Development of a Low-cost, Accurate System for Measuring Low Back Movements During Daily Activities

By

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ABSTRACT

Lower back pain is the leading cause of disability, worldwide. Poor posture, sedentary lifestyle, and incorrect body mechanics during daily activities cause lower back pain. Monitoring the movements of the lower back during daily activities helps prevent the occurrence of injury and avoid lower back pain. This project was initiated to develop a portable, non-invasive system capable of reproducing the outcomes of radiography techniques when monitoring lower back movements for prolonged periods of time. A potentiometer-based sensor system was developed to meet the project goals. A validation study was done on the selected sensor to evaluate its performance. The enclosure of the system was designed based on the universal joint design to allow 3 rotational Degrees of Freedom (DOF). The design was iteratively modified, 3D printed with Polylactic Acid (PLA) and tested to derive the most optimized enclosure design. The results obtained indicate that the selected sensor is linear throughout its operational range with a linearity error less than 2%, has a low hysteresis of 0.02 mV proving that the sensor can produce accurate, precise, and stable outputs. Based on its linearity, an equation was derived to measure the angle (°) for a known voltage output (mV). Upon assembly and integration of sensors and enclosure design, the functionality of the developed system was validated with the aid of a simple mechanical system built with the aid of a stepper motor, where sensor readings were obtained by rotating the motor shaft to predefined values. The results from validation testing showed that the developed sensor system can produce results for flexion/extension, and lateral bending with an error within 1° for an approximate range of $-10°$ to $+10°$ of orientation. For rotation/twisting the error was approximately 2° for this range. This range of measurement for flexion/extension and lateral bending is sufficient to measure intervertebral movements of the lumbar vertebrae. Therefore, by utilizing the recommendations in future work section of the thesis, the developed system has great potential to replace radiography methods for measuring lower back movements.

DECLARATION

I certify that this thesis:

1. Does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university.
2. And the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. To the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signature of student...

Print name of student...Dinithi Rasaara Hemakumara

Date.20/08/2024

I certify that I have read this thesis. In my opinion it is/is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Master of Engineering (Biomedical). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/fully (please circle).

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Print name of Principal Supervisor...

Date...

John Costi

Digitally signed by John Costi
Date: 2024.08.20 13:17:49 +09'30'

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1. INTRODUCTION

Lower back pain is the leading cause of disability worldwide (Wu et al., 2020). Occupational factors such as prolonged sitting and standing, heavy lifting, repetitive movements, and incorrect posture are highly contributing factors for lower back pain. Therefore, disability associated with lower back pain is causing substantial healthcare costs and economic burden while affecting individuals' quality of life (Lodato & Kaplan, 2013).

Of the 33 vertebrae of the human spine, the largest and strongest 5 vertebrae located in the bottom of the vertebral column are considered as Lumbar spine or Lower back. They are named from L1 to L5 from top to bottom. The lower back is responsible for bearing upper body weight, holding the body upright, and allowing movements of standing, sitting, and walking. An unhealthy lower back can cause chronic back pain and injury resulting in disability.

Observation of lower back movements over a prolonged period of time during daily activities, such as household tasks, work related tasks, and physical activities, can help minimize the risk of injury associated with the lower back. Lower back movements can be classified and quantified in three-dimensional space as flexion-extension (forward bending and backward arching), lateral bending (side bending) and rotation (twisting) (Modes & Lafci Fahrioglu, 2024).

1.1. Background

Researchers have employed different approaches to quantify lower back movements. Of them, radiography techniques are the gold standard (Littlewood & May, 2007). Existing studies show that radiography methods have a resolution of 1° and an error less than 1.5° (M. J. Pearcy & Tibrewal, 1984). Radiography methods allow to measure movement of the lumbar spine, as well as inter-vertebral movements of lumbar vertebrae (M. Pearcy et al., 1984; M. J. Pearcy & Tibrewal, 1984). However, radiographic analysis is not suitable for measuring lower back movements during daily activities as it is only limited to laboratory environments and prolonged exposure to radiation can cause harmful side effects. Optical motion capture systems are also a highly accurate, non-invasive method of measuring lower back movements (Grooten et al., 2022; Yamamoto et al., 2017). However, it is also not applicable as the setup is limited to laboratory environments. Inertial Measurement Units (IMU) (Garcia-de-Villa et al., 2023; Muller et al., 2022; Stenlund et al., 2014), Electro-Goniometers (Radwan et al., 2014), and Electromagnetic tracking systems (Mills et al., 2007; Schuler et al., 2005) have also been used in existing studies to measure lower back movements. In addition to these well-known measurement techniques, researchers have developed other ways of assessing lower back movements based on 1st principles of measurement such as Epionic SPINE (Vaisy et al., 2015), and a belt and wire system (Akin et al., 2017). These techniques can cater to the necessity of measuring lower back measurements during daily activities. To the best of the author's knowledge, the accuracy of these methods is less when compared to radiography methods and their capabilities of measuring movements between adjacent lumbar vertebrae is limited. Section 2.3.1. discusses the capabilities of each of these measuring techniques in detail. Therefore, there is no technique that is non-invasive, portable, and low cost with the capability of measuring lower back movements with the accuracy of radiography technique.

