Implementation of a Control System on a Robotic Spine Model

Design Activity No. 10: Final Project Report

MECH 463

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April 12, 2019

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Cover Letter

To whom it may concern,

This project is part of a Mechanical Engineering Project Course of the Faculty of Engineering of McGill University. It is meant to fulfill academic objectives by having students apply their knowledge to the development, design, and construction of a prototype, which responds to the needs identified by the sponsor. The project is first and foremost a training tool for future engineers, which brings invaluable experience to us.

The fact that the prototype developed by the students be fit for commercial, industrial, or private use is not a primary objective of the project. We did our best to provide you with a machine that works, but it is not necessarily fit to withstand the rigors of regular use. We do not guarantee that it will perform adequately and consistently if you put it to regular use.

We are proud to have built a prototype, which apparently responds to your requirements. However, please keep in mind that it is only a prototype. If you are considering putting this prototype to use, you must ensure that it is first fully checked for safety. It may be necessary, for example, to provide emergency shut-off switches and other safety features. Some safety recommendations may be found in this report, but there may be others we did not think of. Furthermore, some features of this prototype have been designed with safety in mind; therefore, disabling or modifying parts of the equipment may have a direct impact on the safety of those using it. The safety of those using the machine should always be a primary concern and users should be properly trained to avoid accidents. McGill University, its students, employees, professors, agents and governors decline any responsibility with respect to this prototype, its performance and safety.

The prototype has been delivered at the exhibition on April 4th, 2019 and the prototype is now in the client's possession and is their responsibility. The prototype development was documented in the problem statement, conceptual design report, design report and detailed drawings that the client had an opportunity to contribute to through regular meetings and feedback. A summary of the results presented in this documentation can be found in the attached report which also describes prototype assembly and any performance results obtained.

Acknowledgements

We would like to thank Shante Zaccaria for the Burkert equipment and assistance in their application. We would like to thank Mario Iacobaccio and Prof. James Forbes for their technical expertise and assistance with control systems. Finally, we thank Prof. Mark Driscoll for his invaluable guidance and advice throughout the course of the project.

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Executive Summary

Lower back pain (LBP) places a significant impact on individuals and on society, as spinal injuries often result in medical sick leaves and healthcare consultations. According to Statistics Canada, spinal disorders and discomfort will affect 4 out of 5 individuals at some point in their lifetime. Severity of spinal injuries can be both acute or chronic, with symptoms ranging from minor aches and pains to stiffness or tension in back muscles, loss of stability or range of motion, and even weakness or numbness in the lower extremities. However, the etiology of LBP is not always apparent. To advance patient care and medical diagnosis of spinal disorders and dysfunctions, there must be a further understanding of the biomechanics of the spine.

To increase the understanding of spinal disorders and to help improve treatment and diagnosis, a robotic spine was designed last year complete with analogue bones, pneumatic muscles, and artificial cavities. As a continuation of last year's project, this project aimed to automate the robotic spine model by implementing a control system. This would improve last year's model which was previously controlled manually.

This report provides a detailed explanation for each device selected as well as the apparatus setup for the robotic spine model. The major devices that make up the apparatus include a tracking system, air pressure sensors, microfluidic valves, an air compressor, and a data acquisition system (DAQ). The devices were integrated through LabVIEW, which was compatible with the DAQ, and an ON/OFF control system was implemented. Using the tracking system, if the spine model was deemed to be unstable, the control system would automatically regulate the airflow to the pneumatic muscles in order to correct for spinal deflection.

The model functions as a test device for first design passes or for cross-comparison with computational models. The automation of this device will allow for increased accuracy and efficiency during testing and will also allow for more complex analyses to be conducted, since it was previously controlled manually. The robotic spine model aims to enhance the understanding of spinal disorders, since each muscle on the model can be "turned off" by restricting airflow to that muscle. The effect that this weakened ("turned off") muscle has on the stability of the spine can be observed, as well as the increase in muscular pressure in the remaining pneumatic muscles required to maintain stability. These studies can be used to understand potential spinal injuries, such as the possibility that overcompensation by certain back muscles may result in long lasting, high pressure contractions, contributing to reduced blood flow to the muscles and risk of ischemia.

A brief user's manual is included in Appendix D for information regarding the prototype set up and running the various software simultaneously.

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1 Introduction

Lower back pain (LBP) places a substantial economic burden on health and welfare systems as back pain often results in the need for medical consultations and work absences [1]. LBP will affect 70-85% of individuals at some point in their lifetime [2-5]. However, the etiology of LBP is often unknown [3, 6-8]. The lack of understanding regarding the causes of LBP inhibits the diagnosis and the understanding of spinal dysfunctions.

To be able to advance patient care and medical diagnosis of spinal disorders and dysfunctions, there must be a further understanding of the biomechanics of the spine. Mechanically, flawed spinal stability is associated with spinal disorders. The stability of an individual's spine can be affected by variation in intra-abdominal pressure [9, 10], in muscle pressure and strength [11], or by longer lasting muscle contractions [8, 11], among other effects. Therefore, it was concluded that it is important to include the forces supplied by the back muscles and internal cavities in order to have accurate results when analyzing spinal stability [12-14].

A robotic spine model, previously designed and built by a capstone design team at McGill University in the 2017-2018 academic year, will be used for this project. The model is complete with the following:

- Analogue bones, including the spinal column, the rib cage, and the pelvic bones.
- Thoracic and abdominal-pelvic cavities custom made from PVC material.
- McKibben pneumatic muscles, made from latex tubing, custom end caps and valves, and an expandable mesh, representing the multifidus, erector spinae, psoas major, and rectus abdominus muscles.

As a continuation of last year's design in which the muscles and cavities were inflated manually, this project will aim to automate the inflation of the pneumatic muscles and the internal cavities of the spine model through a control system, complete with a tracking system, automatic valves, pressure sensors, and an air compressor. This advancement will aim to gain further understanding of the musculoskeletal system of the spine and the potential causes of LBP.

This report provides a final overview of the project, including the problem statement, initial design phase, concept generation and concept evaluation. The design embodiment and fabrication of the prototype, as well as the prototype performance, will be described in detail. Lastly, this report will include lessons learned, as well as future recommendations for the spine model.

2 Problem Definition

The objective of this project is to automate the provided robotic spine model so that it may respond to a compressive load in a physiologically correct manner. This will require the integration of an air supply, pressure sensors, electric valves and a tracking system all linked to one computer control system that will be developed. By studying the biomechanics of the spine model and the possible causes for spinal instability, we hope to gain a better understanding of spinal disorders and dysfunctions.

The loading system developed will have to induce a 50 N static load on the spine. This load should aim to be physiologically realistic, although this is not a high priority specification.

The tracking system will be required to measure the spinal deflection in the 3D plane, preferably having 6 degrees-of-freedom. The tracking system will have to work in unison with the control system to relay the measurements in real time, allowing the pressure in the pneumatic muscles and artificial cavities to be adjusted accordingly to stabilize the spine.

The pressure sensors will need to measure the internal pressure of the muscles and the cavities with pressure ranges of 0-70 psi and 0-5 psi respectively. The sensors will have to relay the recorded pressures in real time to the control system to allow the valves to regulate the air flow into or out of the muscles and cavities.

Finally, in achieving the above, microfluidic valves and an air compressor will have to be integrated into the system that can function harmoniously with the chosen components for tracking spinal deflection and measuring internal pressure. With each component implemented, the final presented design should aim to be as aesthetically pleasing as possible.

3 Evaluation Criteria

The objective tree in Figure 24 (see Appendix A) was created in order to construct the set of all devices required for our application, as well as to determine the parameters upon which they will be compared.

Our supervisor and client, Prof. Mark Driscoll, ranked the priority of the project objectives as seen in Table 1. The weighting ranged between 1 and 10 where 1 had the least priority and 10 had the greatest priority. This ranking served as the basis for the selection of our conceptualized loading strategy as well as for the selection of the devices needed for our apparatus.

Table 1: Weighted design specifications from the client

Weight	Specification
10	Control the pressure in the muscles between 0-70 psi using the control system
10	Control the pressure in the cavities between 0-5 psi using the control system
9	Measure the pressure in the muscles between 0-70 psi
8	Measure the pressure in the cavities between 0-5 psi
8	Implement a tracking system to measure spinal deflection in a 3D plane
7	The spine model should be stabilized with the control system
6	Spine model should be able to withstand a 50 N static load
6	Stabilize the pelvic bones of the model so pivoting of the model does not affect results
5	Spine model should be able to withstand a 100 N static load
4	The model should be aesthetically pleasing and organized with no unnecessary clutter
3	Implement a thoracolumbar fascia connective tissue
2	The device should have minimal noise from the compressor(s)
1	The device should be portable
1	The load applied should be physiologically relative to the load on a human spine

Lastly, the pairwise comparison charts in Tables 3-5 (see Appendix A) were used to compare all parameters head to head to determine which parameter was more important.

4 Concept Alternatives

Concept alternatives were generated for each of the following project requirements: the spinal loading method, the implementation of the tracking system, the pneumatic muscle and artificial cavities pressure sensors, the automatic valves, and the valve air supply.

4.1 Spinal Loading

The spinal loading method is important to consider for this project. The weight should induce a disturbance on the spine, therefore causing instability. The pneumatic muscles and artificial cavities will then be used to counteract this disturbance and re-establish spinal stability.

4.1.1 Concept 1

This concept consists of applying a vertical, compressive load on the spine. The spine model already has a metal rod that passes through each vertebra in the spinal column. Since all cervical vertebra have been removed, with the exception of C7, a portion of the metal rod is left protruding from the top of the spinal column, as depicted in Figure 1 below. Therefore, a weight (in red) similar to a gym weighted plate could be used. Since the weight would have a hole in the center, it could easily be placed over the metal rod protruding from the top of the spine. The rod would keep the weight centered over the model and would not allow for displacement of the weight. Applying a weight in this manner would induce a vertically compressive force on the spine.

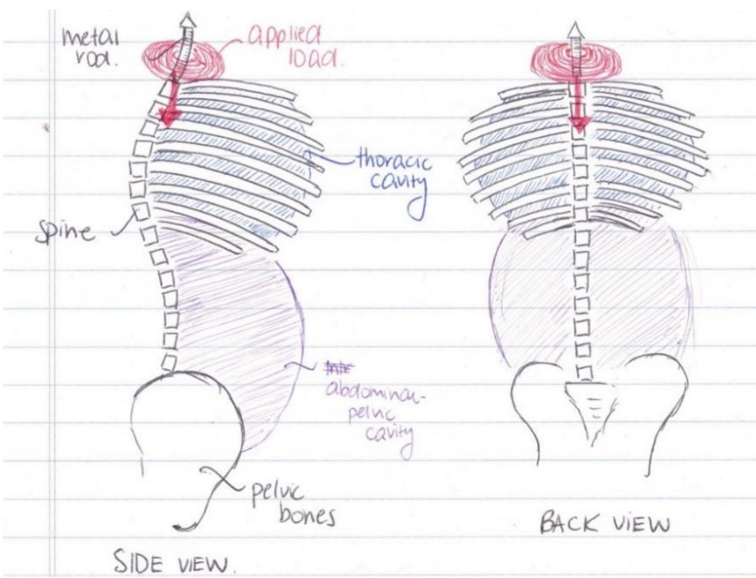

Figure 1: Concept 1 for spinal loading; vertical compressional load.

4.1.2 Concept 2

This concept of a follower load path aims to mimic the load distribution experienced in human spines. The follower load would allow for a consistent compressive force that is normal to each vertebra in the examined spine. According to an article by Patwardhan et al. [15], a similar methodology would be used on our model. As seen in Figure 2, a cable (preferably nylon) under tension from an applied load is run bilaterally along the spine. The placement of a ring on C7 with the cable tied to it would ensure that the load is being applied exclusively to the model's vertebrae. The cable would pass through a channel of swivel rods that are secured on rings/zip ties fixated to each vertebra. With each ring wrapped around the vertebra's center of rotation and the swivel rods able to freely rotate, the cable tension would ideally produce a normal loading distribution on each vertebra. Since the weight would need to hang from C7, a platform like a scale in a grocery store can be designed to hold the weighted plates from below the model.

