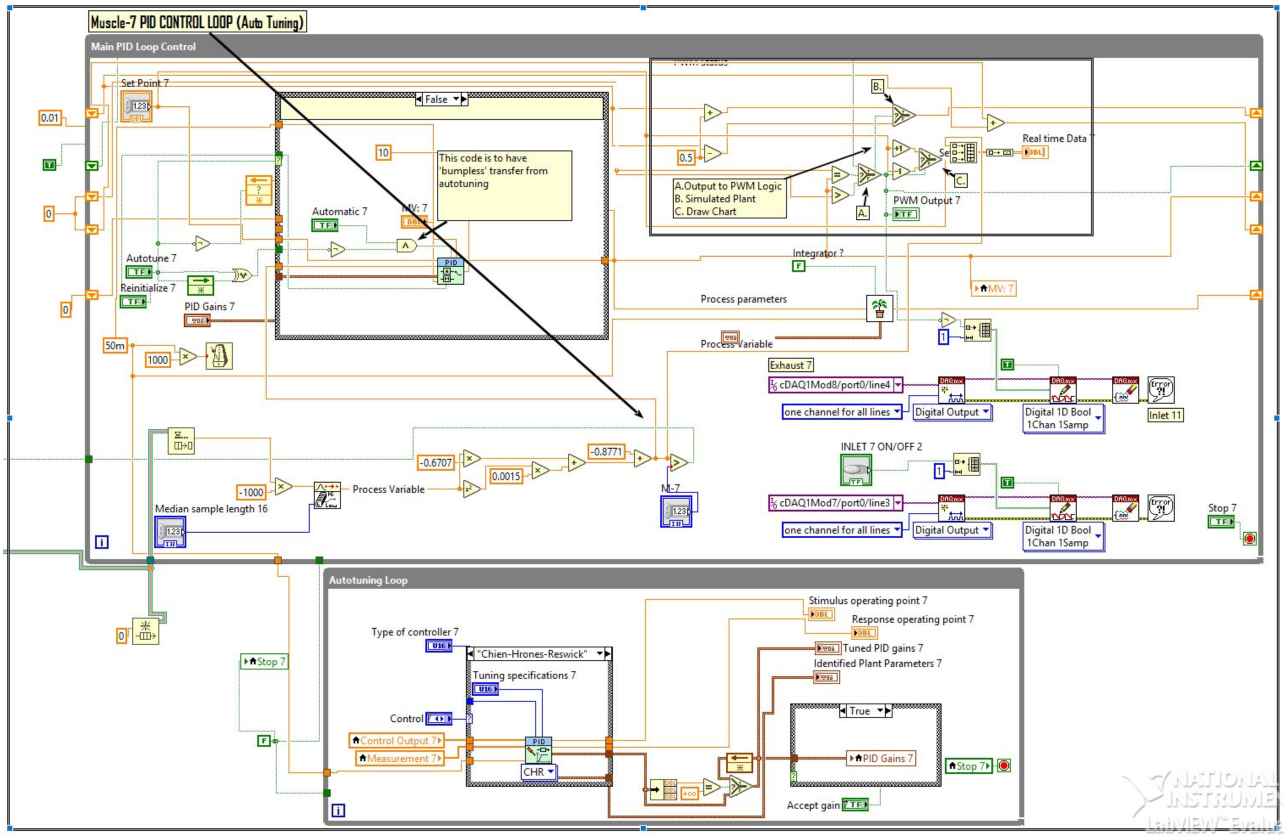

Fig.9 Muscle control loop developed in LABView

5. Spinal movement

Spinal deflection is one of the main criteria in defining the stability of the spine. So it is important to track the positional data of the spine under loading conditions.

5.1 Polhemus tracking system

Polhemus position tracking system is used for this purpose. 4 sensors are fixed on the spine to track its movements. The real time data is read into LabView and is plotted on the XY graph. Polhemus library is used for the serial communication of the device. The sensor is a MicroSensor 1.8 and the tracker is Polhemus Fastrak III. The sensor works in non line of sight also. The tracker is fixed on the base plate of the setup. The USB from the Fastrak III is plugged into the computer for the serial communication.

Polhemus Library has Vis that are used to connect to the device in a step by step process. The Sequence gives out an array called “XYZAER” which is read into a while loop that updates the current value of the variable. The “XYZAER” array is a 1D array of a cluster of 6 elements called “6VEC”. The array contains data of all the 4 sensors and each cluster of “6VEC” corresponds to a sensor. The cluster is further split into individual data points for plotting and recording. In the above shown VI, only the x,y,z coordinates are extracted and as the orientation does not matter for a point.If there is a need to read the orientation angles: a,e,r, they can be read from the cluster.

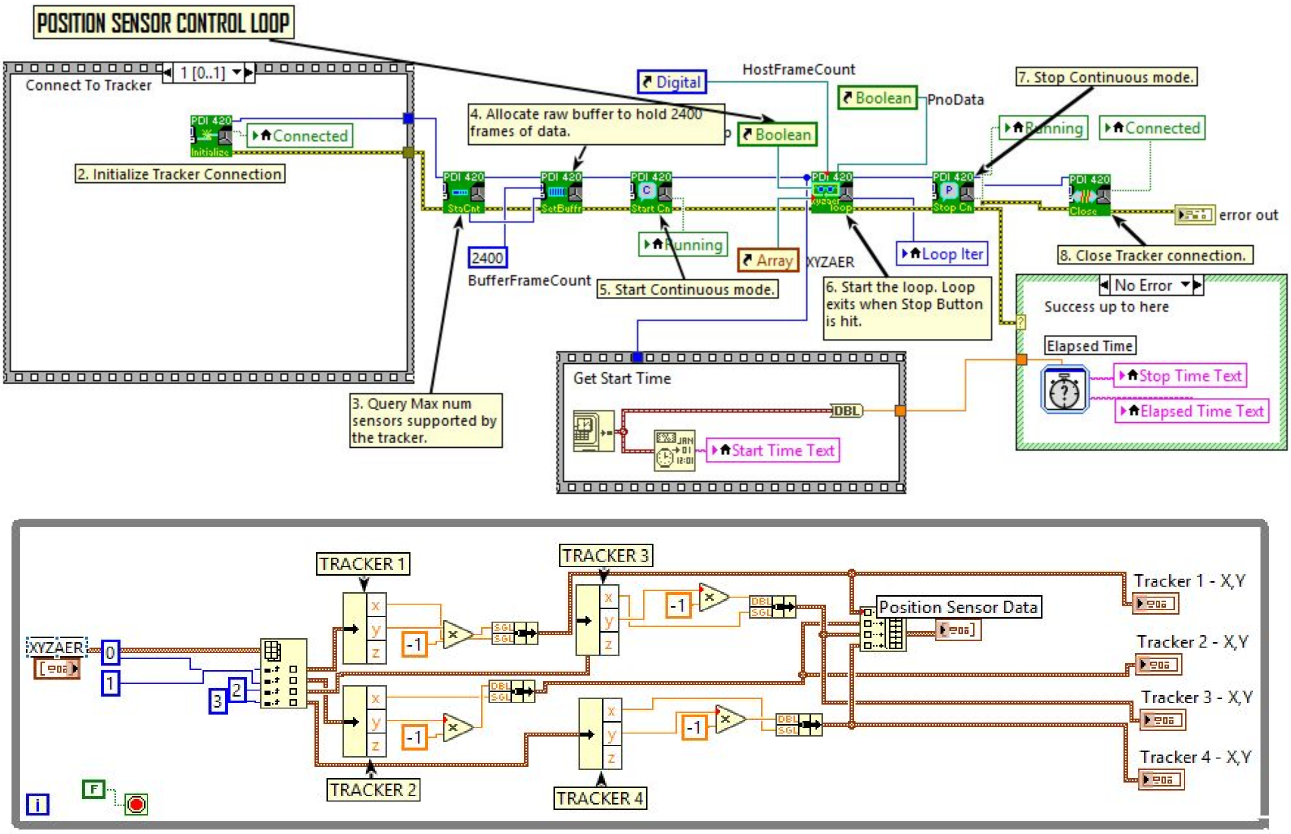

Fig.10 Position Sensor control loop developed in LABView

5.2 Sensor Placement

To track the displacement of the spine, the 4 position sensors are strategically placed on the ends L5, C7 and on the inflection points L2, T9. These positions are selected because they are the inflection points of the spine. Once the positions of these points are obtained, it is easy to interpret the shape of the spine.