Studies on the lower back using wearable sensors have been done to evaluate the progress after injury (Gombatto et al., 2024; Triantafyllou et al., 2022, 2023). Although post-surgery monitoring is essential, pre-injury monitoring of the lower back movements for prolonged periods during daily activities can help prevent occurrence of bad posture and injury at a later stage of life. To the best of the author's understanding, no studies of preinjury monitoring of the lower back for a prolonged period of time during daily activities have been conducted using wearable sensors.

1.2. Aims

The primary objective of this project is to develop an affordable and accurate system for the measurement of intervertebral movements of the lumbar vertebrae during daily activities, to help prevent lower back pain. This study aims to reproduce the work done by Pearcy et al., 1984, in measuring lower back movements with radiography techniques, with non-invasive sensor technology. Project objectives can be listed as follows:

I. Develop a sensor system to non-invasively measure lower back movements and posture, including intervertebral movements of the lumbar spine.
II. Create a novel, affordable sensor system with the ability to measure lower back movements for prolonged periods of time. This device should be portable and can be used during daily activities.
III. Validate the system to have an accuracy within ±1° for measuring rotational movements. This accuracy range was selected such that it had similar accuracy to gold standard radiographic methods (Pearcy et al., 1984).

1.3. Significance and Contribution

Monitoring lower back movements during daily activities help in reducing occurrence of injury and lower back pain. This study will contribute by developing a novel, affordable sensor system, that has the capability to measure lower back movements for prolonged periods.

This study makes significant contributions to sensor technology in healthcare, rehabilitation, ergonomics and understanding of human lower back movements. The novel sensor system addresses important challenges in movement analysis and opens new possibilities for research, clinical practice and applications in various domains. Researchers can utilize this portable measurement tool to monitor the lower back movements for prolonged periods of time, in different environments, to study the behaviour of lumbar vertebrae according to their interests. The general population can use this device to track risk factors for lower back pain.

1.4. Thesis Outline

This study was primarily conducted to research and develop a novel device for measuring intervertebral movements of the lumbar vertebrae to assess the factors that cause lower back pain during daily activities. To gather background knowledge for this thesis, an extensive literature review was conducted as detailed in chapter 2. This chapter details the findings from existing studies on human lower back, human lower back pain, risk factors for lower back pain, and prevailing measurement techniques to measure and monitor lower back posture and movements. Through this literature review, gaps in research were identified which were used as areas of investigation in this study.

Chapter 3 discusses the methodology followed in this study to develop the novel device to measure lower back movements. This chapter details the sensor selection procedure, enclosure design, and tests conducted for validation purposes of the selected sensor and the developed system.

Chapter 4 presents the results obtained from conducting the validation experiments mentioned in chapter 3. This chapter provides an understanding of the capabilities of the selected sensor, and the performance of the developed system.

In chapter 5, a detailed discussion is presented on the findings of this study. Chapter 6 and 7 conclude the thesis by providing an overall summary of the research carried out and some suggestions for future work that requires to be conducted to further enhance the quality of this research.

2. LITERATURE REVIEW

2.1. The Human Lower Back

The human spine is a combination of 33 individual vertebrae. These vertebrae are classified and divided into five sections based on their anatomical features and functions. They are the cervical (neck), thoracic (upper back), Lumbar (lower back), sacrum and coccyx.

The five largest and strongest vertebrae, labelled from L1 to L5, belong to the lumbar region which make up the human lower back. They play an important role in providing structural support to the body by enhancing stability. In addition to that, they perform essential functions such as bearing the upper body weight, maintaining upright posture and shock absorption during daily activities such as walking, running, or heavy lifting.