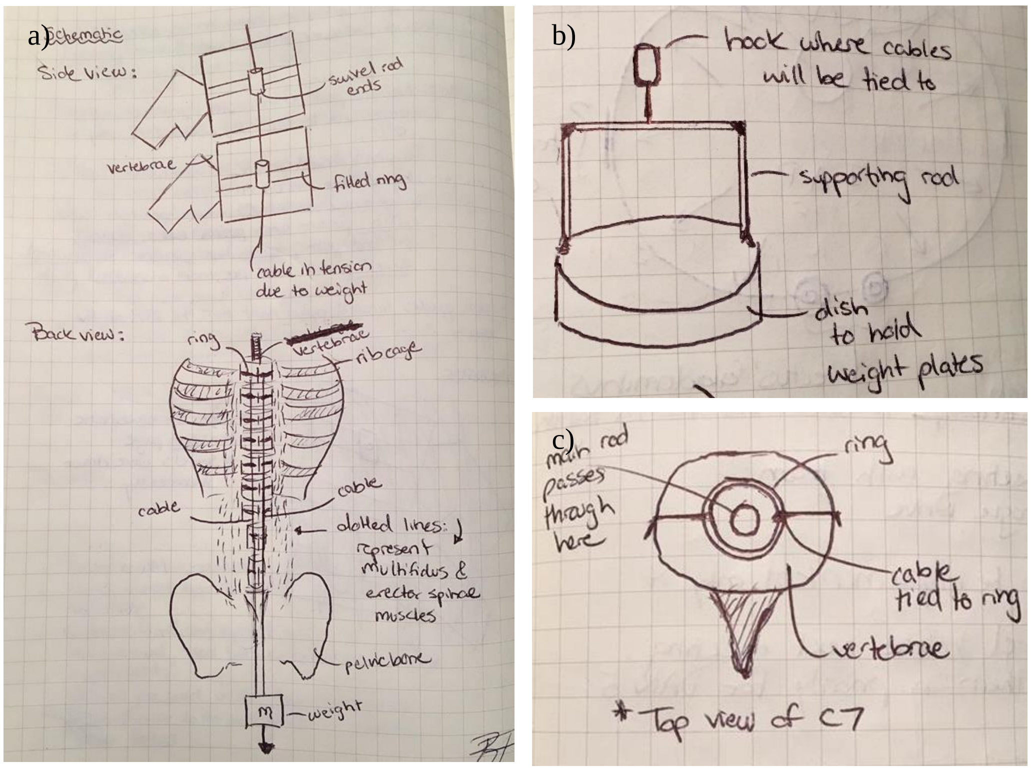

Figure 2: Concept 2 for spinal loading; a) schematic of bilateral loading mechanism to mimic follower load path; b) platform design to hold weights activating spine under tension; c) top view of C7 with ring to demonstrate how cables are fixed in bilateral fashion.

4.1.3 Concept 3

With the idea of applying a compressive load on the spine, this concept would have a cable attached at the base of the spine running up one side and then back down the other to a spindle connected to a high-torque motor. The motor, when on, would then pull the cable which would apply a force at the top of the spine pulling it compressively towards the base. The power given to the motor evidently would have to be correlated to the applied force on the spine. This design would make use of the pre-existing "hoops" on each side of the vertebrae to pass the cable. Furthermore, a 3D-printed piece at the top of the model can be manufactured to pass the cable so as not to damage the C7 vertebra.

The disadvantage of this concept is that when a force is applied, the spine will want to correct itself by the passing cable through the hoops of each vertebra, ultimately inducing stability. The load stabilizing the spine would be an unwanted characteristic since the muscles and cavities should aim to counteract a spinal instability. This stabilization by forces is illustrated in Figure 3.

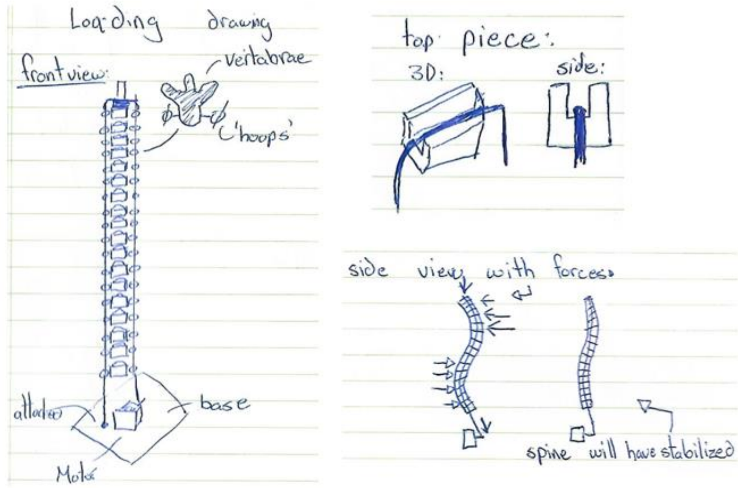

Figure 3: Concept 3 for spinal loading; cable attached to motor.

4.1.4 Concept 4
This concept consists of mimicking the load that a backpack would have on the spine. For this design, the scapula and clavicles will have to be added to the spine model. While the force is entirely a vertical compressive load placed on the clavicles of the model, the torque that a backpack would typically apply on an individual's skeleton is not present in this design. To balance the weights, high friction padding would be placed around the clavicles and fastened onto the spine model. Subsequently, the weights could then be placed on this padding and wrapped securely with cellophane. Applying this type of loading would induce a vertically compressive force distributed across the transverse plane. The disadvantage to this loading mechanism is the need to add a part of the skeleton to the model. Also, the fastening mechanisms for the weights may obstruct the view of the model mechanics and could also be tedious to set up and remove.

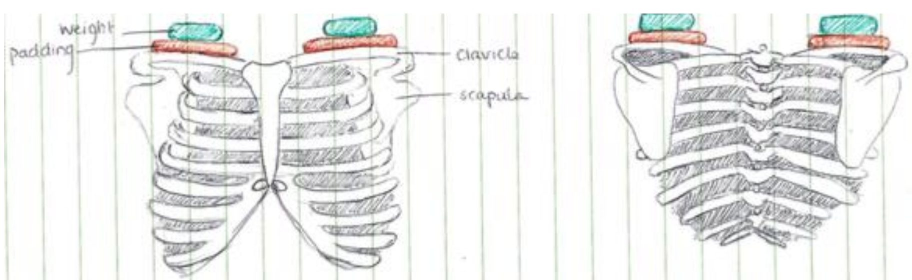

Figure 4: Concept 4 for spinal loading; backpack loading mechanism.

4.2 Tracking System
A tracking system must be implemented in order to track the spinal deflection. A given range will be defined as “stable” and any movement away from this range must be able to be tracked, recorded, and relayed to our computer control system.

4.2.1 Concept 1

One alternative tracking system is optical tracking. As depicted in Figure 5 below, the cameras light up the desired object to be tracked using infrared (IR) light. The object is fitted with multiple markers placed randomly on the surface. These retro-reflective markers reflect the IR light back to the cameras, which then track the movement of the object. For the purpose of this project, the object fitted with the retro-reflective markers would be the top vertebra, C7, with the possibility of imaging another part of the spine if deemed necessary.

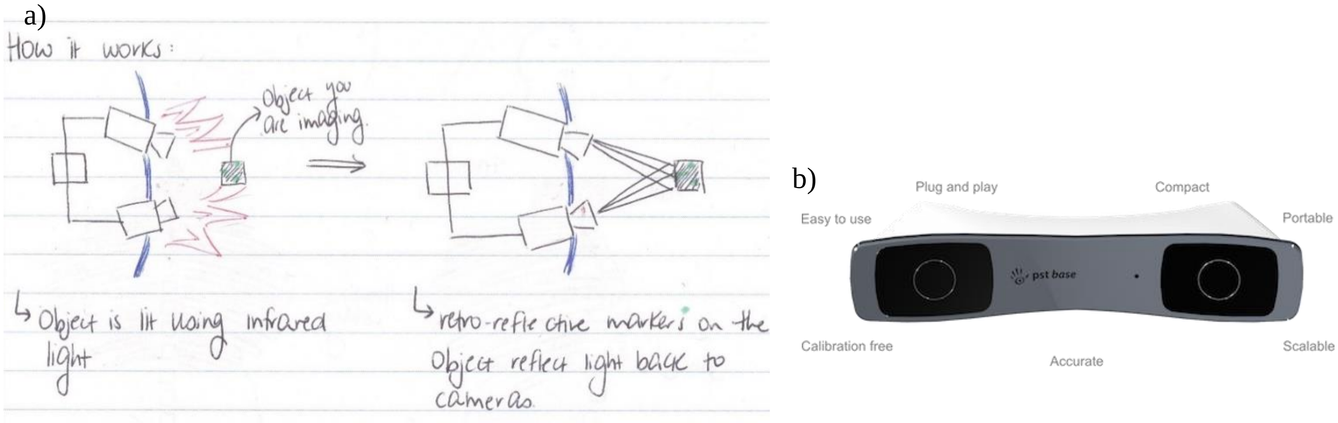

Figure 5: Concept 1 for tracking system; a) optical tracking device; b) PS-Tech's optical tracking system product: PST Base [16].

Some advantages of this tracking system are that it is less susceptible to surrounding noise and it allows multiple objects to be tracked. In addition, it is a wireless system. However, multiple cameras may be needed to track the object in a 3D position, which may become costly. Furthermore, line of sight is required.

One possible product is the PST Base product from PS-Tech. This product has a tracking distance of 20 cm-3 m with an accuracy of <0.5 mm for position and <1 degree for orientation [16], which is suitable for our application. In addition, the product comes equipped with an optical tracking software which can be installed on a computer.

4.2.2 Concept 2

Another alternative is to use electromagnetic tracking, specifically the Polhemus G4 tracking system. Some of its desirable attributes include wireless motion and 6 degrees-of-freedom capabilities, no line-of-sight restrictions (meaning the signal can be reacquired if the device is out of range) and ease of use. Furthermore, the Polhemus G4 provides exceptional accuracy from a 12-24 inch range, offering a resolution between 0.003-0.001 inches and 0.0008-0.002 degrees for position and orientation respectively [17]. The Polhemus G4 is also equipped with a systems electronic unit, a standard sensor (which is to be placed on the topmost vertebra) and the power source. While the power source is slightly heavy, the tracking system is also comprised of an internal battery that can last up to 10 hours and is rechargeable by USB.

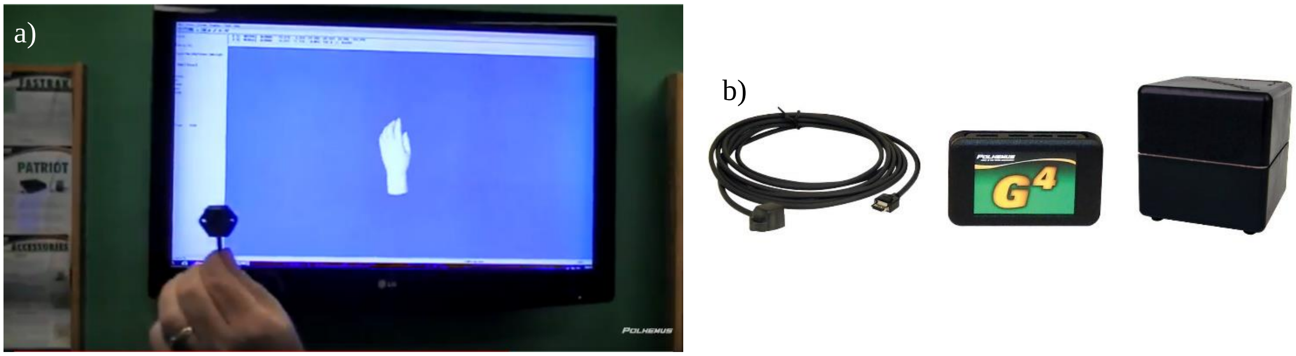

Figure 6: Concept 2 for tracking system; a) demonstration of Polhemus G4 wireless tracking [18]; b) system components [17].

4.2.3 Concept 3

A similar solution for tracking would be the microBIRD magnetic tracking system. Equipped with 6 degrees-of-freedom magnetic tracking, its sensor is only 1.8 mm in diameter. It requires no line of sight and it is also metal tolerant, which would be beneficial for any metals used in the loading system or the spine model itself. The sensor transmits position in real time up to 90 times per second, while capable of outputting location in x, y, and z coordinates of data. Its operating range is 20-70 cm in the x axis (into/away from transmitter) and 30 cm in y and z coordinates [19]. Its accuracy is 1.4 mm in position and 0.5 degrees in orientation [19]. The downside of the sensor would be that it is not wireless, being accompanied with a 2m cable for its operation power [19]. The sensor would be place at C7 with the cable fed down the back of the spine (such that it is less visible) and then connected to the source. Meanwhile, the receiver could be placed on the base created for the spine, as no line of sight is required.

Figure 7: Concept 3 for tracking system; MicroBIRD sensors [19].

4.2.4 Concept 4

The fourth concept consists of the THALES IS-900 as an alternative electromagnetic tracking system. This system offers wireless tracking and 6 degrees-of-freedom motion sensing. It is immune to metallic interference and has no line-of-sight restrictions thanks to the nature of the electromagnetic system. The system also has a resolution of 1.5 mm and 0.10 degrees for position and orientation respectively when used wirelessly [20]. The THALES IS-900 comes equipped with an electronic unit, a sensor, and a power source. The system also comes with a docking station for recharging.

Figure 8: Concept 4 for tracking system; THALES IS-900 Electronic Unit [20].

4.3 Pressure Sensors

The pressure sensors will be integrated into the pneumatic muscles and artificial cavities to read intramuscular pressure (IMP), intra-abdominal pressure, and intrathoracic pressure. The chosen sensors must be able to relay the internal pressure to the computer control system as feedback. The pressure sensors must be able to read the following ranges of pressures: [0-70] psi ([0-3670] mmHg) for the pneumatic muscles and [0-5] psi ([0-259] mmHg) for the artificial cavities.

4.3.1 Concept 1

One possible pressure sensor that could be used to measure the muscle pressure is a wireless pressure sensor as seen in Figure 9 below. This product is available from multiple companies, including TE Connectivity and Phoenix Sensors. This pressure sensor can be threaded into a plug on one end of the pneumatic muscle in order to read the IMP. The threaded end of the sensor has 1/4”-1/8” NPT threads [21], which would therefore fit within our inner diameter of the tube for the pneumatic muscles, measured at 3/8’’. The pressure sensors can read a range of 0-5 psi and 0-100 psi [21], making them suitable for both the cavities and the muscles. Placing the pressure sensor at the opposite end of the muscle from the airflow inlet end will help to mitigate any disturbances caused by airflow circulation.