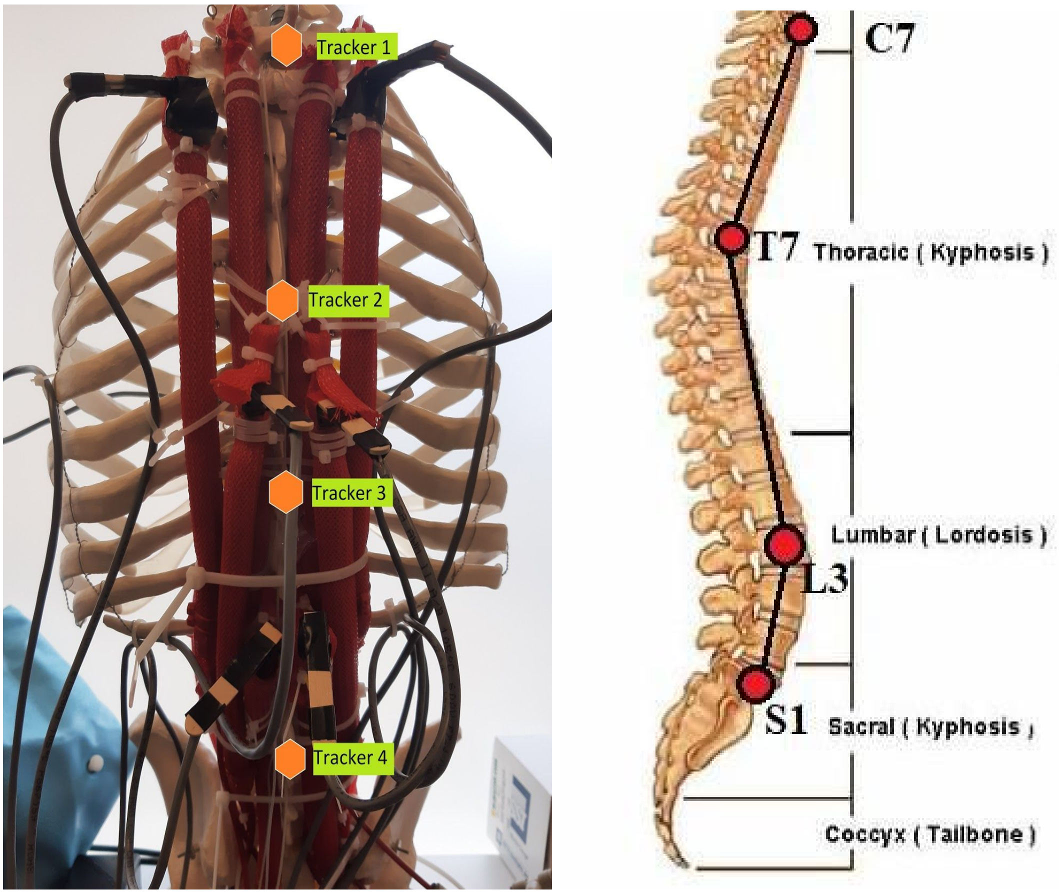

Fig.11 Position Sensor placement - From the work of Brittany Stott, Laura Fasanella, Benjamin Francolini, Jody Haig.

6. Intradiscal Pressure

Intradiscal pressure is defined as the pressure experienced by the vertebral disc due to the compressive forces and moments on the spine. The study of IDP is important as high values of IDP is an indication of low back pressure, disc degeneration or rupture.

6.1. Flexiforce Sensor

Resistive force sensors are selected because of their flexible design. In particular the FlexiForce A201 Sensor is selected with a range of 25lb.

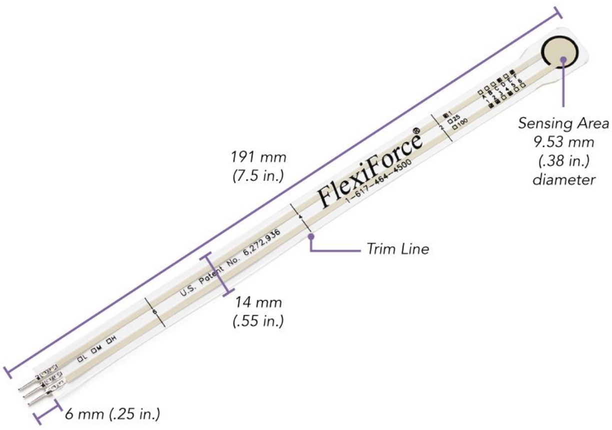

Fig.12 Flexiforce sensor from Tekscan

The output from the sensor is read through serial communication module - NI VISA in Labview. Then, the sensitivity of the sensors are adjusted to the use case and are calibrated. A linear fit model is used in the calibration graph with an acceptable R^2 value. The calibration graphs are shown in section 13. The force values are then dynamically plotted on the waveform chart from where they can be exported to Excel for analyzing the data. A control loop is developed in LABView to read the data using NI-Visa for serial communication.

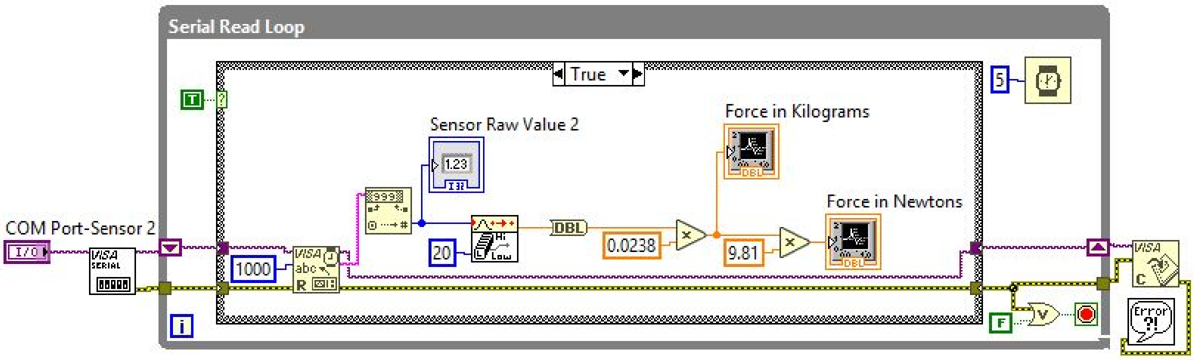

Fig.13 Serial Read loop for Force sensor data

The theoretical intradiscal pressure can be estimated by obtaining the average reaction force between the two vertebrae and dividing it by the disc cross section area. The average cross section area of the T8-T9 disc is 671 mm2 according to the vivo data provided in [3]. But the benchtop model vertebrae cross section areas are smaller and are approximated as 625mm2 and 400mm2 for L3-L4 and T8-T9 respectively.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
UEW (mm)	24.5	24.9	24.6	24.5	24.9	26.2	27.8	29.5	30.6	31.9	34.9	39.0
UED (mm)	18.5	19.6	22.7	23.3	24.3	26.0	27.4	27.9	29.3	30.5	31.9	32.8
LEW (mm)	27.8	27.4	25.9	26.0	27.0	28.2	29.1	30.5	33.0	35.4	39.1	42.1
LED (mm)	19.7	21.6	23.3	24.5	25.8	26.9	28.5	29.4	31.0	31.6	31.8	33.4
VBHp (mm)	14.1	15.6	15.7	16.2	16.2	17.4	18.2	18.7	19.3	20.2	21.3	22.7
UEA (mm^2)	300.	333.	373.	381.	426.	483.	547.	605.	678.	727.	842.	954.
LEA (mm^2)	376.	398.	412.	444.	495.	552.	603.	664.	755.	834.	945.	1024.
UEIt (degrees)	0.8	1.7	2.4	1.5	2.1	2.1	1.6	1.3	0.9	0.5	2.7	2.2
LEIt (degrees)	3.9	1.8	2.1	2.0	1.8	2.0	2.3	1.2	1.2	2.2	1.8	2.0
SCW (mm)	21.8	19.5	18.3	17.0	17.1	17.3	17.3	17.7	17.9	18.2	19.4	22.2
SCD (mm)	16.4	15.3	15.9	16.2	16.3	16.5	16.1	15.9	15.7	15.5	16.0	18.1
SCA (mm)	213.	200.	189.	192.	201.	206.	199.	194.	200.	202.	220.	280.
PDW (mm)	8.2	8.4	7.0	5.5	6.2	6.0	6.5	6.7	7.6	8.3	8.8	8.8
PDH (mm)	9.3	11.1	11.8	11.9	11.2	12.0	11.8	12.5	13.9	14.7	16.9	16.5
PDA (mm^2)	52.2	46.3	38.1	32.5	31.6	3.5	36.8	43.8	52.3	64.8	88.4	90.9
PDIs (degrees)	28.1	28.9	22.5	21.8	20.2	19.4	23.4	22.5	19.3	14.4	12.9	8.0
PDIt (degrees)	4.6	16.5	8.1	6.4	8.6	7.0	10.9	12.1	8.3	6.8	8.9	4.8
SPL (mm)	50.1	52.1	51.7	51.1	52.1	53.8	50.5	52.8	51.3	49.3	45.6	47.4
TPW (mm)	75.3	69.4	60.8	56.9	61.1	61.3	60.4	59.9	59.3	58.4	52.2	46.9

Key: The first two letters indicate anatomic part; the third letter indicates dimension. Figure 1–18 depicts the anatomy of a vertebra in detail.