Lower back movements can be classified based on their translation or rotation within the 3-axis coordinate system. Typically, the translational motion of lumbar vertebrae falls within the range of 1-2 mm, therefore is negligible (Pearcy et al., 1984). The rotational motion is classified as flexion/extension (forward bending and backward arching), lateral bending (side bending) and rotation (twisting). Lower back has a range of motion for flexion-extension that spans from $83° - 102°$, while lateral bending covers a range of $20° - 35°$, and axial rotation encompasses a range of $25° - 40°$ (Modes & Lafci Fahrioglu, 2024; Standring, 2008). Based on radiography methods, it was discovered that for the intervertebral rotations of the lumbar spine, flexion-extension has a range of $1° - 13°$, lateral bending ranges from $3° - 11°$, and axial rotation ranges from $2° - 3°$ (M. Pearcy et al., 1984; M. J. Pearcy & Tibrewal, 1984) (Appendices Table 2).

2.2. Lower Back Pain

Lower back pain is a common medical condition. Its symptoms can vary from discomfort, pain, or stiffness in the lumbar region. Lower back pain has been identified as the leading cause of disability, globally (Hoy et al., 2014). Estimates suggest that over 500 million people suffer from lower back pain at any given time. Lower back pain causes severe pain, activity limitation, lack of sleep and poor mental health (De Souza & Frank, 2007; Hoy et al., 2014). Therefore, it has often become a reason for sick leave, causing limitation of activity and effecting the quality of life of an individual (Heneweer et al., 2011). It also has adverse effects on the global economy as it causes productivity loss as well as substantial healthcare costs (Heneweer et al., 2011).

Therefore, it is important that lower back is assessed, and preventive measures are implemented to avoid the occurrence of lower back pain.

2.2.1. Risk Factors for Lower Back Pain

Poor posture, sedentary lifestyle, repetitive loading of the spine, and heavy loading on spine are risk factors for lower back pain (Hajihosseinali et al., 2015). Occupational factors such as prolonged sitting, poor posture, repetitive movements, lack of proper ergonomics and heavy lifting are common reasons for the occurrence of lower back pain in individuals (Helfenstein Junior et al., 2010; Lyons, 2002). Since a significant amount of the population is employed, it is important to investigate these factors to prevent lower back pain.

2.3. Measuring Lower Back Posture and Movement

There exist various technologies to monitor the lower back posture and movements of an individual. While some of these technologies can be utilized in any environment due to their portability, there are other advanced technologies that require to be implemented in laboratory or clinical set ups.

Laboratory measurements of lower back movements provide accurate and detailed results, with higher precision when compared to other portable techniques. However, these methods have limited access and require expert knowledge making them unsuitable for measuring lower back movements during daily activities. Portable technologies such as wearable sensors are more user friendly and can be implemented in real-world scenarios. However, these inexpensive methods are less reliable when compared to laboratory methods.

To assess lower back posture and movements, it is required to measure the 3 rotational degrees of freedom of each lumbar vertebra. In addition, it is important for the measuring technique to have the capability to take prolonged measurements of the lower back in dynamic scenarios. Portability is also an important aspect, as prolonged inspection of lower back during daily activities is the key consideration when investigating factors that cause lower back pain.

2.3.1. Lower Back Posture and Movement Measurement Techniques

This section elaborates on different techniques that can be employed to measure lower back posture and movements.

<u>Radiography</u>

X-ray radiography techniques are considered to be the gold-standard for measuring lower back movements (Littlewood & May, 2007). It can produce measurements to an accuracy of 1° in rotation with an error less than 1.5° (Pearcy et al., 1984). 3D measurements of individual lumbar vertebrae can be obtained with the aid of bi-planar x-ray radiography (Pearcy et al., 1984; M. J. Pearcy & Tibrewal, 1984).

Although it provides accurate details of the lower back movements, exposure to x-ray radiation for prolonged periods is harmful and can cause mutations in healthy human beings. Therefore, this technique has limited capabilities in assessing lower back movements (Marin et al., 2010). In addition to that, this technique requires high-end machinery that needs to be operated by a licensed professional (Campbell-Kyureghyan et al., 2005). Therefore, this method is not the best option for prolonged measurement of lower back posture and movements during daily activities.