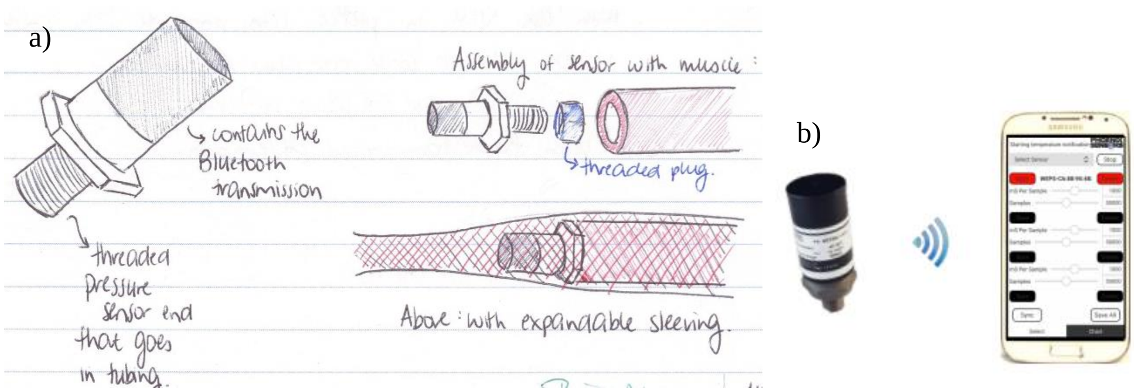

Figure 9: Concept 1 for pressure sensors; a) possible sensor and method of implementation; b) sensor product from Phoenix Sensors [21].

Although this option seems viable for the pneumatic muscles as it meets the desired size and pressure ranges required for our project, this was deemed not to be a suitable concept. After speaking to a sales representative at Phoenix Sensors, he explained that this product can only connect to their Bluetooth application. Although creating our own code to interface between the pressure readings and MATLAB is possible, it would be extremely challenging.

4.3.2 Concept 2

Another suggested concept was the MPS4 Elveflow Microfluidic pressure sensor. This pressure sensor offers a range of up to 100 psi and provides readings with ±0.2% repeatability [22], which fits our desired range for pneumatic muscle pressures. The Elveflow sensors are also compatible with C, Python, MATLAB and even LabView programming, which corresponds to the programming language to be employed by our control system interface. Aside from its automation and user-friendly flow control, the interface provided by the sensors can also be maintained from one single software. In our assembly, it would make more sense to opt for the large package model which provides a 3/32” ID opposed to the 1/16” OD. However, the location and the fitting required for the sensor to measure the pressure in the 3/8” ID muscle and large cavities (without bleeding of air) still remains a challenge. Nevertheless, the computer interface provides a convenient feature such that the microfluidic air flow path can be controlled by defining our final valve system configuration.

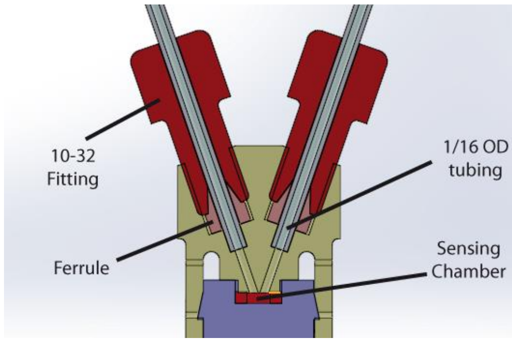

Figure 10: Concept 2 for pressure sensors; Elveflow microfluidic pressure sensors [22].

4.3.3 Concept 3

Another concept that could be considered is customizable low frequency RFID pressure sensors, supplied by Phase IV. Small enough to fit in a honeycomb [23], these sensors would simply be placed inside each muscle and cavity, while the reader records the pressure through the muscles/cavities boundary. The sensors have no batteries, allowing for extended time of testing and use before being replaced well down the line. These sensors would be a non-intrusive and aesthetically pleasing solution as they would not be visible. Therefore, the Phase IV RFID readers would only be able to measure readings from a few inches away, with large antenna readers required for ranges of more than 1 foot. Although one RFID reader can measure for multiple sensors, multiple RFID readers would likely have to be placed around the spine to read all the sensors simultaneously.

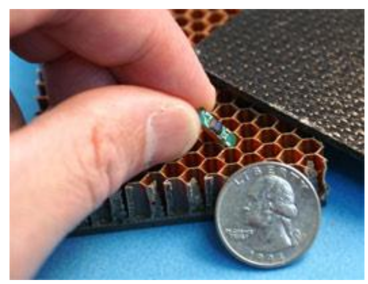

Figure 11: Concept 3 for pressure sensors; Phase IV RFID pressure sensor [23].

4.3.4 Concept 4

Another option for pressure sensing is the OMEGA PX26 series pressure sensors. The PX26-100GV is a wet/wet gage which functions within a pressure range of 0 to 100 psig [24], which is an ideal range for sensing pressure within the model’s muscles. The PX26-005DV is a differential pressure sensor which functions within a range of 0 to 5 psig [24], a suitable range for sensing pressure within the cavities. They are also shaped in a fashion that facilitates attachment to both the muscles and cavities while minimizing air leakage at the point of connection. One disadvantage is the protruding prongs, which are responsible for receiving/transferring a signal to the DAQ system. As the muscles are tightly and closely packed together, the sensors may physically interfere with each other.

Figure 12: Concept 4 for pressure sensors; OMEGA PX26 series [24].

4.4 Valves

The valves chosen for this project were pre-determined before the beginning of the project, although there was the option of finding another supplier for the valves. After researching alternate suppliers and valve types, it was determined that the supplier currently chosen, Bürkert Fluid Control Systems, was the most suitable choice.

The valves recommended by Bürkert consist of the plunger valve, 2/2 way direct-acting, Type 6011 [25], as seen in Figure 13. This microfluidic valve will allow us to control the airflow into the muscles and cavities, as well as the air exhaust from of the muscles and cavities, which will assist in regulating the internal pressure. There will be two valves per muscle or cavity for the aforementioned functions. The muscles and cavities will both use Type 6011 valves, although the orifice size will differ slightly to satisfy the desired airflow into the muscles and cavities. In order to simplify organization on the numerous valves, the microfluidic valves used for the muscles will be mounted on a manifold.

Figure 13: Type 6011 valve from Bürkert [25].

4.5 Air Supply

The air supply will be used to provide air inflow that will subsequently pressurize the pneumatic muscles and artificial cavities of our model. Considering that the pressure ranges required to be maintained in the muscles and cavities are significantly different (i.e. range differs by an order of 10), there may be a need for more than one source of air supply.

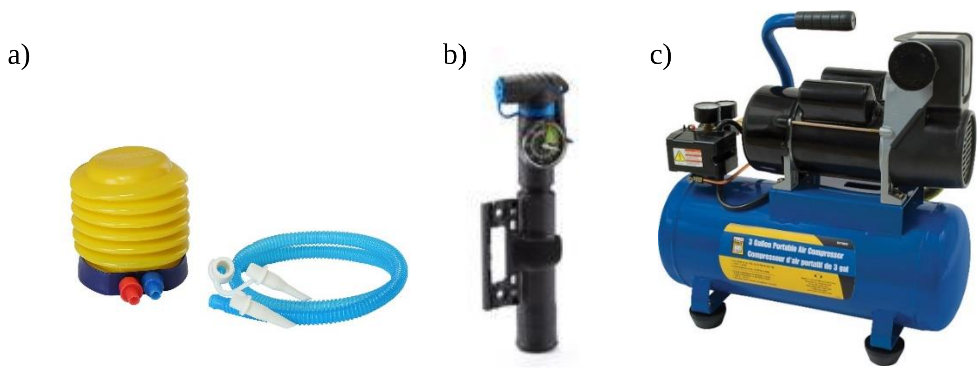

Figure 14: a) Manual air pump used for thoracic and abdominal cavities [26]; b) Manual bike pump used for pneumatic muscles [27]; c) Concept for portable air compressor to replace manual pumps [28].

The conceptualization of our air supply component led to comparing air compressors against manual pumps while considering design constraints. One limitation of the manual pump is its difficulty in regulating air flow to the pneumatic muscles. For this project, the air inflow to the muscles will need to be adjustable, which would be facilitated by using an air compressor rather than a pump each time the spine is vertically compressed and deflected. Furthermore, from an ergonomic perspective, continuous pumping action required to reach our safety limit of 60 psi in all twelve pneumatic muscles from a manual pump would be tedious. Lastly, the integration of our air supply with other components is also important to achieve seamless air flow through the nylon tubing connected to the muscles and the valves. This will be more difficult to achieve with multiple manual air pumps connected simultaneously. Consequently, selecting an air compressor with a given port diameter simply becomes a matter of finding the appropriate, off-the-shelf fittings between each of the tubes connected to the muscles.

5 Evaluation Process

A Pugh matrix (see Appendix A, Table 6) was implemented in order to select the concepts that would best satisfy the needs of the project. The weighted column allowed each criterion to be assigned a weight from 1, the least important, to 5, the most important. The dedicated weighs were determined based on the client's weighted design specifications, found in Table 1, and the pairwise comparison charts, Tables 3-5 (see Appendix A).

Based on the total value given to each concept for the spinal loading, tracking system, and pressure sensors, the following concepts were determined to be the concepts that best satisfy the project requirements.

- <u>Spinal loading</u>: Concept 1 – Vertical compressive load applied on the spine.
- <u>Tracking system</u>: Concept 2 – Polhemus G4 tracking system
- <u>Pressure sensors</u>: Concept 4 – OMEGA PX26 series pressure sensors

6 Chosen Concepts and Design Embodiment

The concepts outlined below were chosen among the possible alternatives based on the results from the Pugh matrix while taking into consideration the needs and wants of the client.

6.1 Spinal Loading

The spinal loading mechanism chosen for this design is the applied vertical compressive load. The load will be applied in vertical compression on the spine by means of applying a weight centered on the top of the spine.

This concept was chosen based on simplicity and ease of implementation when compared to the other alternatives. In addition, this option was deemed to be the most cost effective. Lastly, this concept satisfied the most important criteria in the simplest manner, which is the effect of inducing a required disturbance on the spine when loaded.

6.2 Tracking System

Upon further evaluation, the Polhemus tracking system was chosen. It is the most affordable among the other alternatives without compromising convenience and it also provides impeccable resolution. Initially, the chosen Polhemus product was the G4 tracking system. However, upon consultation with a sales representative, the recommended product chosen for our project was the Polhemus Fastrak with four 1.8mm microsensors. The four sensors will be placed on the inflection points of the spine model, as seen in Figure 15, and are small enough to be placed on the C7 vertebra with minimal interference. The transmitter from Polhemus will be used as the reference point for the sensors and will be placed at the base of the spine. The Polhemus Fastrak interface is compatible with MATLAB by using a script that can run in conjunction with our control system.

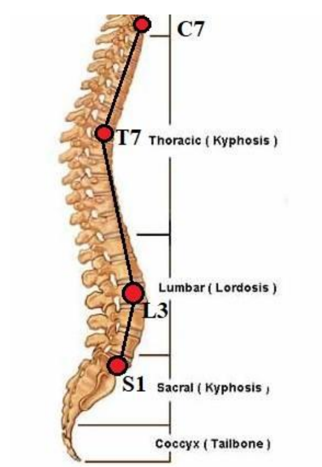

Figure 15: Inflection points for placement of Polhemus microsensors.

6.3 Pressure Sensors

After evaluating all alternatives, the OMEGA PX26 series pressure sensors were selected for our system. These sensors are the most affordable option and are well suited for our application. The two types of OMEGA PX26 series sensors, PX26-005GV and PX26-100GV, measure pressure ranges from [0-5]psi and [0-100]psi for the cavities and muscles, respectively, therefore maximizing the resolution. In addition, the pressure sensors weigh 2g each which does not compromise the stability of the spine or the pneumatic muscles with significant additional weight.

Initially, it was planned that the prongs from the sensors would protrude from between the mesh. However, upon receiving the sensors and realizing the fragility of the prongs, a modification was made to the attachment method of the pressure sensors to the pneumatic muscles. The sensors will be pierced through the expandable mesh instead of the prongs protruding through the mesh. The lack of contact between the sensor and mesh will reduce the risk of damaging either part.

6.4 Valves

As specified previously, the valves were purchased from Bürkert Fluidic Control Systems. Bürkert recommended microfluidic valves for this project, specifically the plunger valve, 2/2 way direct-acting, Type 6011. This project requires two valves per muscle and per cavity: one for air intake and one for air exhaust. A push-to-connect tee connector will be used to connect both of the valves to the muscle. When the muscle or cavity requires pressure, the inlet valve will open while the exhaust valve will remain closed, creating unidirectional flow towards the muscles. In the case where a decrease in pressure is required, the exhaust valve will open, while the inlet valve will remain closed, creating unidirectional flow in the opposing direction and allowing air to escape from the muscle or cavity.

There are 24 valves for the 12 pneumatic muscles on the spine model. These valves are arranged on four manifolds, each possessing 6 valves. For simplicity, only two manifolds with 3 valves each were portrayed in the sketch in Figure 16.