UE = upper end-plate
LE = lower end-plate
PD = pedicle
SP = spinous process
SC = spinal canal
TP = transverse process
PI = pars interarticularis
VH = vertebral body

W = width
A = area
D = depth
H = height
I = inclination
t = transverse plane
p = posterior

(Based upon data from Berry, et al.,[31] Cotterill, et al.,[47] and Panjabi, et al.[182])

Fig.14 Average values of the Thoracic vertebral dimensions

6.2 Sensor Placement

Two force sensors are inserted in the discs to track the changes in the IDP while loading as we have a knowledge of the average cross sectional disc areas. The position of the sensors can be changed as per the requirement. Fig.15 shows the arrangement of the sensors. The sensors are strategically placed at the inflection points of the spinal cord.

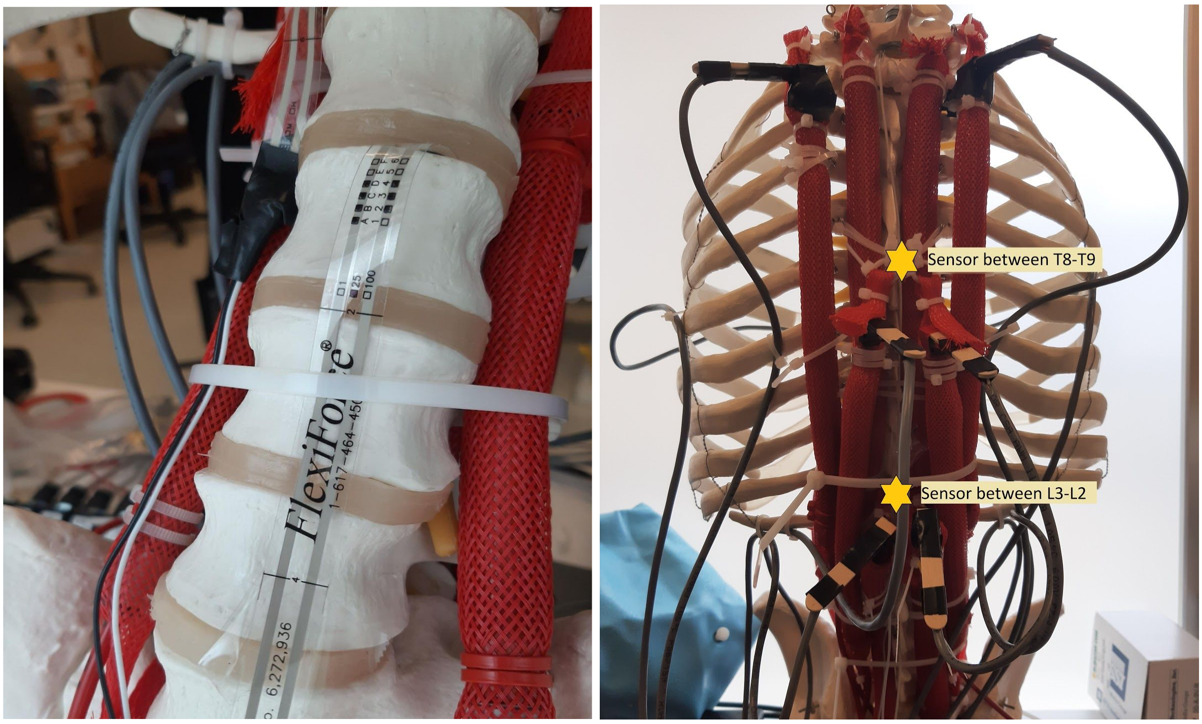

Fig.15 Force sensor placement

7. Loading scheme

The spine is subjected to a compressive load of 5kg. The artificial muscles are pumped with air and maintained at appropriate pressures to stabilize the spine. There are different definitions for spinal stability. The one in consideration is quoted in section 7.1. As per this definition, the benchtop model is validated.

7.1 Definition of Spinal Stability

The following definition is taken from the “White Paper on Sagittal Plane Alignment” by “Scoliosis Research Society“.

“Normal sagittal balance = congruent postural alignment of cervical lordosis, thoracic kyphosis and lumbar lordosis that is proportional and produces a sagittal plumb line passing from the center of C7 through the L5-S1 disc space or within 2 centimeters of the sacral promontory and through or behind the hip axis.”

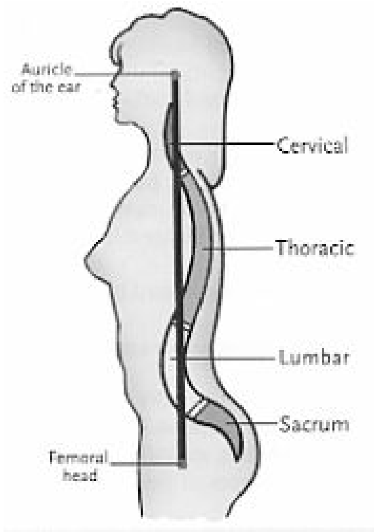

Fig.16 Definition of Spinal Stability

7.2 Plumb Line

The plumb line is drawn from the top of the spine i.e. C7. The plumb line should be ±2 cm (0.787 in) from the posterior superior aspect of the S1 vertebra. The position of the C7 vertebra can be easily tracked by the polhemus tracking system. Thus, under loading, the aim is to balance the spine along with the active four erector spinae, four multifidi, two psoas major, and two rectus abdominis.

7.3. Test Protocol

Step 1: Set the muscle group set points to the required calculated values.
Step 2: Fill the compressor to 150 PSI and release the valve.
Step 3: Run the VI and wait for the pressure to stabilize.
If there is a significant deviation in the setpoint and the actual pressure, the gains can be tuned using Autotuning as per the instructions mentioned in the VI.
Note that this is only done if there is a need.
Step 4: Start the Force sensors by pressing the button “S1” on the breakout circuit.
If this is not done, a dialogue box appears summarizing the timeout issue.
If this happens, restart the VI.
Step 5: Make sure that the Polhemus tracking system is connected.
Make sure that the indicators in the VI turn green.
If this does not happen, restart the VI.
Step 6: Load the spine carefully and wait for the pressure to stabilize.
Run the test for 90 seconds after the stabilization.
Step 7: Unload the spine and stop the VI.
Step 8: Export the data to excel sheet from the front panel for post processing.

8. Results

8.1 PID Performance

The performance of the PID controller can be quantified by the plant variables like Reaction time, offset, oscillation etc. These parameters are highly dynamic and depend on the sensor response, valve timing etc. Fig.17 shows the performance of the algorithm. The reaction time is 4 seconds before it reaches the set point and the error is ± 1 PSI.