<u>Optical Motion Capture</u>

Optical Motion Capture systems use reflective markers and cameras to capture and monitor the position and orientation of these markers in real-time. This method does not use harmful ionizing radiation and is used in clinical or laboratory settings. The gold standard of optical motion capture systems, Vicon systems (Karatzas et al., 2024), produce results for an accuracy of 0.017mm(Vicon, n.d.). However, unlike radiography methods, optical motion capture systems are not capable of directly assessing the motion of the lower back vertebrae. To track the motion of bone segments, reflective markers are placed over the skin on identified anatomical landmarks (Benoit et al., 2006; Grooten et al., 2022; Yamamoto et al., 2017). Due to the undesired skin motion relative to the bone segment, there is an error introduced to the reading, which is referred to as skin motion artefact (Lu & O'Connor, 1999). To avoid the effect of skin motion artefact, for lower back posture and movement measurements, special markers that can be inserted and fixated directly on the bones through a surgical procedure are used, which is an invasive procedure. (Reinschmidt et al., 1997).

In addition to the skin motion artefact, there are other limitations of optical motion capture techniques. The initial cost is very high due to the high cost of cameras and special laboratory settings with necessary lighting requirements need to be accommodated for the success of measurements (Mayagoitia et al., 2002). Therefore, optical motion capture methods are unsuitable for assessing lower back movements during daily activities due to their limitations in portability and cost.

Inertial Sensors

Inertial sensors are a combination of accelerometers and gyroscopes and sometimes magnetometers. They can measure linear and rotational measurements in all 3 axes. The major advantage with inertial sensors is that they are portable, and much less expensive, unlike the radiography techniques and optical motion capture methods. Inertial sensors are also noninvasive. Depending on the battery life of the sensors, they can facilitate up to 8 hours of continuous measurement (Muller et al., 2022).

However, the accuracy and reliability of inertial measurement units when measuring lower back movements are less when compared to the gold standard. They can measure lower back movements with an accuracy of $2° - 3°$ (Stenlund et al., 2014; Weygers et al., 2020). Another limitation is the drift for long term measurements. Previous studies show that the IMU sensor readings have a drift of $2°$ per hour (Stanzani et al., 2020). Lumbar vertebrae segments are closely packed and the average height of a lumbar vertebrae segment is 27 mm (Witek et al., 2019). Due to the size and weight of the sensors, inertial sensor placement on lower back can negatively affect the reliability of sensor measurements. A study showed that when verified with the optical motion capture system VICON, inertial sensors showed an error of $3.1°$ on lower back measurements (Goodvin et al., 2006). This external error added with the skin motion artefact make Inertial sensors less reliable for lower back kinematics measurements.

Electro-Goniometers

Electro-goniometers are a non-invasive method of measuring static and dynamic joint kinematics. They are portable and can produce stable measurements for prolonged periods of time.

However, their accuracy is less when compared to the gold standard. A previous study showed that electro-goniometers had average differences in flexion, extension, left and right lateral bending in the amounts of $13°, -2.1°, 6.2°,$ and $6.3°$ respectively, when validated against radiographic techniques (Petersen et al., 2008). Another limitation of electro-goniometers is they have limited ranges of measurements as they are interfered from wire connections (Schall et al., 2015).

Electromagnetic Tracking Systems

This non-invasive method uses an electromagnetic field generator and sensors to capture the movement of objects. They have an accuracy of 0.3°-0.9° in static measurements (Schuler et al., 2005). However, their accuracy and reliability are questionable in dynamic movements (Mills et al., 2007). They can operate in limited capture volumes due to interference from surrounding environments. This is a major limitation of this technique. Therefore, it is unsuitable to measure lower back movements of individuals surrounded by metallic objects, electric devices and other magnetic fields.

Table 1 summarizes the above discussed techniques under the key aspects of accuracy, surgical invasiveness, use of harmful ionizing energy, duration of measurement taking, portability and initial costs of installation and purchasing.

Table 1: Key considerations of lower back posture and movement measurement techniques

Criteria	**Radiography**	**Optical Motion Capture**	**Inertial sensors**	**Electro-goniometers**	**Electro-magnetic tracking**	**Belts and wires**	**Epionic SPINE**
Direct measurement of vertebrae kinematics	Yes	No	No	No	No	No	No
Accuracy	1.5°	1 mm	$2° - 3°$	~13°	$0.3° - 0.9°$	5.73°	2.5°
Use of Ionizing radiation	Yes	No	No	No	No	No	No
Surgical invasiveness	No	No	No	No	No	No	No
Durations of measurement taking	A few seconds	8+ hours	8+ hours	8+ hours	8+ hours	8+ hours	8+ hours
Portability	No	No	Yes	Yes	No	Yes	Yes
Initial cost of device and setting up	High	High	Less	Less	Less	Less	Less

2.4. Gaps in Previous Research

Literature shows many techniques adopted by different studies to assess the posture and movement of lower back. However, to the best of the author’s knowledge, there exist some gaps in previous research.