6.5 Air Supply

As previously mentioned, air compressors are more favourable than manual air pumps in terms of efficiency, performance, and ease of use. Therefore, a portable air compressor was selected.

The air compressor will connect to a manifold capable of splitting the flow into 12 outlets on a single rectangular manifold. Each of these outlets will lead to 1 microfluidic valve that will regulate air inflow to its respective muscle. For simplicity, a manifold with only 6 outlets (3 outlets on the top face and 3 outlets on the side face of the manifold) was portrayed in Figure 16.

6.6 Conceptualized Setup

Figure 16 below depicts the conceptualized setup of the elements previously outlined in detail: the spinal loading mechanism, the tracking system, the pressure sensors, the valves, and the air supply. In addition, a data acquisition (DAQ) system is crucial to convert all sampling signals from the tracking system, pressure sensors, and microfluidic valves into digital, numeric values that can be manipulated by our computer control system. Furthermore, manifolds split the airflow where required and also mount the microfluidic valves for the pneumatic muscles.

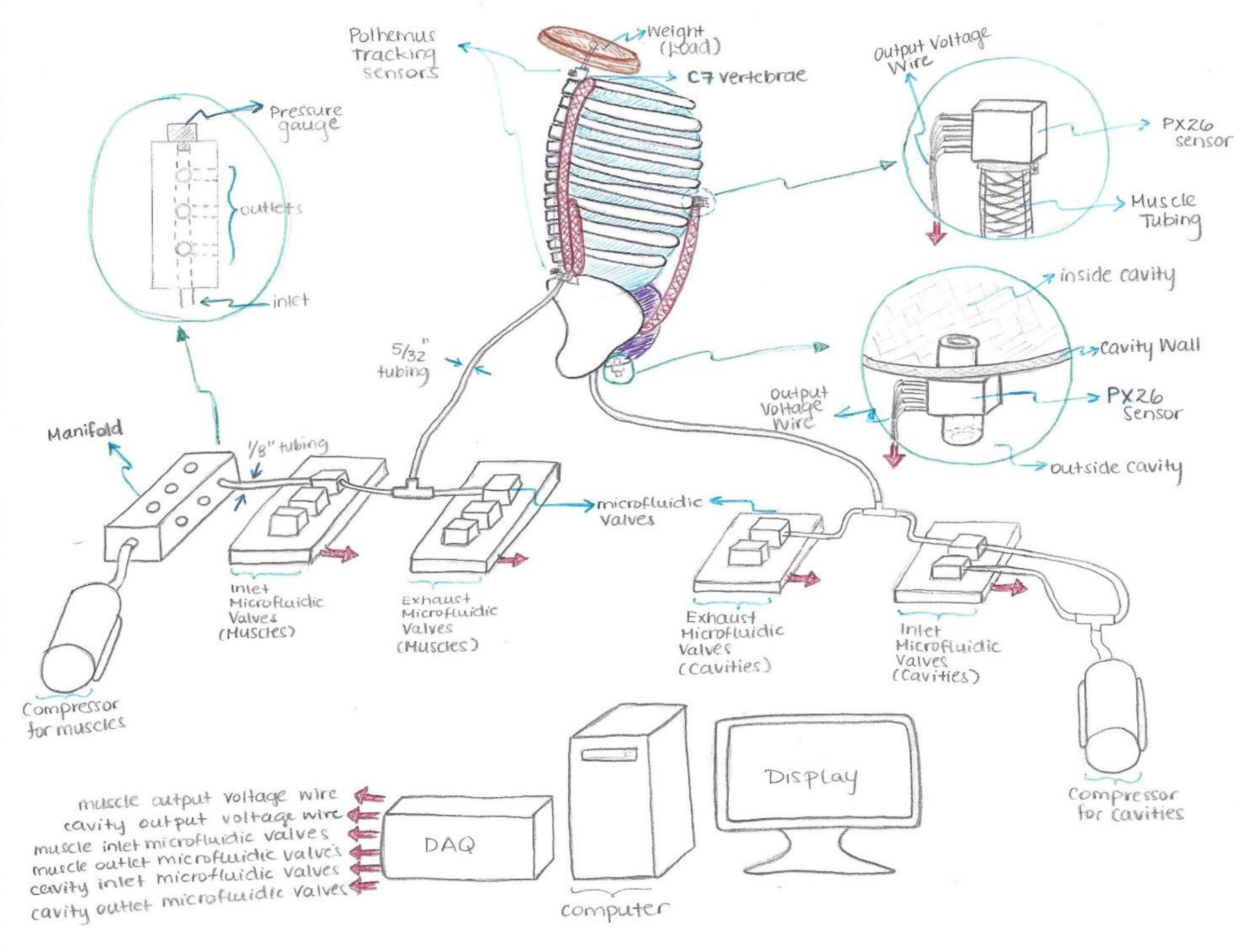

Figure 16: Final design concept of apparatus setup.

7 Fabrication

The implementation for a robotic spine model involved the integration of several devices working in conjunction with the spine model designed from last year's capstone project. Considering this project required more technologically advanced hardware for simulation and control, our apparatus primarily consisted of purchased, off-the-shelf (OTS) components. The main devices incorporated in our system are summarized in the condensed bill of materials below. A complete bill of materials can be seen in Table 7 (see Appendix B). Furthermore, a list of ranked stakeholders who were of assistance throughout this project can be seen in Table 8 (see Appendix B).

Table 2: Bill of materials for primary components of tracking system, pressure sensors, microfluidic valves and data acquisition system (DAQ).

Device	Description	Quantity	Total Cost
Polhemus Fastrak Digitizer Unit	Tracking system transmits signal from microsensor	1	5,557.50
Polhemus Microsensor	Relays 6-degrees-of-freedom coordinates to MATLAB	4	4,560.00
Bürkert Microfluidic Valve	Controlled valve allows air passage to pneumatic muscles (including 4 manifolds)	24	2694.28
Bürkert Microfluidic Valve	Controlled valve allows air passage to cavities	4	275.40
OMEGA PX26-100GV Pressure Sensor	Converts pressure into voltage for the pneumatic muscles, which is interpreted by DAQ and LabVIEW	12	665.28
OMEGA PX26-005GV Pressure Sensor	Converts pressure into voltage for the cavities	2	146.00
NI-9205 Voltage Input Module	DAQ module for pressure readings input	1	1,107.00
NI-9485 Relay Switch Module	DAQ module for control of microfluidic valves	4	1,944.00
Miscellaneous supplies from McMaster-Carr, Home Depot, Rona, Access Electronique, and LabVIEW, and shipping costs	Various fittings, tubing, manifolds, plugs, and air compressor	N/A	1027.50
		TOTAL	17,976.96

7.1 Assembly Workflow and Design Embodiment Adjustments

7.1.1 Microfluidic Valves

Initially, a hydraulic manifold with 2-inlets and 12-outlets was purchased from McMaster-Carr with the intent of diverting air to the twelve muscles that were to be inflated. However, as shown in Figure 17 a)-b), the microfluidic valves were already pre-mounted on four sets of hydraulic manifolds, each also equipped with two inlets and six outlets corresponding to the six mounted valves. As a result, additional threaded plugs needed to be purchased to cap one inlet from each valve manifold to prevent undesirable air leakage. In addition, the 12-outlet hydraulic manifold purchased to split the airflow from the compressor was replaced with a 1-inlet 2-outlet manifold to connect to air compressor to the valves.

Furthermore, each valve was connected using a 22 gauge, 3-conductor wire, where two wires served for power (positive/negative terminals) and the other for ground, as shown in Figure 17 c). The power supply originally used for each of the valve hydraulic manifolds was rated 24 VDC and 800mA. However, considering each valve consumed 6.5 W, the valve current-draw would be approximately 0.27A, which was miscalculated when the first power supply was selected. To rectify the error, an appropriate power supply with a maximum amperage of 5A was used instead.

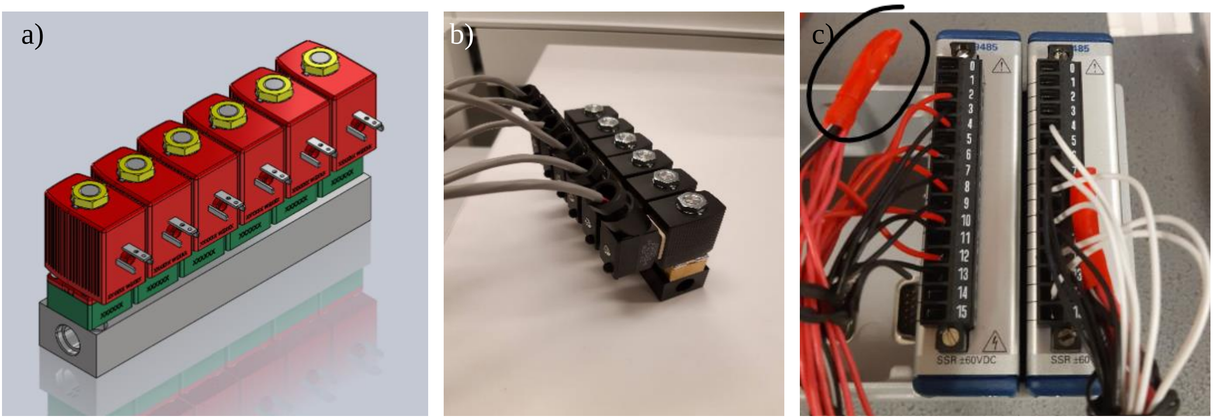

Figure 17: a) 3-D CAD of six Bürkert microfluidic valves mounted on a hydraulic manifold. The wiring interface is not shown in this model; b) Six microfluidic valves pre-mounted on manifold with wiring interface and connected via 3-conductor wire; c) NI-9485 Relay Switch module for air inflow (left) and exhaust (right). All valves on a manifold are wired and soldered in parallel to one power supply, secured with red electrical tape.

The power supply's positive terminal was soldered in a parallel circuit with the valve positive terminals to ensure that each received the same voltage. The valve's negative terminal was subsequently connected to a port in the NI-9485 relay switch module. A total of 24 ports were used from the four NI-9485 modules to accompany the 24 valves either delivering or exhausting air from the pneumatic muscles. As a safety precaution, electrical tape was used to wrap any exposed conductors that were soldered together, illustrated in Figure 17 c).

7.1.2 Pressure Sensors

The OMEGA PX26 pressure sensors were connected with a 22 gauge, 4-conductor wire, where two wires served for excitation (positive/negative terminals) while the other two served for input and output to the DAQ NI-9205 module. One issue present during the assembly phase was the excess clearance between the sensor and the pneumatic muscle. A solution was proposed to 3-D print an insert tube shown in Figure 18 a) to achieve the desired interference fit and prevent air leakage from one end of the muscle while inflating. However, the piece was too rigid to fit comfortably over the sensor head, even if the insert ridges provided a suitable seal in the pneumatic muscles themselves. Therefore, an alternative solution using a double-tube seal was used to ensure

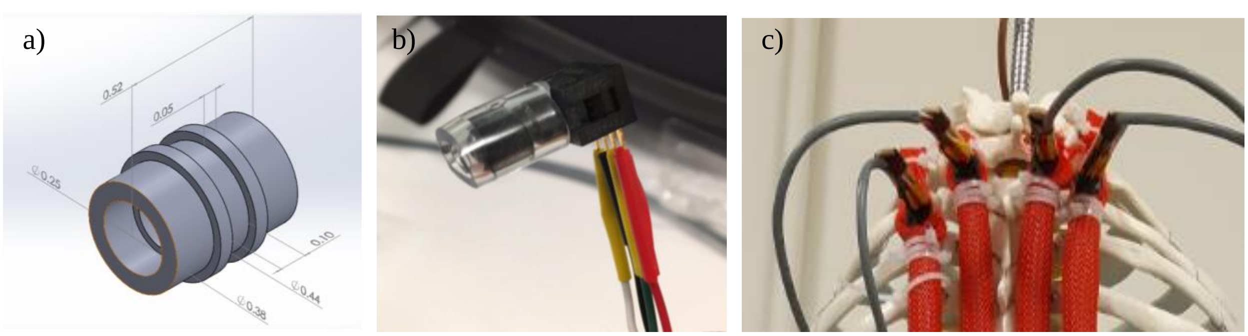

Figure 18: a) 3-D CAD of printed piece to secure sensor and fit inside pneumatic muscle; b) Double-tube seal fastened around head of OMEGA pressure sensor; c) 3 plastic cable-ties fastened around end of pneumatic muscle to avoid additional air leakage.

rigidity inside the pneumatic muscle without compromising flexibility to fit closely over the sensor head. As a measure to prevent further air leakage, three cable ties were sufficient to maintain seal between 30-40 psi, as seen in Figure 18 c).

The sensor is equipped with four prongs, which were soldered to the four conductive wires. Nevertheless, the prongs were fragile and very sensitive to bending, which posed a problem in fitting the sensors inside the muscles. Additionally, the contraction of the pneumatic muscles as they were inflated led to the connected wire pulling on the prongs, causing undesirable strain. Therefore, a simple solution shown in Figure 19 b) was devised to add a popsicle stick as a stilt in maintaining the structural integrity of the prongs. The sensor and the wire were taped to the bottom of the popsicle stick to maintain the wire upright instead of becoming too slack, seen in Figure 19 c). Since one of the sensor prongs fractured, seen in Figure 19 a), the amount of available sensors at our disposal reduced to 11. Therefore, the decision was made to fit the pressure sensors solely into the erector spinae and multifidus. Consequently, the psoas major muscles located on the interior of the spine were neglected considering the inflated cavity would have interfered with the placement of the sensor.