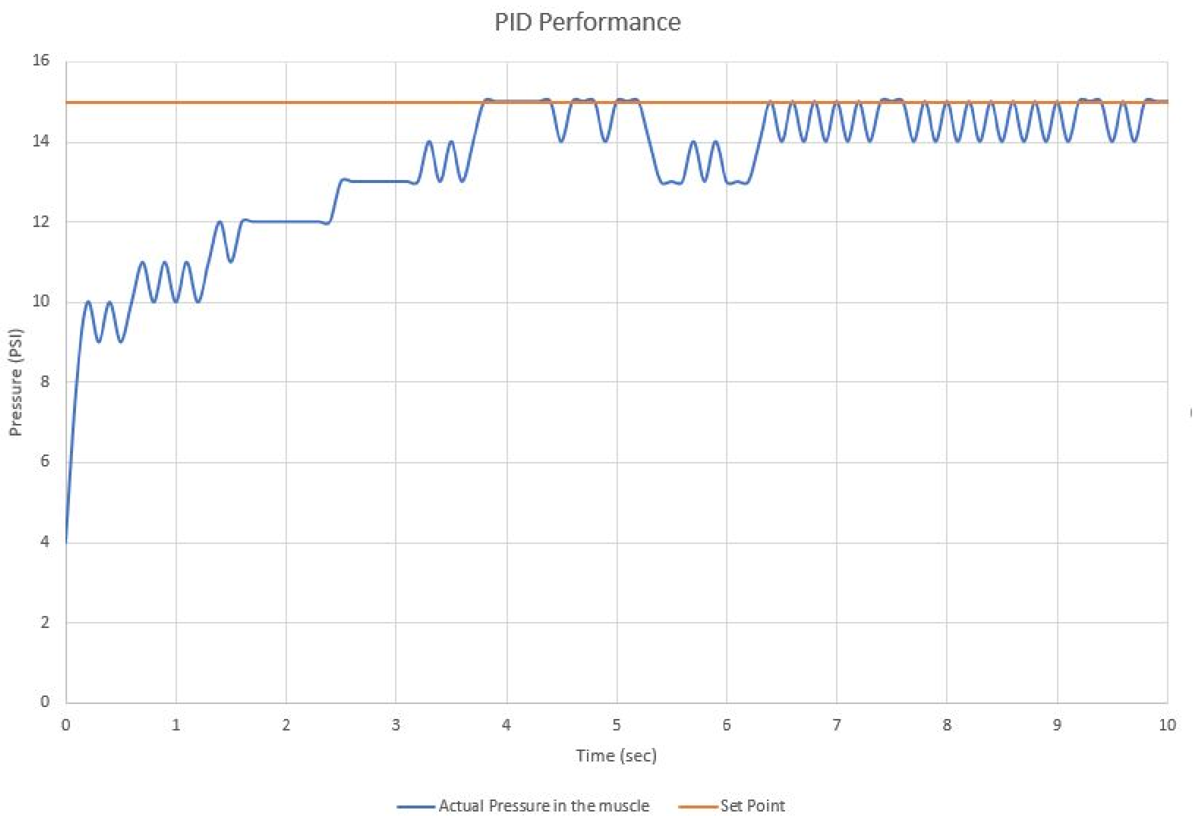

Fig.17 PID Performance

The performance of the algorithm can be improved by tuning the controller and by selecting the right hardware. The pressure sensor output is very noisy and had to be passed through a median filter for smoothing. This filter takes in 100 values at a time and computes the median. This process increases the reaction time thus affecting the performance of the PID. Other filters can also be applied.

8.2 Loading Graphs

With the direct compressive load of 5kg on the spine, and when the IMP is maintained at 15 PSI in all the muscles, the IDP is found to be 0.08 MPa between L3-L4 and T8-T9. The IAP is maintained at 0.8 PSI approximately.
The weights are placed directly on the T1 of the spine. This loading scenario may be compared to a person carrying load on the head (Head-Carrying). This practise is commonly

observed in most rural parts of the world as an alternative to carrying loads on the back and shoulders etc.

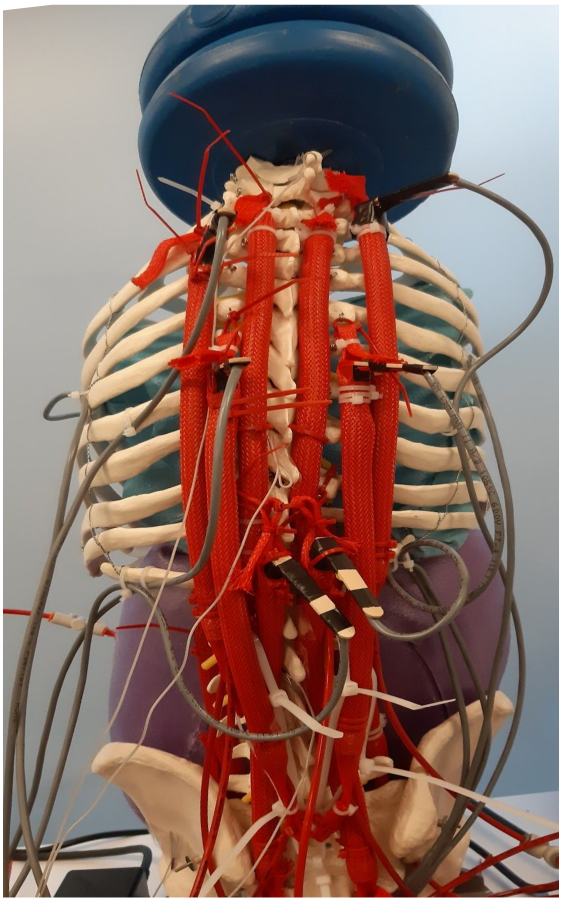

Fig.18 Compressive load on the benchtop model

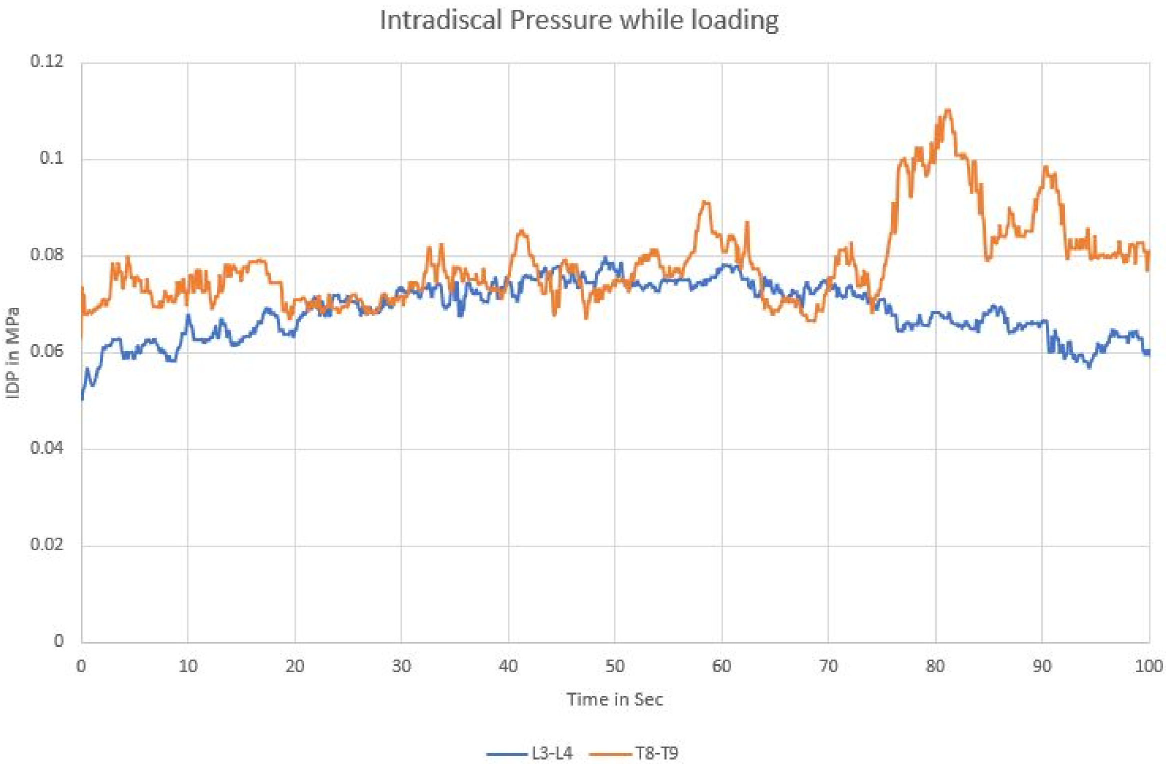

Fig.19 Intradiscal Pressure while compressive loading on the benchtop model

8.3 Spinal Deflection

According to the definition of spinal definition as explained in section 7.1, a plumb line is drawn from C7 until the bottom of the spine. This line should be within ± 2 cm from the posterior superior aspect of the S1 vertebra.

Position sensors are placed on the spine according to section 5.2 and care is taken that the spine is stable throughout the loading. If the spine is not stable, the muscle positions and tensions on the spine are corrected manually and the experiment is freshly started.

8.4 interpretation

The in-vivo measurements of the IDP range from 0.5 to 1.5 MPa between L3-L4in an average human being. The IDP observed in the benchtop model is around 0.08 MPa.
This is due to the fact that only 1 muscles in total are actively supporting the spine and the vertebrae and the discs themselves vastly vary from the in-vivo data in physical properties.

It is observed that the abdomen plays an important role in the biomechanics of the spine. The Intra-abdominal Pressure supports the spine in carrying the load and keeping the spine in upright position under loading. The less the IAP, the more the deflection of the T1 from the plumb line. Also, the IAP helps in lowering the IDP by sharing a part of the applied compressive load.

9. Conclusion and Future Works

The aim of the project is to develop a control algorithm from muscle pressures and to validate the benchtop model. The control system for muscle pressures is developed and is fully functional. Currently, there are only 6 pressure sensors working as the muscles are grouped into 6 groups. With the addition of more pressure sensors, all the muscles can be individually controlled. The position and force sensors are integrated into the same GUI containing the pressure control for ease of use. In-vivo data is studied for the purpose of validation of the benchtop model. The results from the tests conducted on the benchtop are described in section 8. These results don't correlate with the actual invivo results because of the following reasons:

1. Inclusion of only 12 muscles in total. In reality, there are many more.
2. Physical properties of the benchtop model like weight, density does not compare to that of the actual human spine.
3. Compression properties of the artificial muscle are different from the human muscle.

The fact that the recorded IMP in the benchtop model being as high as 30PSI can be justified by the argument that only 12 muscles are used in the benchtop model. Each muscle in the model can be considered as a collection of muscles in reality.

In this work, only the exhaust valve is actively controlled by the PID control. The inlet valve is left open. Active control of both inlet and exhaust valves for more precise control and to minimize the muscle pressure fluctuations can be implemented. The pressure sensor hardware can be upgraded to a better model. The present hardware is highly unreliable and needs frequent calibration. This affects the efficiency of the PID algorithm as this hardware is the only source of feedback from the system.