- No technique that can measure lower back kinematics for prolonged periods to an accuracy of radiography techniques, while being non-invasive, portable, and low cost.

- To the best of the author's knowledge, no non-invasive and non-ionizing method exists to measure intervertebral movements of adjacent vertebrae in the lumbar spine (e.g., movement between L1-L2, L2-L3, etc.).

The aim of this research is to fill these research gaps and gather knowledge that can be applied to reduce the occurrence of lower back pain in individuals.

3. METHODOLOGY

This section outlines the steps involved in development of the prototype of the sensor design and testing its accuracy and reliability in capturing lower back movements. This study was inspired by the pioneering work of Pearcy et al., 1984, where he employed radiographic methods to measure lower back movements and inter-vertebral movements of the lumbar vertebrae to an accuracy of 1°. This study aims to reproduce this accuracy of measuring intervertebral movements of the lumbar vertebrae, but with non-invasive, low cost, and portable sensor technology. The methodology section encompasses the sensor selection procedure, development of the enclosure for sensors, calibration procedure, and validation measures.

3.1. Sensor Selection

The most suitable sensor for this project was selected by conducting thorough research and testing of a variety of sensors. Following sections outline the selection procedure of the sensor utilized in this project.

3.1.1. Research and evaluation.

An extensive review of available sensor technologies for rotational movement measurement was conducted. This review included an examination of various sensor types such as IMU sensors, strain gauges, electromagnetic sensors, and potentiometers. The following key requirements were considered when choosing the sensor.

- Continuous measurements – The sensor must provide continuous data to measure lower back movements for prolonged periods.
- Compact size – The sensor should be compact in size and light weight to accurately measure the movement of a vertebra that is approximately 27 mm in height, without adding significant weight that could cause it to shift due to gravity.
- Lower power consumption – This is crucial to prevent the battery from depleting during prolonged measurements.
- Low cost – This is an important factor to ensure that the sensor remains affordable.

Potentiometers were chosen based on their ability to provide continuous analogue measurements of rotational displacement, cost effectiveness, compact size, ease of integration, durability, longevity, and lower power consumption.

3.1.2. Comparison and selection

Specific requirements such as measurement range, torque, linearity, resolution, and cost were considered when selecting the potentiometers from different manufacturers and models (Appendix B, Table 4). Based on this comparison, Panasonic 10mm GS Position Sensor was selected as the most suitable sensor for this project, considering its wide range of applications in the robotics field in measuring rotational measurements. This 10 kΩ potentiometer has low rotational torque of 3 mN m with a linearity of ±2% of its total range of 343° (Appendix B, Table 3)

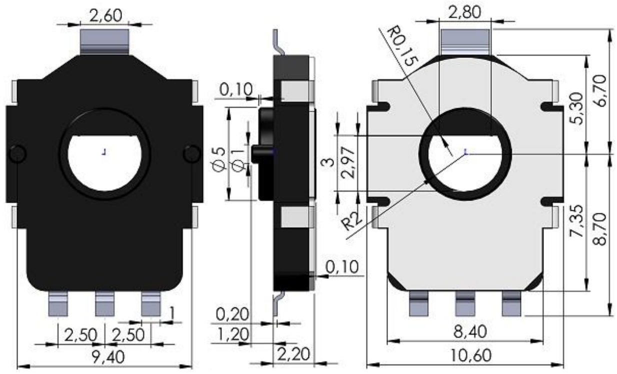

Figure 1: Panasonic 10mm GS Position Sensor

3.1.3. Validation and testing

Validation procedures were developed to verify the performance and reliability of the selected potentiometer. This involved conducting tests with the aid of stepper motor, Wantai (Model: 42BYGHM809). The chosen stepper motor has a resolution of 0.9°/step. To increase its resolution up to 0.225°/step (quarter of its initial resolution), an Arduino Dual Stepper Motor Driver Shield 1.1 by ITEAD STUDIO was integrated to the setup. In the dual stepper motor shield, the hardware jumpers were set as Low and High for MS1(X/Y) and MS2 (X/Y) respectively for quarter step resolution. Here, X and Y refer to two motors that can be connected to the driver shield. This motor driver was mounted on an Arduino UNO (ATMEGA 328P) development board. It was controlled and powered through Arduino UNO board that was connected to a PC through USB as shown in Figure 2.