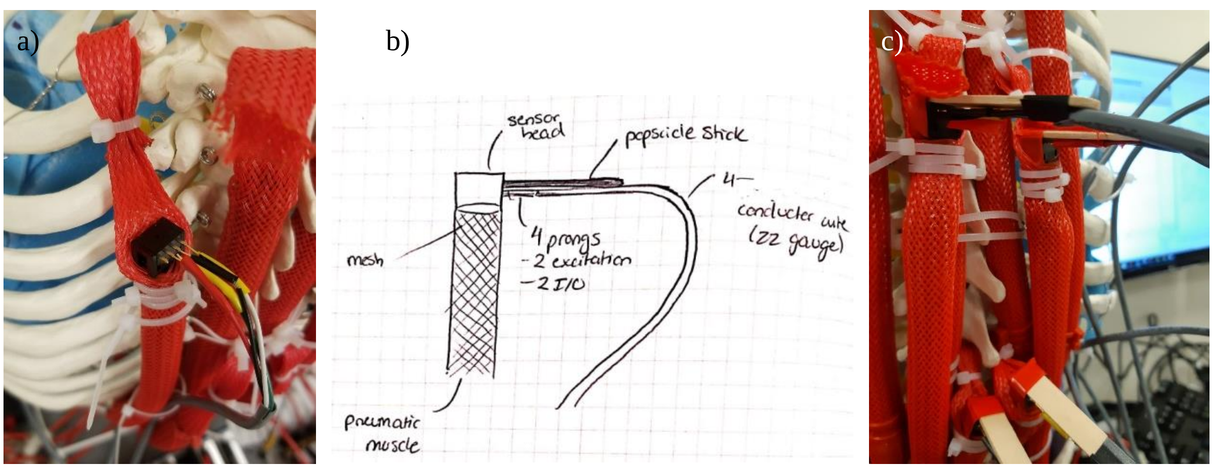

Figure 19: a) Broken sensor prong due to excess bending and strain; b) Concept sketch of popsicle stick supporting sensor prongs; c) Pressure sensor and 22-gauge wire taped to underside of popsicle stick.

The positive and negative terminals were connected in a parallel circuit on an electronic breadboard to a power supply providing 10 VDC and 5A, included in Figure 20 b). Since the pressure sensors required only 2mA of current, the power supply was more than sufficient. The input and output terminals were connected horizontally to correspond to one channel, seen in Figure 20 a). This channel was then accessed through the DAQ assistant in our LabVIEW pressure control VI, which is then able to output the pressure readings in terms of voltage. However, since it was more desirable for the sensor to output in terms of pressure, we calibrated each sensor by calculating the linear relationship between the pressure detected and the voltage outputted. The values obtained in LabVIEW were then corrected for each sensor such that they can be display in the appropriate units.

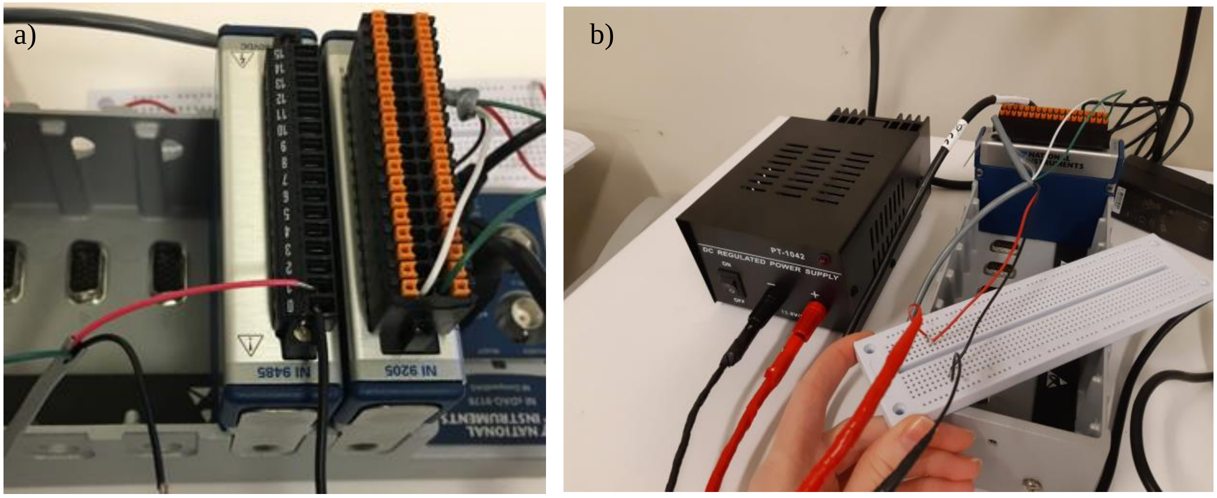

Figure 20: a) NI-9485 Relay Switch module connected to valve conductor in series (left module). NI-9205 module with input (green) and output (white) conductors connected horizontally, corresponding to one channel in LabVIEW; b) Pressure sensor power supply terminals, positive (red) and negative (black) connected to breadboard. Pressure sensor excitation conductors, positive (red) and negative (black) connected in parallel configuration to breadboard.

7.1.3 Air Supply and Pneumatic System

The portable air compressor from McMaster-Carr was the air supply used to inflate the pneumatic muscles on our robotic spine model. A Milton coupler was used to connect the hose to the compressor outlet serving as the main line for air delivery. Furthermore, a ball valve purchased from Rona was used to adjust air flow through the robotic spine model in Figure 21 a). Once the compressor is turned on and the tank pressure reaches 150 psi, the regulator knob corrects the pressure of the air flow through our system. As portrayed in Figure 21 b), the main hose was connected to a hydraulic manifold which diverted the air to the two inlet valve manifolds.

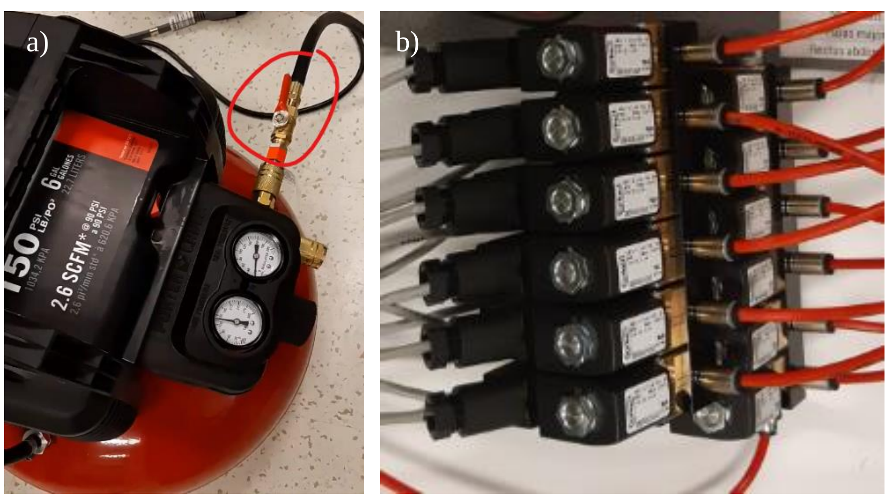

Figure 21: a) Porter Cable air compressor connected with ball valve fitting to main hose; b) Red nylon tubing connected from compressor to hydraulic manifold in one inlet with the other inlet capped by a threaded screw (not shown). Six nylon tubes protruding from each valve manifold to deliver or expel air from pneumatic muscle.

While assembling the prototype, we noticed the air supply required for the thoracic and abdominal cavities presented a separate issue. Based on the design of the pneumatic system, the pressure inside the muscles can be maintained from the air compressor operating between 30-40 psi. However, the cavity pressure required was on a smaller scale between 0-5 psi, which would require a separate method to supply air autonomously. Therefore, for simplicity, inflating the cavities was neglected from the design and the air inflow to the muscles became the primary focus of the prototype setup.

7.1.4 Polhemus Tracking System

Although four microsensors were ordered from Polhemus, only one was sufficient to track spinal deflection uniaxially under a load. As a measure to secure the micro-sensor, it was placed inside a clear, plastic tube taped to the anterior C7 vertebrae. In addition, a frequency module was secured at the spine's base. Theoretically, spinal deflection would allow relative displacement of the sensor away from the base, which would transmit positional data to the Fastrak Digitizer indicating that the system was "unstable".

8 Final Prototype Description

8.1 Mechanical Prototype

The final prototype consisted of a robotic spine composed of analog bones (thoracic and lumbar spine, pelvis, sacrum and rib cage), thoracic and abdominal-pelvic cavities, and muscles (multifidus, erector spinae, psoas major, and rectus abdominus). The contraction of all muscles except the rectus abdominus (located at the front of the skeleton and considered the abdominal region) and psoas major muscles (attached from the lumbar region of the spine through the pelvic area) were automated through a control system, as seen in Figure 22.

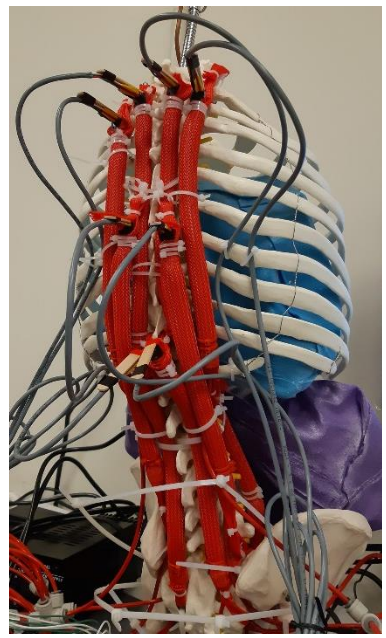

Figure 22: Robotic spine model with implemented control system and pressure sensors for the muscles.

8.2 Control System

The control system consisted of both electrical and software components.

8.2.1 Electrical System

The electrical system consisted of the following, which can be seen in Figure 23:

- 24 x Bürkert microfluidic valves (12 for muscle air inlet, 12 for muscle air exhaust)
- 8 x OMEGA PX26 pressure sensors
- National Instruments Compact data acquisition system (cDAQ)
- Polhemus Fastrak Digitizer Tracking System
- 6 Gal. 150PSI Portable Electric Air Compressor

The pneumatic muscles were individually connected to one inlet and one exhaust valve. The inlet valves were connected to an air compressor, supplying the muscles with air when the inlet valves were open. The exhaust valves, on the other hand, allowed the air inside the muscles to drain when open. While each muscle was connected to a valve on one end, each was also connected to a pressure sensor on the opposing end. These sensors served to measure the change in pressure within the muscles as the valves turned on and off. The valves and the pressure sensors were connected to the DAQ, allowing both devices to be interfaced using the LabVIEW software. Lastly, a position tracking sensor was attached to the C7 vertebra, while the reference transmitter was placed at the base of the spine, allowing for any displacement between the reference and the sensor to be recorded by the Fastrack tracking system.

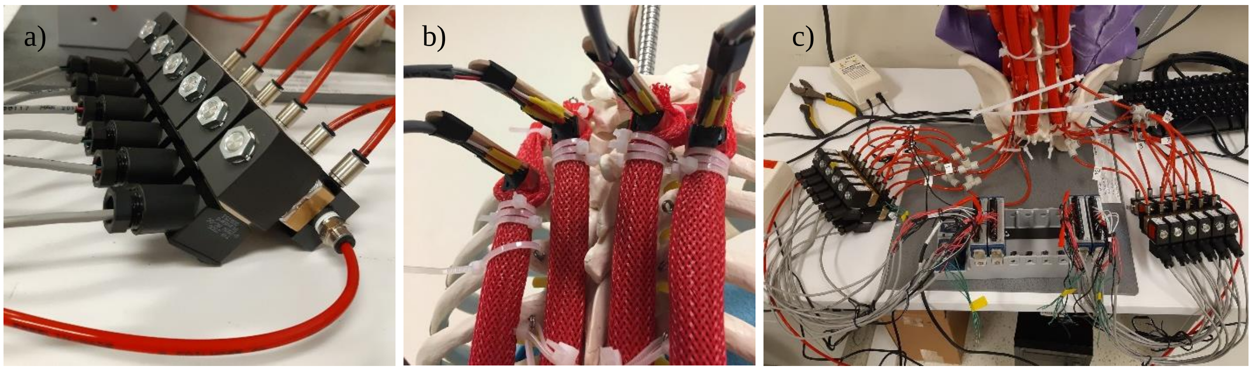

Figure 23: a) 6 Microfluidic valves on a manifold. Red tubes are for air supply to the muscles, the grey tubing contains three conducting wires for excitation and connects each valve in series with the relay switch. All 6 valves are connected in parallel with the 24V/5A AC/DC converter; b) Each pressure sensor acts as a plug on the upper end of each muscle. The grey tubing holds 4 conducting wires, 2 are connected to the 13.8V power supply for excitation, and 2 are connected to the DAQ module for signal output; c) Valves connected to the muscles and the DAQ system.