10. References

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11. A.Rohlmann , T.Zander,M.Rao,G.Bergmann, "Realistic loading conditions for upper body bending", 20 January 2009.
12. William S.Cobb, Justin M.Burns, Kent W.Kercher, Brent D.Matthews, H.James Norton, B.Todd Heniford, "Normal Intraabdominal Pressure in Healthy Adults"

11. Control Manual

Step 1 : Place the abdomen sack (purple) and the lungs sack (sky-blue) in place.
Step 2 : Switch on the compressor and let the pressure reach the cutoff point i.e. 150 PSI
Step 3 : Fill both the sacks with required pressures. The abdomen pressure is set to 1 PSI in the above experiment. The lungs sack is just for representation.
Step 4 : Check the connections in the DAQ.

If not altered, the connections should remain as mentioned below.

Muscle No	Pressure Sensor	Inlet Valve	Exhaust Valve	Muscle Groups
1	ACH 1	DAQ2 - CH7	DAQ1 - CH7	
5	--	DAQ2 - CH5	DAQ1 - CH5	
3	--	DAQ7 - CH6	DAQ8 - CH7	
4	ACH 4	DAQ7 - CH4	DAQ8 - CH5	
2	ACH 2	DAQ2 - CH6	DAQ1 - CH6	
7	ACH 7	DAQ7 - CH3	DAQ8 - CH4	
6	ACH 6	DAQ2 - CH4	DAQ1 - CH4	
8	--	DAQ7 - CH2	DAQ8 - CH3	
9	--	DAQ2 - CH3	DAQ1 - CH3	
10	--	DAQ7 - CH5	DAQ8 - CH6	
11	ACH 5	DAQ2 - CH2	DAQ1 - CH2	
12	--	DAQ7 - CH1	DAQ8 - CH2	

Table.2 DAQ Connections

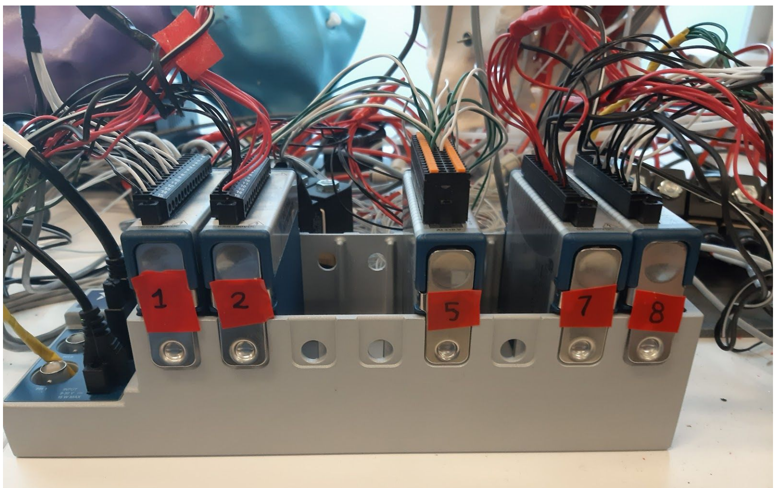

Fig.20 DAQ and the solid state relays in the slots

Step 5 : Power the DAQ
Step 6 : Power the pressure sensors by powering the 24V power supply.

Fig.21 Power supply unit to the pressure sensors

Step 7 : Power the inlet and exhaust valves through AC to DC adaptors.
Step 8 : Connect the USB cables from the force sensor breakouts directly to the CPU.
Step 9 : Find the Labview file named “Modified for Testing” and run it. The following page should appear.

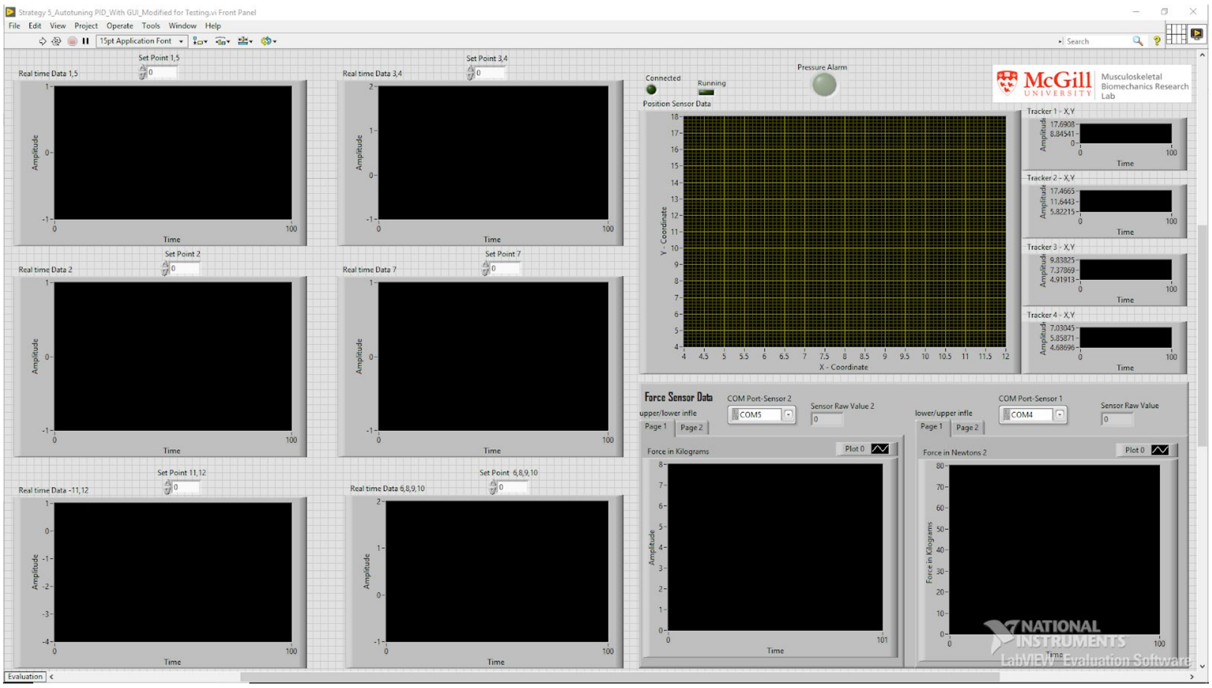

Fig.22 GUI

Step 10 : Set the individual muscle group pressure set points and run the VI.

Step 11 : Press the “S1” button on the force sensor breakout board to start the force sensor. “S2” button is for tare.
Step 12 : After the testing is done, to extract the test data, right click on the graph and export the data points to excel.

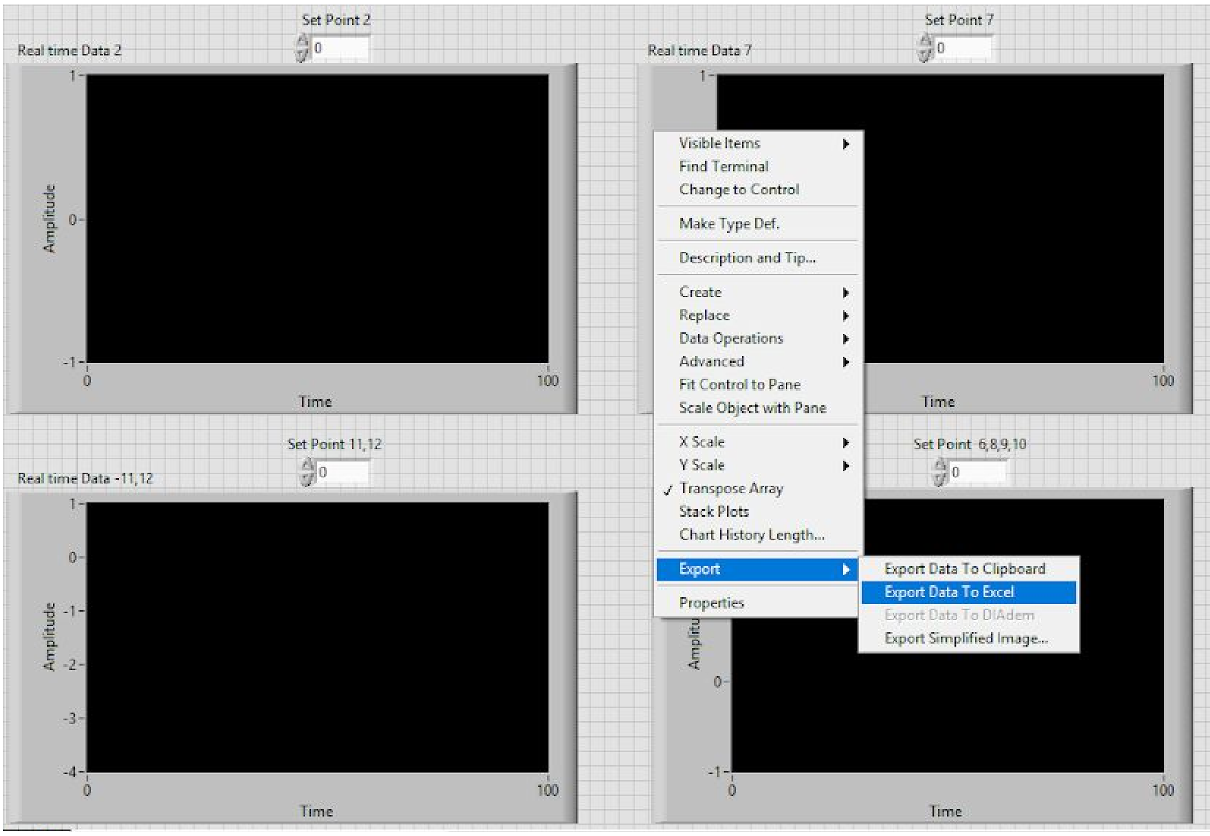

Fig.24 Saving data to Excel

<u>Note:</u> The data buffer is set to 1024000 points for all the graphs. If more data points are needed, this value can be increased depending on the system RAM usage.