The shaft of the motor was connected to the wiper of the potentiometer. The shaft of the motor was programmed to rotate with a resolution of 0.225° at a time. The output voltages from potentiometer for the respective motor shaft movements were measured and recorded through Arduino UNO (ATMEGA 328P) development board. To further enhance the sensitivity and resolution of potentiometer readings, the analog input from potentiometer was connected to DFRobot 16 bit Analog to Digital Converter (ADC) module, which was then connected to Arduino UNO development board through I2C communication. The ADC module was powered through 3.3V output of Arduino board. Therefore, the range of potentiometer readings varied from 0V to 3.3V.

The circuit connections of the final set up are shown in Figure 2.

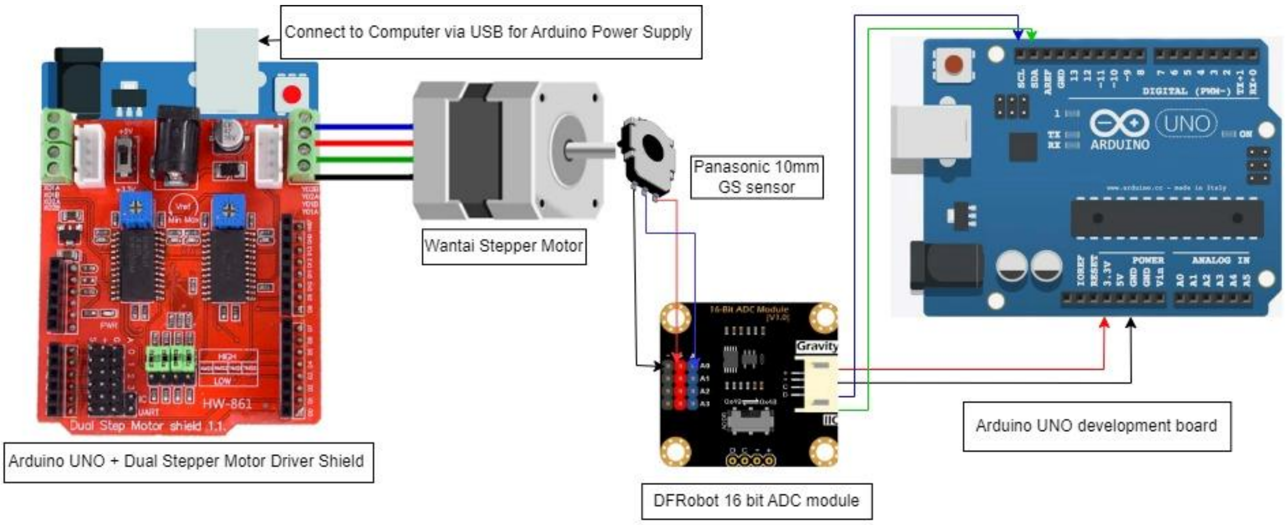

Figure 2: Set-up to test sensor specifications.

With the aid of this set up, the selected potentiometer was tested for its linearity, hysteresis, stability and drift with time using the following protocols:

1. Test for linearity: A simple test was performed to determine the linearity of the outputs of the potentiometer for its full operating region. The wiper of the potentiometer was rotated in clockwise direction at intervals of 0.225° across its full operating region. The voltage output for each rotation was recorded against angle of rotation to determine its linearity. Linearity error percentage was obtained by comparing the expected linear output for each rotation with the observed output voltage value.

$$Linearity\ Error\ (\%) = \frac{(Measured\ Output - Expected\ Output)}{Full\ Scale\ Output} x100$$

2. Test for hysteresis: A simple test was performed to determine the difference between output voltages for a given position of the potentiometer wiper when approached in different directions (increasing versus decreasing). The wiper of the potentiometer was rotated in both clockwise and anti-clockwise directions and the difference between output voltages at a given wiper position was calculated as hysteresis.
3. Test for repeatability: Under same external conditions, the wiper of the potentiometer was rotated in clockwise direction across its full operating region at intervals of 0.225°. This procedure was repeated for 5 times and the output voltages were plotted in the same graph.
4. Test for stability and drift: The output voltage obtained for a given position of the potentiometer was recorded for an extended period, continuously. Readings were analysed to determine significant deviations from the baseline value.

These protocols are detailed in Appendix C.