8.2.2 Software System

The software components consisted mainly of LabVIEW but included MATLAB and the Polhemus Fastrak interface (PFI). The displacement of the tracking sensor was read using the PFI, however, this data was stored in an array in MATLAB (see Appendix C). The array was instantaneously imported to LabVIEW, where the control system was implemented. The valves were controlled using ON/OFF control through LabVIEW. When the tracking system detects that the skeleton has displaced from the defined point of reference, the inlet valves will turn on, sending a supply of air into the muscles.

The pressure sensors were also read from LabVIEW software. All 8 sensors were calibrated, and the pressure of each individual muscle was displayed graphically on the LabVIEW interface. The LabVIEW block diagram for both the ON/OFF control of the valve and the graphical display of the pressure sensor readings can be viewed in Figures 25-26 (see Appendix C).

8.3 Power Supply System

All 24 valves required power. Each valve required 24VDC and 0.27A to function. A 24V/5A AC/DC converter powers one manifold of 6 valves. Since there is a total of 4 manifolds, each loaded with 6 valves, 4 AC/DC converters were needed to power the entire set of valves.

As for the pressure sensors, all 8 sensors could be powered by a 13.8V power supply.

The DAQ system and the Polhemus tracking system were connected to a standard 120VAC power outlet for excitation.

9 Prototype Performance

The performance of the robotic spine satisfies most of the engineering requirements. Pressure sensors were installed in the muscles; however, they were not implemented in the cavities. Similarly, a supply of air, regulated through an electronic valve system, was completed for the muscles but not for the cavities. Lastly, the tracking system was successfully implemented, enabling the instantaneous measurement of the spine displacement. The tracking system allows the control system to activate the opening and closing of the microfluidic valve system, which regulates the pressure in the pneumatic muscles. In addition, when a compressive load was applied on the spine, causing a disturbance, the pneumatic muscles automatically filled with air. The only criterion that was not met was the incorporation of the cavities in the control system. While all parts have been purchased in order to implement the control of the cavity air pressure, this section was not completed due to time constraint. However, the scope of our project was to purchase all necessary equipment for the control of the robotic spine, as well as to create a proof of concept of the control system, which were accomplished.

10 Conclusion

In conclusion, the aim of this project was to implement a control system for the existing spine model so that it may be used to study spinal stability and to better understand LBP. The components implemented in the device included microfluidic valves, a 150-psi compressor, Omega pressure sensors, a Polhemus tracking system with position sensors, and a cDAQ and associated modules, as well as MATLAB and LabVIEW software. All components were chosen using the weighted needs of the client and the desires to best fit the design criteria established. Through position data readings from the tracking system, which were recorded in MATLAB and then implemented into LabVIEW, the system was able to achieve control by activating the valves allowing airflow to the pneumatic muscles when the spine was deflected from its initial position, and releasing airflow once the model was stabilized. Pressure readings in each muscle were achieved by integrating the sensors using double-tube seal fittings at one end of each muscle, with feasible readings of pressures tested up to 30-40 psi. Although the control of the cavities was not achieved in this project, all components required for its development are accounted including valves, pressure sensors, tubing, fittings, DAQ modules, and software. The final prototype presented in this report is a working control system for the robotic spine model.

Certain recommendations can be made for the improvement and progression of the robotic spine model's control system. First, the contraction of the pneumatic muscles by opening and closing the valves could be controlled by a proportional integral derivative (PID) controller in LabVIEW. This would allow the system to achieve and remain at a stable position, doing so with greater precision and accuracy. Furthermore, adding the additional three position sensors along the inflection points of the spine would allow for more accurate control. To facilitate studying the muscles and as an extra measure of safety, it is recommended that each muscle have a cut-off pressure established and have the pressure sensors linked to the control system. With the pressure sensors integrated in each muscle, this would allow the control system to turn off the valves feeding air to the muscles once the internal pressure reaches the cut-off pressure, hindering over inflation. This would further allow the possibility of inflating each muscle to a desired internal pressure in order to study spinal stability under various loading conditions. To help better comprehend the contribution of each muscle and to achieve spinal stability more precisely, it is advised that each muscle and subsequent valves be controlled individually. This would allow the system to respond more effectively to the 3D coordinates of displacement from the tracking system.

Throughout the course of the design projects, many lessons were learned – at times they were learned the easy way and other times they were learned the hard way.

1. It is imperative that one considers lead times when purchasing equipment. Delivery delays should also be assumed.
2. When ordering multiples of one part, order extra in case of unexpected damage to the devices.
3. Asking experts questions can save time and can help one avoid unforeseen issues. Contacting these experts for help can give one better insight on how to approach the problem.
4. When researching which device is most suitable for one's application, it is always best to make an educated decision in a timely matter. It is best not to delay decisions, as this delay will be multiplied when lead times are also taken into consideration.

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Appendix A: Evaluation Criteria and Evaluation Process

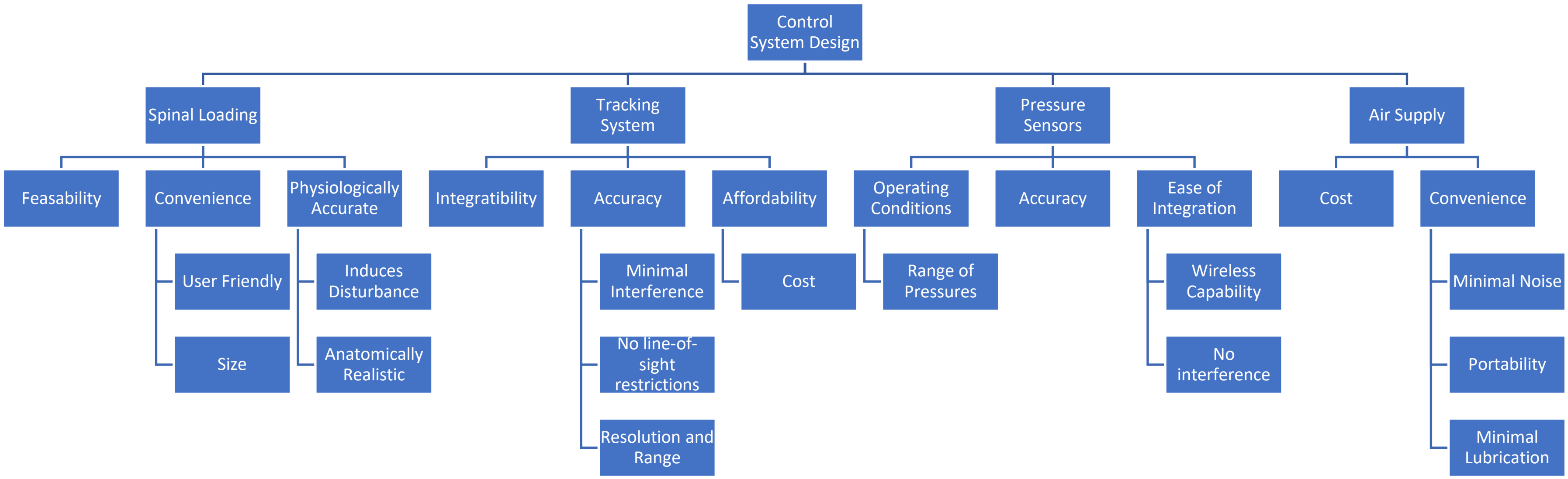


Figure 24: Objective tree.

Table 3: Pairwise comparison chart for spinal loading

SPINAL LOADING	Feasibility	Cost	Aesthetically pleasing	Anatomically realistic looking	Size	User friendly	Physiologically accurate	Induces a disturbance	Total
Feasibility	-	1	1	1	1	1	1	0	6
Cost	0	-	0	1	0	0	1	0	2
Aesthetically pleasing	0	1	-	1	0	0	1	0	3
Anatomically realistic looking	0	0	0	-	0	0	1	0	1
Size	0	1	1	1	-	0	1	0	4
User friendly	0	1	1	1	1	-	1	0	5
Physiologically accurate	0	0	0	0	0	0	-	0	0
Induces a disturbance	1	1	1	1	1	1	1	-	7

Table 4: Pairwise comparison chart for tracking system

TRACKING SYSTEM	Feasibility	Cost	Minimize size of object placed on model	Ease of integration	User friendly	Wireless	Aesthetically pleasing	Resolution	No interference	Degrees of freedom (want: 6)	No line-of-sight	Total
Feasibility	-	1	1	0	1	1	1	1	1	0	1	8
Cost	0	-	1	0	0	1	1	0	0	0	1	4
Minimize size of object placed on model	0	0	-	0	0	1	1	0	0	0	1	3
Ease of integration	1	1	1	-	1	1	1	1	1	0	1	9
User friendly	0	1	1	0	-	1	1	1	1	0	1	7
Wireless	0	0	0	0	0	-	1	0	0	0	0	1
Aesthetically pleasing	0	0	0	0	0	0	-	0	0	0	0	0
Resolution	0	1	1	0	0	1	1	-	0	0	1	5
No interference	0	1	1	0	0	1	1	1	-	0	1	6
Degrees of freedom (want: 6)	1	1	1	1	1	1	1	1	1	-	1	10
No line-of-sight	0	0	0	0	0	1	1	0	0	0	-	2

Table 5: Pairwise comparison chart for pressure sensors

PRESSURE SENSORS	Feasibility	Cost	Weight	Size	Ease of integration	Range of pressures	Aesthetically pleasing	Accuracy	Wireless	No Interference	Battery Life	Total
Feasibility	-	1	1	0	0	0	1	1	1	1	1	7
Cost	0	-	1	0	0	0	1	0	1	0	1	4
Weight	0	0	-	0	0	0	1	0	0	0	0	1
Size	1	1	1	-	0	0	1	1	1	1	1	8
Ease of integration	1	1	1	1	-	0	1	1	1	1	1	9
Range of pressures	1	1	1	1	1	-	1	1	1	1	1	10
Aesthetically pleasing	0	0	0	0	0	0	-	0	0	0	0	0
Accuracy	0	1	1	0	0	0	1	-	1	1	1	6
Wireless	0	0	1	0	0	0	1	0	-	0	1	3
No Interference	0	1	1	0	0	0	1	0	1	-	1	5
Battery life	0	0	1	0	0	0	1	0	0	0	-	2

Table 6: Pugh matrix used to compare concepts for the spinal loading, tracking system, and pressure sensors

Criteria	**Weight**	**Alternative Concepts**			
SPINAL LOADING	Out of 5	Concept 1	Concept 2	Concept 3	Concept 4
Feasibility	4.5	1	0	-1	1
Cost	1	1	-1	-1	1
Aesthetically pleasing	2	-1	1	0	-1
Anatomically realistic looking	0.5	0	1	1	0
Size	3	0	-1	-1	-1
User friendly	4.5	1	-1	-1	1
Physiologically accurate	0.5	1	-1	-1	0
Induces a disturbance (want this)	5	1	-1	-1	1
Sum of +'s		15.5	2.5	0.5	15
Sum of -'s		-2	-14	-18.5	-5
TOTAL		13.5	-11.5	-18	10
TRACKING SYSTEM	Out of 5	Concept 1	Concept 2	Concept 3	Concept 4
Feasibility	4.5	1	1	0	1
Cost	2	-1	-1	-1	-1
Minimize size of object placed on model	1	1	1	1	1
Ease of integration	5	-1	0	-1	-1
User friendly	4	1	1	0	0
Wireless	1	1	0	0	1
Aesthetically pleasing	0.5	1	0	1	0
Resolution	3	0	1	1	0
No interference	4	1	1	1	1
Degrees of freedom (want: 6)	5	1	1	1	1
No line-of-sight	1	-1	1	1	1
Sum of +'s		20	22.5	14.5	16.5
Sum of -'s		-8	-2	-7	-7
TOTAL		12	20.5	7.5	9.5

Criteria	Weight	Alternative Concepts			
PRESSURE SENSORS	Out of 5	Concept 1	Concept 2	Concept 3	Concept 4
Feasibility	4.5	1	-1	0	1
Cost	2.5	-1	0	-1	1
Weight	1	0	1	1	1
Size	5	1	0	1	1
Ease of integration	5	-1	1	0	0
Range of pressures	5	1	1	1	1
Aesthetically pleasing	0.5	1	1	-1	0
Accuracy	4	1	1	1	1
Wireless	2	1	-1	1	-1
No Interference	4	1	1	0	0
Battery life	1.5	1	1	1	0
Sum of +'s		26.5	17	18.5	22
Sum of -'s		-7.5	-6.5	-3	-2
TOTAL		19	14.5	15.5	20

Appendix B: Bill of Materials and List of Stakeholders

Table 7: Bill of Materials

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
1	001	Manifold CLP NPT	Aluminum black	1.0	4	317.05	1268.20	Manifold for the valves for the muscles, NPT 1/8 threaded port	Bürkert	00613840	Shante Zaccaria	34 days	Mounted next to the model	Bürkert	00613840	N/A
2	002	2/2-way solenoid valve, Type 6011, 1.2mm orifice	FKM, brass, polyamide, stainless steel 1.4305	1.0	24	59.42	1426.08	Valves for the pneumatic muscles, direct analogue	Bürkert	00466560	Shante Zaccaria	13 days	Connected to the nylon tubing at the inlet of the pneumatic muscles	Bürkert	00466560	N/A
3	003	2/2-way solenoid valve, Type 6011, 2.4mm orifice	FKM, brass, polyamide, stainless steel 1.4305	1.0	4	68.85	275.40	Valves for the artificial cavities, direct analogue	Bürkert	00466190	Shante Zaccaria	34 days	Connected to the inlet of the cavities	Bürkert	00466190	N/A
4	004	Fastrak SEU	N/A	1.0	1	6032.50	6032.50	Tracking system controller	Polhemus	1A0467-001	Dan Ratta	4 days	Connected to power supply	Polhemus	1A0467-001	Price listed includes 5% discount
5	005	Frequency module	N/A	1.0	1	0.00	0.00	Transmits/ receives signal	Polhemus	1A0473-003	Dan Ratta	4 days	N/A	Polhemus	1A0473-003	Included
6	006	Power supply	N/A	1.0	1	0.00	0.00	Powers Fastrak digitizer	Polhemus	1C0034	Dan Ratta	4 days	Connected to 125 V outlet	Polhemus	1C0034	Included
7	007	110V power cord	N/A	1.0	1	0.00	0.00	Connects to power supply (125 V standard)	Polhemus	17500B-BLK	Dan Ratta	4 days	Plugged in power supply	Polhemus	17500B-BLK	Included