13. Miscellaneous Section

13.1 Pressure sensor calibration graphs

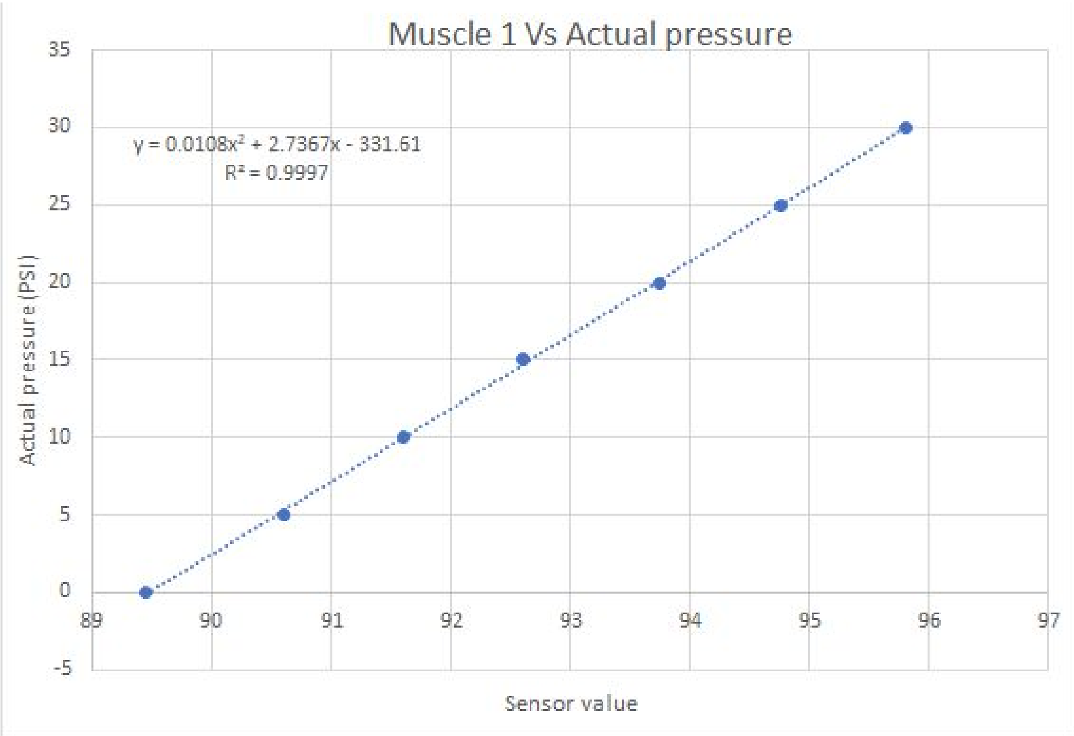

Fig.25 Calibration graph of Pressure sensor on Muscle 1

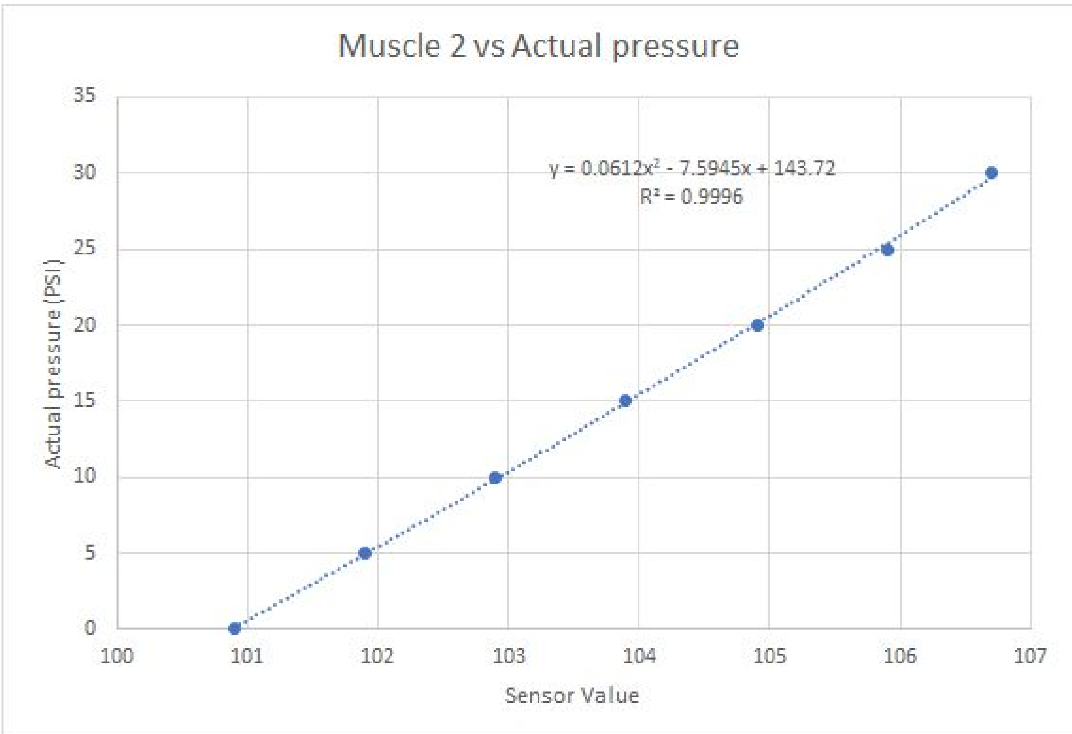

Fig.27 Calibration graph of Pressure sensor on Muscle 2

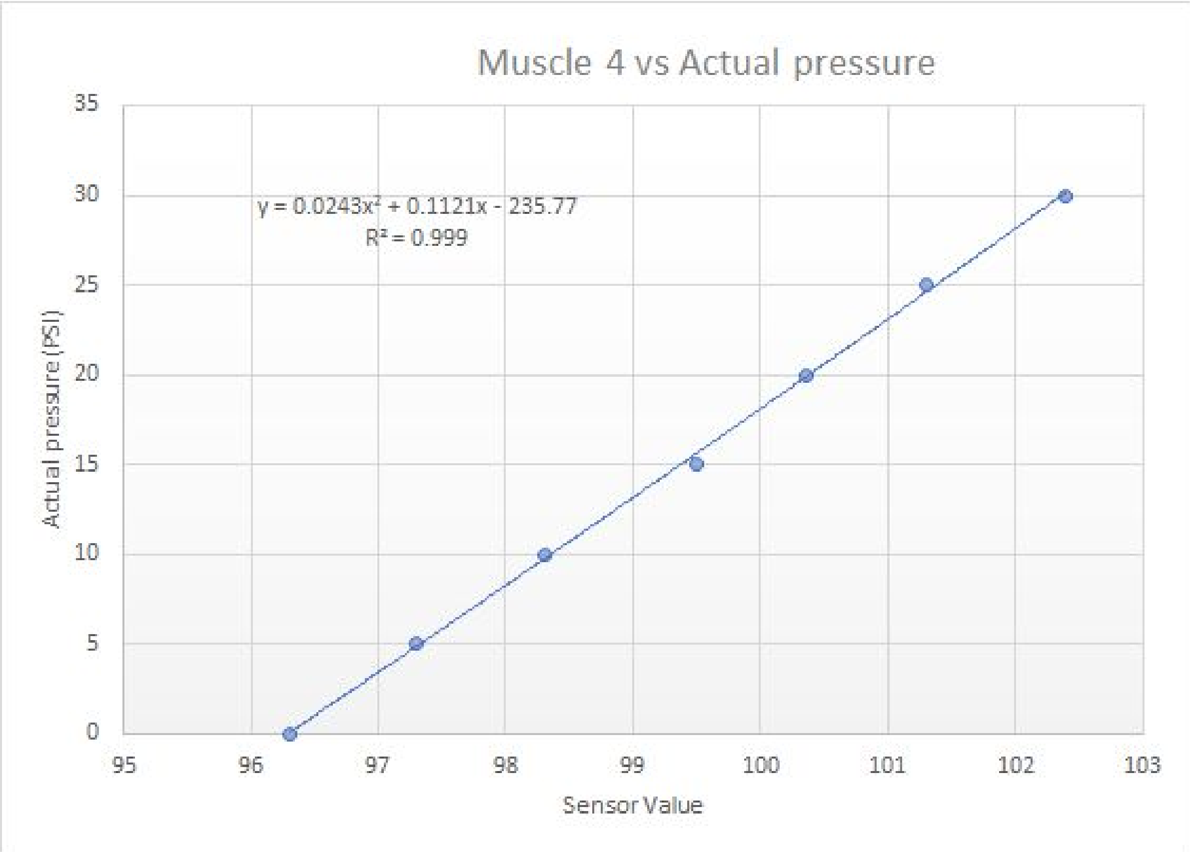