3.1.4. Orientation Calculation

To determine the rotational measurements from the output voltage values of the potentiometer, an expression was derived by considering the linear region of voltage variation of the potentiometer.

When the gradient of the linear region of the graph is *m,* the angle of rotation of the potentiometer can be determined using the following formula.

$$Angle = \frac{output\ voltage\ value\ (mV)}{m\ (mV/°)}$$

3.2. Enclosure Design

This section outlines the methodology followed in designing the enclosure of the potentiometers used in the study. In this study, focus was only given to measuring intervertebral rotations, as intervertebral translations were not considered to be significant (Pearcy et al., 1984). Therefore, 3 potentiometers were used to measure the rotation about the 3 axes to determine flexion/extension, lateral bending, and rotation of the lumbar vertebrae.

3.2.1. Requirements Analysis

To measure the inter-vertebral movements of the lumbar vertebrae, there are key requirements the enclosure of the potentiometers should satisfy. These included:

- Freedom of movement: The enclosure must allow for 3 degrees of rotational freedom. Although the rotational degrees of freedom are only considered, it should also allow an additional degree of freedom in translation to avoid the enclosure from breakage during vertebral movements due to tension as there would be translations in forward displacements during flexion at the upper lumbar levels (Pearcy, M., 1984).
- Stability: The design should provide stability and rigidity to minimize unwanted movements and ensure accurate measurement of rotational motion. It should also allow to securely mount the potentiometers onto it, by utilizing the mechanical features present in the potentiometers. (two extensions on mounting surface).
- Calibration of potentiometers: Wipers of potentiometers should always be turned to the mid-point of the range of rotation at neutral positions, to avoid reaching minimum and maximum reference points during measurements.

3.2.2. Conceptual Design and CAD Modelling

Based on the design requirements, designs for the enclosure were developed and sketched out. The most suitable enclosure design was developed inspired by the universal joint design. This design encompasses two forks, one cube and four studs to hold the cube in between the two forks.

Detailed computer-aided designs (CAD) of the design were re-created using Autodesk Fusion 360 software. CAD models were useful in visualizing the enclosure design details including its dimensions, features, and assembly components. It also allowed to adjust and make changes to the models to optimize the design. The final CAD designs are as follows (all dimensions are in mm):

Cube design to house the 3 potentiometers: 3 similar slots were designed on 3 adjacent perpendicular faces to mount the sensors. Each slot has two holes to attach the sensor mounting surface to it. The centres of these slots have circular holes to accommodate the shaft of the stud designs. All the sharp edges were filleted.

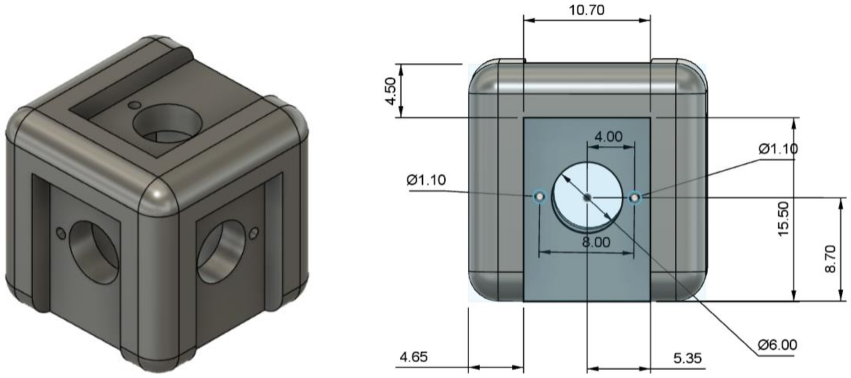

Figure 3: Cube design of the enclosure.

Fork design: This design has two elongated arms with elongated holes in them. Four studs inserted through these holes secure the cube design in the middle of two fork designs. The elongated hole allows one translational degree of freedom for the sensor system.

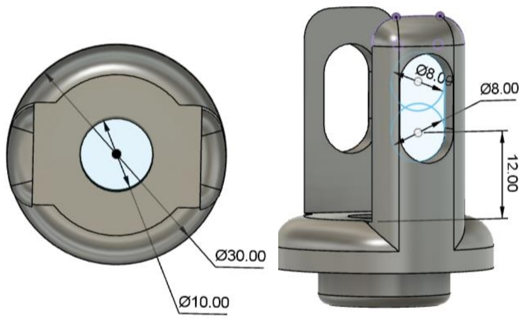

Figure 4: Fork design of the enclosure.