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
8	008	RS-232 cable	N/A	1.0	1	0.00	0.00	Connection between Fastrak and other peripheral devices (ex. computer)	Polhemus	1C0288	Dan Ratta	4 days	Connected to Fastrak RS-232 inlet for RS-232 interface	Polhemus	1C0288	Included
9	009	USB cable	N/A	1.0	1	0.00	0.00	Connects to USB port of Fastrak	Polhemus	1C0289	Dan Ratta	4 days	Connected to Fastrak USB inlet for USB interface	Polhemus	1C0289	Included
10	N/A	Receiver 20ft cable	N/A	1.0	1	-475.00	-475.00	N/A	Polhemus	4A0625-240-BBB	Dan Ratta	4 days	N/A	Polhemus	4A0625-240-BBB	Price listed includes 5% discount. This product was not included, therefore a monetary discount was removed off of the total price
11	011	Transmitter - 2 inch 20ft cable	N/A	1.0	1	0.00	0.00	Transmits signal	Polhemus	2A0870-240-BBB	Dan Ratta	4 days	Connected to Fastrak transmitter inlet	Polhemus	2A0870-240-BBB	Included
12	012	CD-manual, SDK, GUI	N/A	1.0	1	0.00	0.00	Instructions manual for Fastrak setup	Polhemus	1A0196-01	Dan Ratta	4 days	N/A	Polhemus	1A0196-01	Included

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
13	013	Micro sensor flex	N/A	1.0	4	1140.00	4560.00	Motion sensors fixed at pre-determined locations on spine	Polhemus	3A0878-180	Dan Ratta	4 days	Connects the Fastrak micro sensor ports to 4 fixed locations along the spine	Polhemus	3A0878-180	Price listed includes 5% discount
14	014	Cavity Pressure Sensor	Polyethimide, silicon, fluorosilicone	1.0	2	73.00	146.00	Pressure sensor measuring cavity pressure	Omega	PX26-005GV	Joel Thivierge	3 days	Punctured through the cavity. One extremity of the sensor is inside the cavity while the other is exposed to ambient pressure.	Private Label	N/A	N/A
15	015	Muscle Pressure Sensor	Polyethimide, silicon, fluorosilicone	1.0	12	55.44	665.28	Pressure sensor measuring muscle pressure	Omega	PX26-100GV	Joel Thivierge	3 days	Plugged into one side of the muscle tubing	Private Label	N/A	N/A
16	016	Push-to-Connect Fitting for Drinking Water: Tee Connector, 5/32" tube OD	Acetal Plastic	1.0	16	2.92	46.72	Tee connector to split flow from inlet valve, exhaust valve and muscle/ cavity	McMaster-Carr	51055K141	N/A	3 days	Tube to inlet valve, exhaust valve and muscle/cavity connected	John Guest USA, Inc	PM0204S	N/A
17	017	Flexible Nylon Tubing 25 ft, High Pressure, Opaque Red, 0.106" ID, 5/32" OD	Nylon Plastic	1.0	1	8.25	8.25	Tubing used throughout to pass air flow in system	McMaster-Carr	5635K62	N/A	3 days	In between muscles, valves and manifold	Freelin Wade Co.	E-201-05	N/A

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
18	018	Push-to-Connect Tube Fitting for Air Straight Adapter, for 5/32" Tube OD x 1/8 NPT Male	Nickel-Plated Brass	1.0	42	2.48	104.16	'P' fitting for muscle valves (inlet x12, exhaust x12), 'P/A' fitting for cavity valves (x6) and fitting for muscle manifold (x12)	McMaster-Carr	5779K104	N/A	3 days	Connected to output of muscle manifold, pressure feed of muscle valves and both active and pressure feed of cavity valves	Parker Hannifin Corp.	3175 04 11	N/A
19	019	Aluminum Rectangular Manifold Outlets on 2 Sides, 12 Outlets, 1/4 NPT, 9-1/4" Long	Anodized Aluminum	1.0	1	31.40	31.40	Intakes flow of compressor and splits it to feed twelve muscles valves	McMaster-Carr	5975K27	N/A	3 days	Connected to air hose and feeding to tubes connected to muscle valves	Wm. P. Nugent Co.	PCM10-125R-06BW	N/A
20	020	Push-to-Connect Tube Fitting for Air Straight Adapter, for 5/32" Tube OD x 10-32 Thread Male	Nickel-Plated Brass	1.0	12	2.76	33.12	'A' fitting for muscle valves (x12)	McMaster-Carr	5779K244	N/A	3 days	Connected to active feed of muscle valves	Parker Hannifin Corp.	3171 04 20	N/A
21	021	Air Hose 5 ft with 1/4 x 1/4 NPTF Brass Male Fittings, 200 PSI	EPDM Rubber	1.0	1	16.24	16.24	Air hose connected to air compressor	McMaster-Carr	1593N1	N/A	3 days	Connected between compressor and muscle manifold	Tipco Techno-logy Inc.	5304K82	N/A

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
22	022	Single Tank Portable Air Compressor	Aluminum	1.0	1	165.39	165.39	Air compressor feeding muscles	McMaster-Carr	9965K62	N/A	3 days	Connected to manifold by air hose	Black & Decker	C2002	N/A
23	023	Thick Wall PVC Pipe fitting for Water, Plug with Hex Drive Style, 1/4 NPT Male	PVC Plastic	1.0	2	2.21	4.42	Blocking extra input opening of muscle manifold	McMaster-Carr	4596K71	N/A	3 days	Plugging muscle manifold opening that is not needed for airflow	Lasco Fittings	850-002	N/A
24	024	NI-9205 Spring Terminal, 32 Ch	N/A	1.0	1	1107.00	1107.00	Series module to connect to DAQ and take readings for the pressure sensors	National Instruments	785184-01	Andrea Gamboa, Yves Levesque	21 days	Mounted next to the model, connected to cDAQ-9178	National Instru-ments	785184-01	
25	025	NI-9485, 8 Ch	N/A	1.0	4	486.00	1944.00	Relay series module to connect ot DAQ and control the valves	National Instruments	779600-01	Andrea Gamboa, Yves Levesque	21 days	Mounted next to the model, connected to cDAQ-9178	National Instru-ments	779600-01	
26	026	1/4 Inch Female Steel Plug	Steel	1.0	1	4.51	4.51	Connection between compressor and air hose	Home Depot	028893981 725	N/A	N/A	Connected to air compressor	Husky	N/A	Tax included

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
27	027	Ball valve, 1/4"	Brass, steel	1.0	1	19.53	19.53	Connected between air compressor and female steel plug	Rona	7345034	N/A	N/A	Connected to air compressor	Campbell Hausfeld	MP32170 0AV	Tax included When closed, used to fill the air compressor tank to max pressure
28	028	Bread board	Plastic	1.0	1	13.79	13.79	Used to connect pressure sensors to power supply	Access Electro-nique	60428	N/A	N/A	Placed next to DAQ	N/A	N/A	Tax included
29	029	Electrical wires, 4 channels, 30 ft	Copper, plastic	1.0	55	0.46	25.30	Connects pressure sensors to DAQ and power supply	Access Electro-nique	70082	N/A	N/A	Connects pressure sensors to DAQ and power supply	N/A	N/A	Tax included
30	030	Red electrical tape	Vinyl	1.0	1	1.48	1.48	For wires and labelling	Access Electro-nique	90502	N/A	N/A	For wires and labelling	N/A	N/A	Tax included
31	031	Black electrical tape	Vinyl	1.0	1	0.91	0.91	For wires and labelling	Access Electro-nique	269241	N/A	N/A	For wires and labelling	N/A	N/A	Tax included
32	032	Yellow electrical tape	Vinyl	1.0	1	0.91	0.91	For wires and labelling	Access Electro-nique	269242	N/A	N/A	For wires and labelling	N/A	N/A	Tax included
33	033	DC regulated power supply	N/A	1.0	1	51.74	51.74	Power supply for the pressure sensors	Access Electro-nique	160500	N/A	N/A	Connected to breadboard to power pressure sensors	N/A	N/A	Tax included
34	034	Electrical wires, 3 channels, 50 ft	Copper, plastic	1.0	50	0.40	20.13	Connects valves to DAQ and power supply	Access Electro-nique	70081	N/A	N/A	Connects valves to DAQ and power supply	N/A	N/A	Tax included

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
35	035	Banana plugs	Plastic	1.0	2	2.30	4.60	Attachment between wires from bread board to power supply for sensors	Access Electro-nique	272046	N/A	N/A	Attached to power supply for pressure sensors	N/A	N/A	Tax included
36	036	Zip ties	Nylon	1.0	2	5.16	10.33	Used to attach muscles to spine model	Reno Depot	067396008 218	N/A	N/A	Connected to multiple places on the spine	Thomas & Betts	MR10400	Tax included
37	037	24V 800mA AC/DC converter	N/A	1.0	4	13.79	55.15	Power supply for the valves (not used)	Access Electro-nique	160544	N/A	N/A	Connected to valves	N/A	MEE-8324	Tax included
38	038	Red wire clips	Plastic	1.0	1	1.14	1.14	For wire protection	Access Electro-nique	170788	N/A	N/A	For wire protection	N/A	N/A	Tax included
39	039	3D printed intermedi-ary tube	PLA	1.0	1	12.23	12.23	Placed between pressure sensor and muscle (not used)	The Cube	N/A	N/A	3 days	Attached to top of muscle	The Cube	N/A	
40	040	LabVIEW Student Edition	N/A	1.0	1	34.50	34.50	Needed for National Instruments Data Acquisition System	LabVIEW	N/A	N/A	N/A	On desktop computer	LabVIE W	N/A	1 year accessibi-lity
41	041	Clear Vinyl Tubing	Vinyl	1.0	1	6.44	6.44	Intermediary connection between pressure sensor and muscle	Home Depot	775583200 122	N/A	N/A	Connection between pressure sensor and muscle	Home Depot	77558320 0122	Tax included

Item No.	Part No.	Part Name	Material	Revision	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Supplier Part No.	Point of Contact	Lead Time	Placement	Manufacturer Name	Manufacturer Part No.	Comments
42	042	Straight-Flow Rectangular Manifold	Anodized Aluminum	1.0	1	21.67	21.67	Used to split airflow from compressor to two valve manifolds for air inflow	McMaster-Carr	1023N11	N/A	1 day	Connected to air hose and feeding to tubes connected to muscle valve manifolds	Datum-A-Industries Inc	SPHA180-02-1/8	
43	043	Low-Pressure Aluminum Pipe Fitting	Aluminum	1.0	4	2.78	11.12	Plug to block the airflow from the valve manifold	McMaster-Carr	44705K382	N/A	1 day	Attached to valve manifold	Latrobe Foundry	N/A	
44	044	24V 2A AC/DC Converter	N/A	1.0	4	19.54	78.15	Power supply for the valves	Access Electro-nique	269918	N/A	N/A	Placed next to valves	Gacun	GACUN-2420	Tax included
45	045	Power cord for AC/DC converter	N/A	1.0	4	8.04	32.15	Power cable for the AC/DC converter	Access Electro-nique	130481	N/A	N/A	Attached to AC/DC converter	Blue Diamond	776704050022	Tax included

Item No.	Additional costs	Quantity	Price/ Unit	Total Price	Description	Supplier Name	Point of Contact	Lead times	Comments
046	Freight - FE Intl	1	149.38	149.38	Cost of shipping tracking system	Polhemus	Dan Ratta	3 days	N/A
047	Ground Shipping	1	24.00	24.00	Cost of shipping valves	Omega	Joel Thivierge	3 days	N/A
			TOTAL	17976.96					