Fig.26 Calibration graph of Pressure sensor on Muscle 4

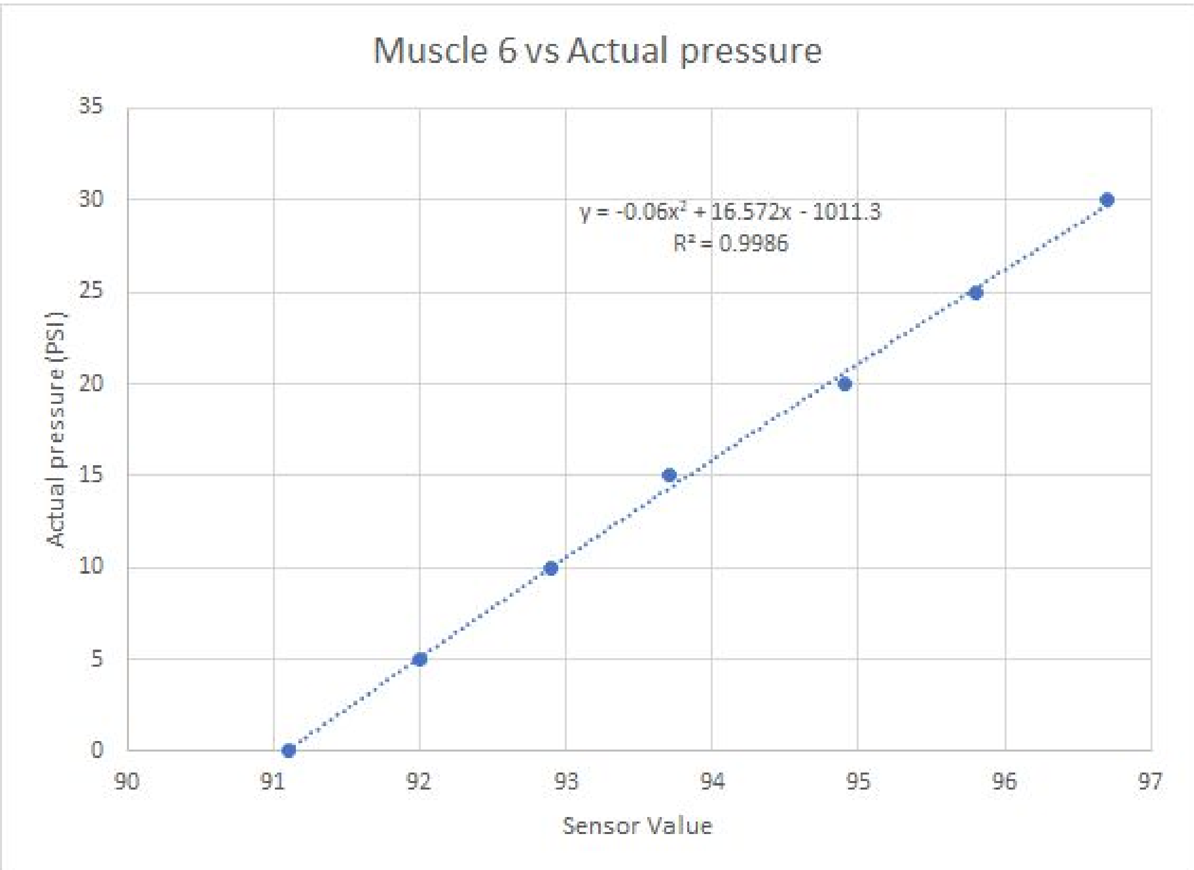

Fig.29 Calibration graph of Pressure sensor on Muscle 6

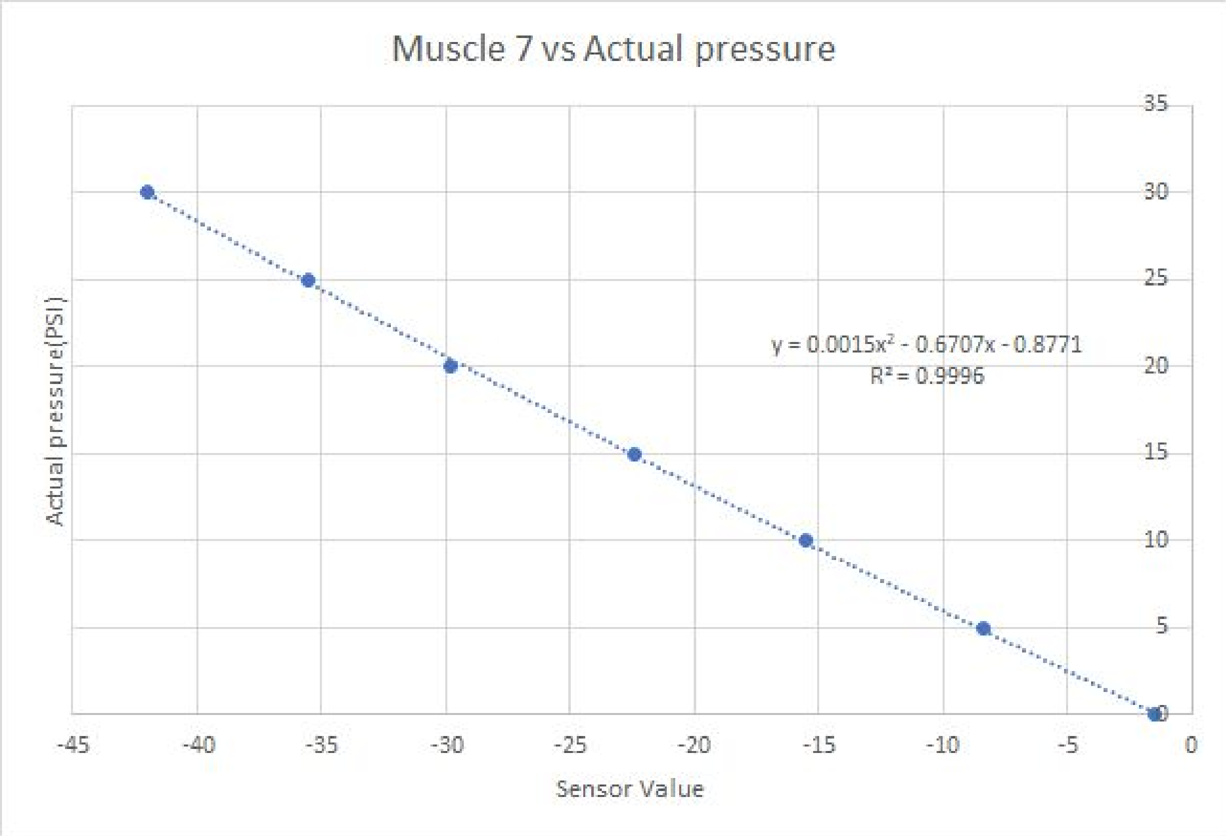

Fig.28 Calibration graph of Pressure sensor on Muscle 7

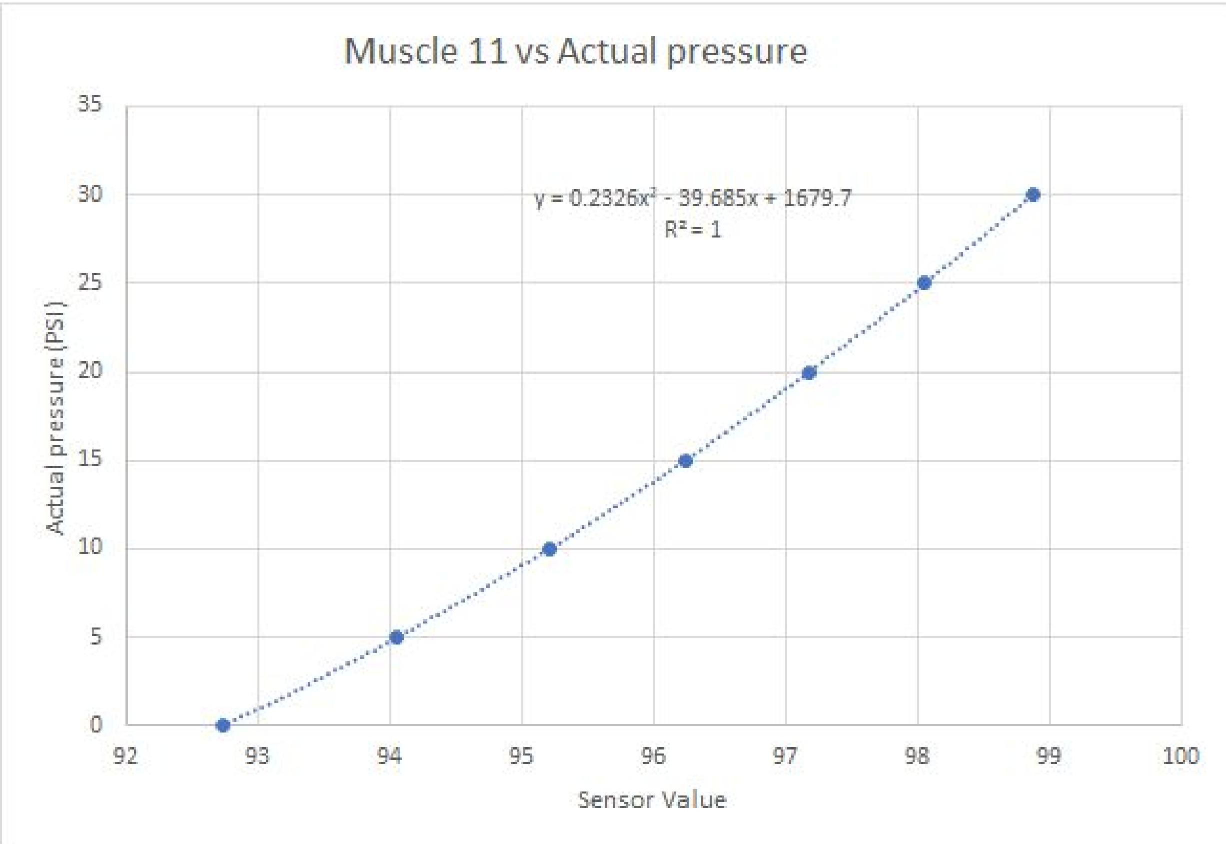

Fig.30 Calibration graph of Pressure sensor on Muscle 11

13.2 Force Sensor Calibration graphs

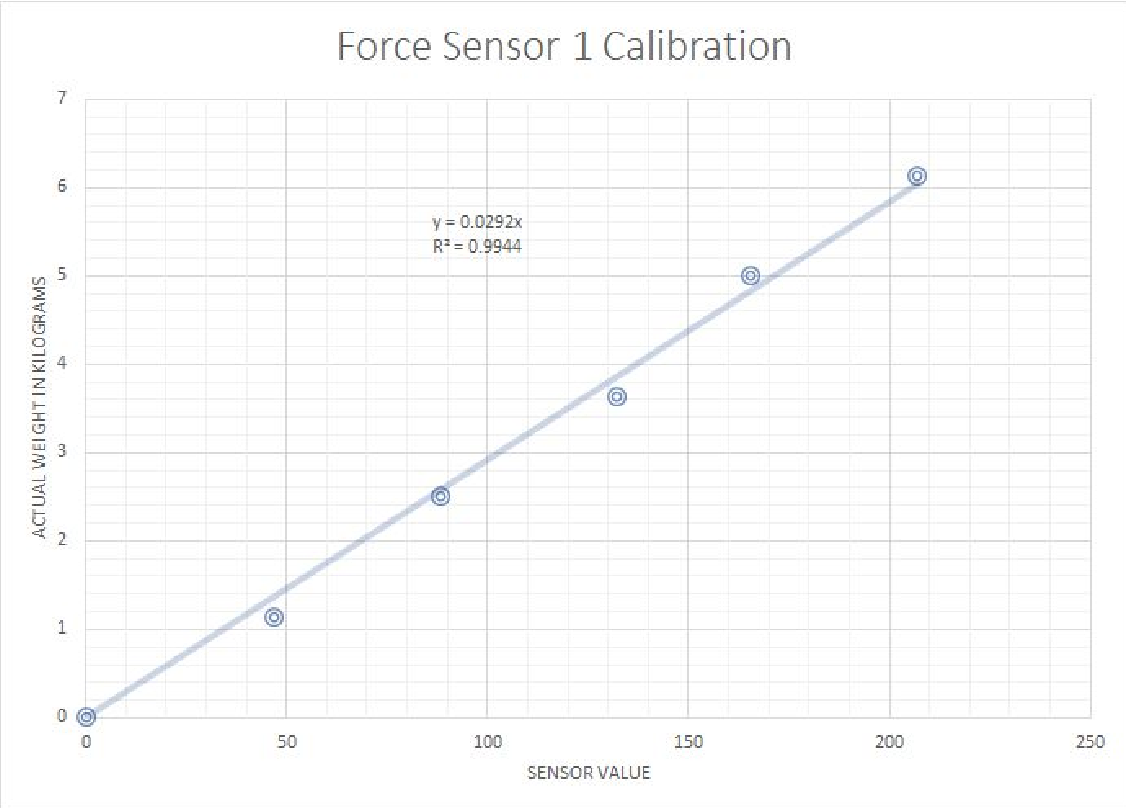

Fig.31 Calibration graph of force sensor between T8-T9

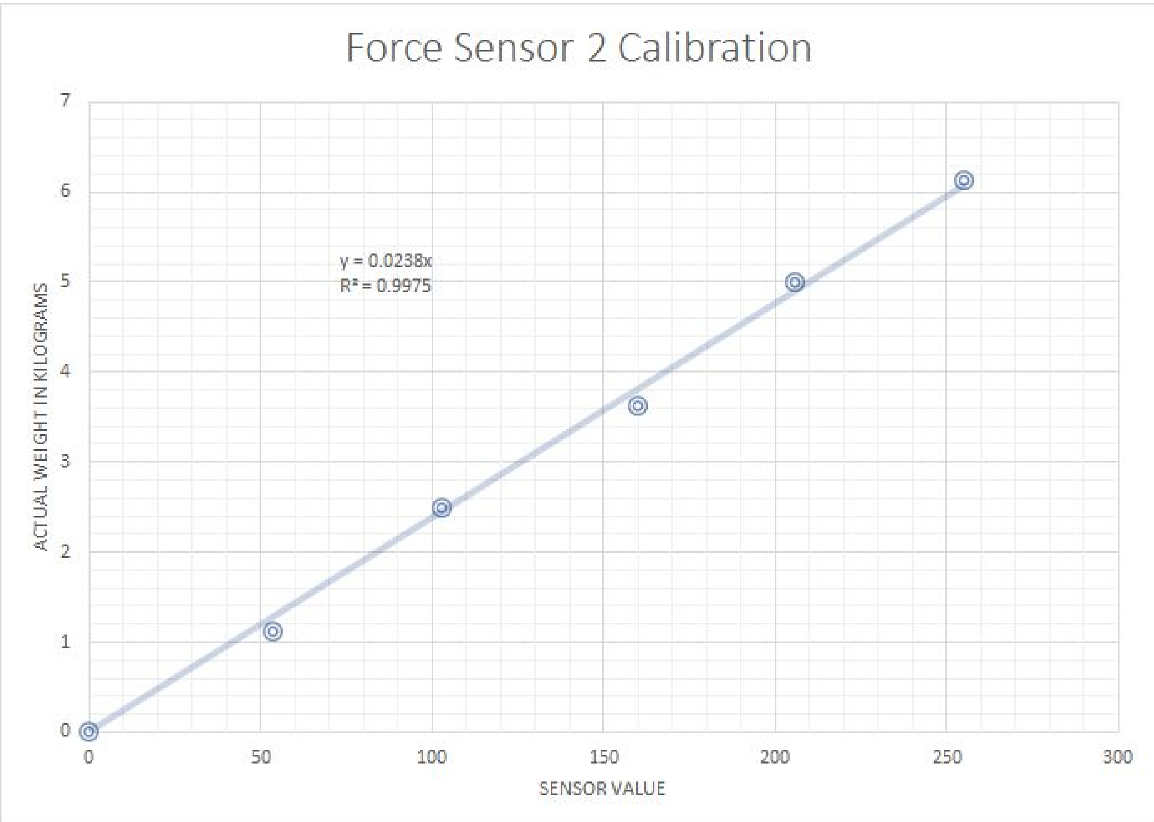

Fig.32 Calibration graph of force sensor between L3-L4