Table 8: List of stakeholders and rankings

Stakeholder Rank	Name	Contact Information	Role
1	Mark Driscoll	Mark.driscoll@mcgill.ca	Advisor/Client/Professor
2	Brittany Stott	Brittany.stott@mail.mcgill.ca	Team member
2	Laura Fasanella	Laura.fasanella@mail.mcgill.ca	Team member
2	Benjamin Francolini	Benjamin.francolini@mail.mcgill.ca	Team member
2	Jody Haig	John.haig@mail.mcgill.ca	Team member
3	Thomas Jansen	Thomas.jansen2@mail.mcgill.ca	Thesis researcher for pneumatic muscles
3	Shante Zaccaria	shante.zaccaria@burkert.com	Supplier – Bürkert Fluid Control System
3	James Richard Forbes	James.richard.forbes@mcgill.ca	Professor – contact for control system
3	Mario Iacobaccio	Mario.iacobaccio@mcgill.ca	Measurement Lab Staff – contact for DAQ
3	Sneha Patel	Sneha.patel@mail.mcgill.ca	PhD student – contact for DAQ
3	Khaled El-Monajjed	Khaled.el-monajjed@mail.mcgill.ca	PhD student – contact for tracking system
3	Ibrahim El Bojairami	Ibrahim.elbojairami@mail.mcgill.ca	PhD student – contact for muscle pressure
3	Natasha Jacobson	Natasha.jacobson@mail.mcgill.ca	TA/PhD student – contact for abdominal pressure
3	Trevor Cotter	Trevor.cotter@mail.mcgill.ca	PhD student – assistance with LabVIEW
3	Marshall Hooker	Marshall.hooker@mail.mcgill.ca	Undergraduate student – assistance with LabVIEW
4	Rosaire Mongrain	Rosaire.mongrain@mcgill.ca	Professor
4	Paola Ulachia Flores	Paola.ulaciaflores@mcgill.ca	TA

Appendix C: MATLAB Code and LabVIEW Block Diagrams

PNO_initial.m

```
clear all
clc

%for loop not necessary to read initial reference point for each sensor
table=cell2mat(fstclient('127.0.0.1',7234,0.1));

%Takes last row of table, as this is most recent values (x,y,z)
initialSensor1 = table(end,:)

%For four sensors:
% initialSensor1 = table(end-3,:)
% initialSensor2 = table(end-2,:)
% initialSensor3 = table(end-1,:)
% initialSensor4 = table(end,:)

initialSensor1 = double(initialSensor1);
save('PNO_initial_1.txt','initialSensor1','-ascii')
type('PNO_initial_1.txt')

%For four sensors:
% initialSensor2 = double(initialSensor2)
% save('PNO_initial_2.txt','initialSensor2','-ascii')
% type('PNO_initial_2.txt')
% initialSensor3 = double(initialSensor3)
% save('PNO_initial_3.txt','initialSensor3','-ascii')
% type('PNO_initial_3.txt')
% initialSensor4 = double(initialSensor4)
% save('PNO_initial_4.txt','initialSensor4','-ascii')
% type('PNO_initial_4.txt')
```

PNO_data.m

```
clear all
clc
for i=1:1:100
%%cell2mat: Converts readings from fastrak to an array
%%fstclient(host string name, port number, time of data collection (s))
table=cell2mat(fstclient('127.0.0.1',7234,0.1));

%Takes last row of table, as this is most recent values (x,y,z)
Sensor1 = table(end,:)

%For four sensors:
% Sensor1 = table(end-3,:)
% Sensor2 = table(end-2,:)
% Sensor3 = table(end-1,:)
% Sensor4 = table(end,:)
```

```
% % % InitialSensor1 = load('PNO_initial_1.txt')

Sensor1 = double(Sensor1);
save('PNO_data1.txt','Sensor1','-ascii')
type('PNO_data1.txt')

%For four sensors:
% Sensor2 = double(Sensor2)
% save('PNO_data2.txt','Sensor2','-ascii')
% type('PNO_data2.txt')
% Sensor3 = double(Sensor3)
% save('PNO_data3.txt','Sensor3','-ascii')
% type('PNO_data3.txt')
% Sensor4 = double(Sensor4)
% save('PNO_data4.txt','Sensor4','-ascii')
% type('PNO_data4.txt')

end
```

Fstclient.m

```
used to connect to fserver and parse frames, assumes default output
% records and that the tracker is a Fastrak (any version)
function pno_data = fstclient(host_str, port_num, seconds)

    % use java Socket and DataInputStream classes
    import java.net.Socket
    import java.io.*

    % connect to the socket and open the data stream
    for attempt = 1:5
        try
            fprintf(1, 'Attempt #%d to connect...', attempt);
            socket = Socket(host_str, port_num);
            stream = socket.getInputStream;
            di_stream = DataInputStream(stream);
            fprintf(1, 'Success\n');
            break;
        catch
            fprintf(1, 'Failure\n');
            if ~isempty(socket)
                socket.close;
            end
            if attempt == 5
                error('Failed all attempts to connect');
            end
            pause(1);
        end % try
    end % for

    pno_data = {};

    % collect data and store it in the array
```

```
    t1 = tic;
    while toc(t1) < seconds
        try
            % skip #bytes in header to station number
            tmp = zeros(1,1);
            di_stream.read(tmp,0,1);

            % get station number
            snum = single(di_stream.readByte) - 48;

            % skip more of the header
            tmp = zeros(1,1);
            di_stream.read(tmp,0,1);

            % get pno data
            pno = zeros(1,6,'single');

            for i = 1:6
                pno(i) = swapbytes(single(di_stream.readFloat) );
            end

            % skip crlf
            tmp = zeros(1,2);
            di_stream.read(tmp,0,2);

            % create row with data
            %%following line commented to exclude rotational degrees of
            %%freedom
            %pno_row = {snum pno(1) pno(2) pno(3) pno(4) pno(5) pno(6)};
            pno_row = {pno(2)};  %only x

            % append row to pno_data
            pno_data = cat(1,pno_data,pno_row);

        catch err
            fprintf(1, err.message() );
            break;
        end
    end

    % disconnect from the socket
    fprintf(1, 'Disconnected...\n');
    socket.close();
end
```

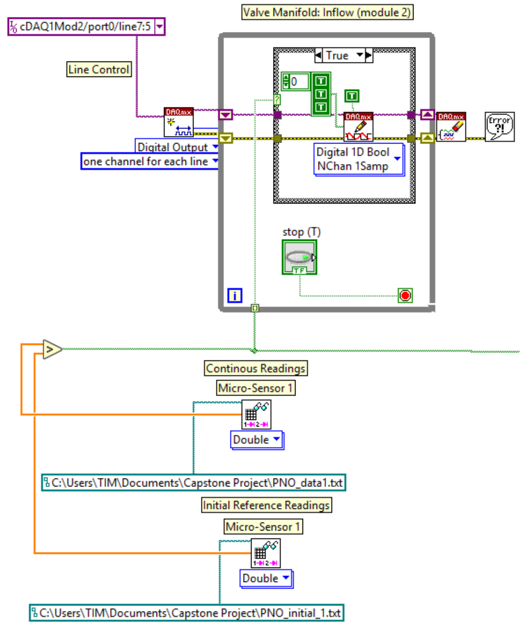


Figure 25: LabVIEW block diagram for ON/OFF control of one inlet valve manifold (6 valves).

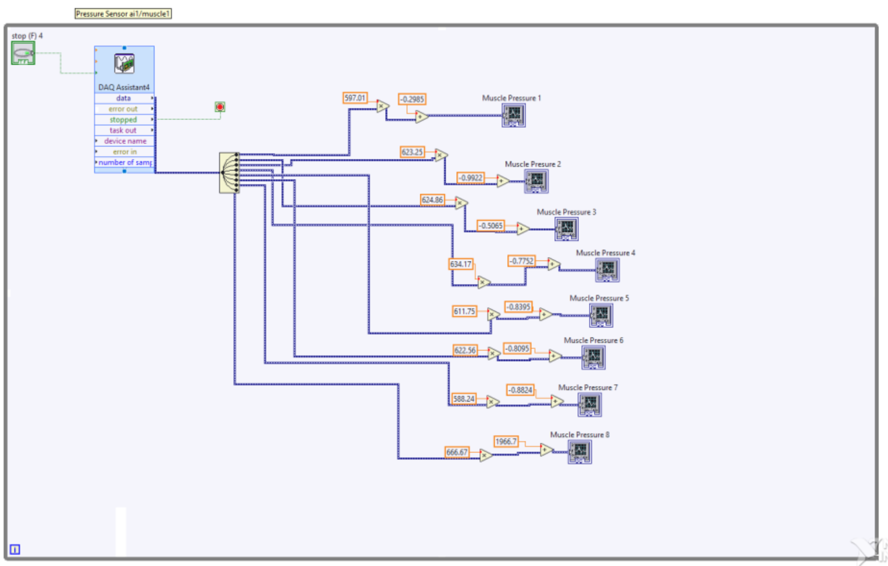
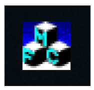


Figure 26: LabVIEW block diagram for the graphical display of the pressure readings received from all 8 pressure sensors on each individual muscle.

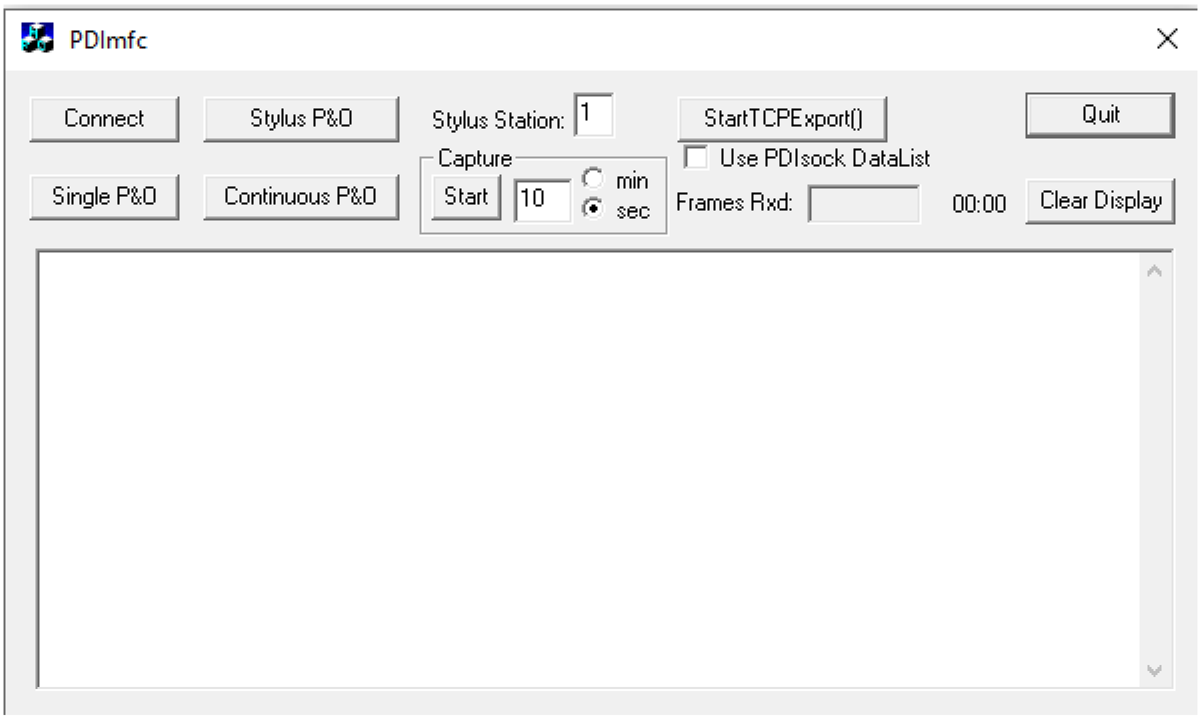
Appendix D: User Manual

Starting tracking system

1. Turn on tracking system, you can refer to FasTrak User Manual, [“Getting Started”] (Note: installation has already been completed of software on computer this is simply for plugging in system)

2. Open PDImfc 

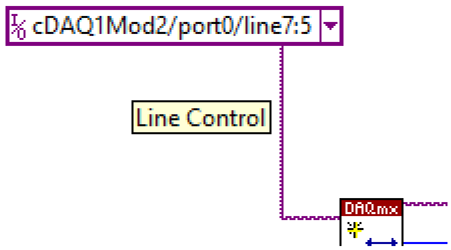
3. This should pop up:



4. Click Connect
5. Click StartTCPExport()
Note: you may need to wait for connection to be established after step 4 & 5
6. Click Continuous P&O: continuous readings should begin to appear on interface.
7. Open MATLAB
8. Open files: PNO_data.m , fstclient.m and PNO_initial.m
9. Run: PNO_initial.m (gives reference point/point of stability)
10. Run: PNO_data.m (gives points as data in matlab for LabVIEW to process)

Labview Valves

1. Open LabView
2. In “Open Existing” select file: Valve_Control.VI (select “Capstone project” → “Valve_Control.VI”)
3. Go to “Window” → “Show Block Diagram”
4. Make sure that the DAQ is connected to power.
5. Plug in the AC/DC converters in order to power all of the valves.
6. Make sure to select the 6 corresponding port lines where the relay module (NI-9485) connects to the valves. (Using the I/O drop down menu seen on the right)
   Note: if wires have not been changed the current file should match the set up



7. After starting the tracking system (see steps on the page above), run the LabVIEW program continuously.

Pressure Sensors

1. In Labview, select “File” → “Open” → “Capstone Project” → “Pressure_Control.VI”
2. Go to “Window” → “Show Block Diagram”
3. All waveform graphs should correspond to the corresponding muscle. Therefore, DO NOT unplug pressure sensor wires from the module without labelling which channel they correspond to beforehand.) (NOTE: Channel pairing 0/8 may be faulty, we recommend not using them.)
4. Making sure that the DAQ is plugged in and turning on the power supply (13.8V) for the pressure sensors, run the labview program continuously. (It doesn’t matter when this is run with respect to the other softwares as it only measures the pressure in the muscles.)