Stud (screw) designs: The final design has two stud designs. The difference between the two studs is the shape of the shaft. The shaft of the stud that enters the cube through potentiometer, has a negative cross-sectional shape to the hole in the sensor. This stud design allows to rotate the wiper of the potentiometer to determine rotational movement. The head of both studs have a rectangular shape to avoid rotation of stud relative to the fork design. This makes sure that movements of stud do not contribute to potentiometer readings.

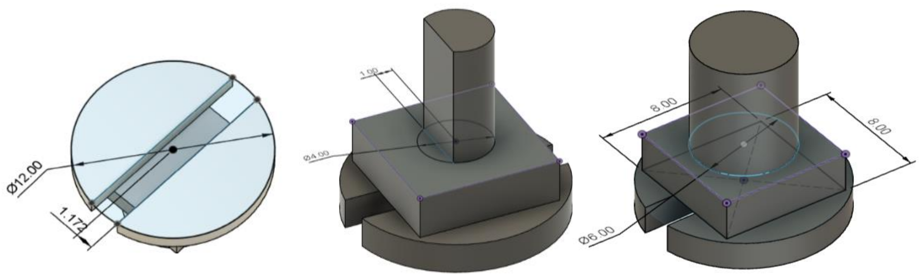

Figure 5: Stud design of the enclosure.

In addition to these parts, two extensions that can be attached to the bottom of the fork design were created, to aid in attaching the sensor to two lumbar vertebrae, when measuring intervertebral lumbar measurements (Figure 7). One of these parts rigidly attach to one of the forks so that there is no relative motion between the part and the fork design.. The other part can be attached to the fork in a way that allows relative motion between the part and the fork about their vertical axis. This additional part has a shaft design that inserts into the potentiometer responsible for measuring rotation/twisting of the vertebrae.

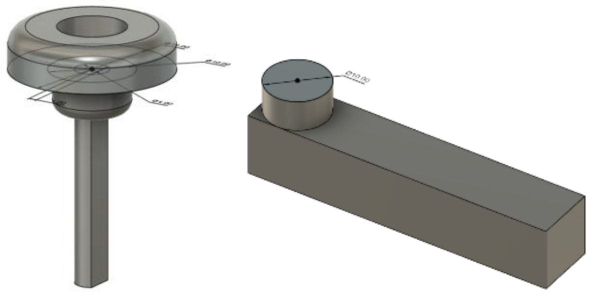

Figure 6: Part to attach enclosure design to measuring body.

3.2.3. Prototype Development

Upon finalizing the CAD models, the designs were 3D printed using materials Polylactic Acid (PLA) and Phrozen ABS like 3D printing Resin with the aid of Ultimaker 2+ and Phrozen Sonic Mighty 8K printers, respectively. The prototype design was improved based on feedback from observations and evaluation to ensure that it satisfied all the requirements (Appendix D). Based on the properties of each material (Appendix D, Table 4), PLA was selected to print the final prototype as it provides rigidity, flexibility, and more impact resistance to the enclosure.

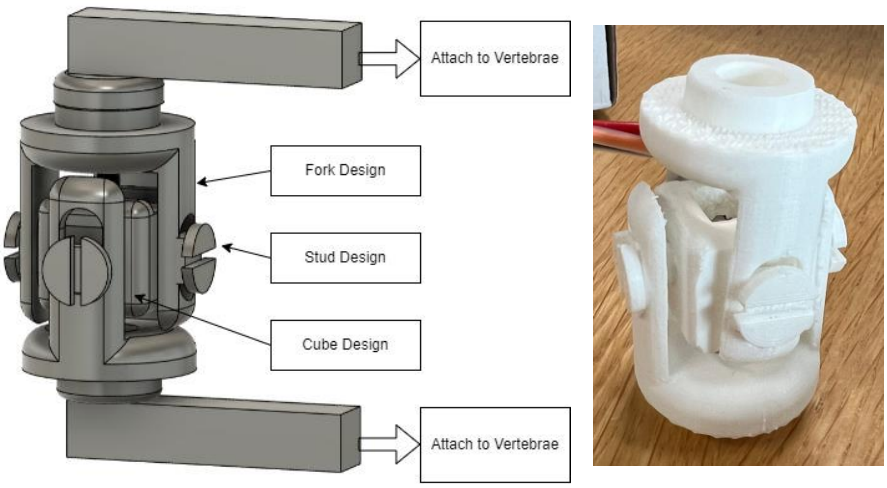

Figure 7: Enclosure Assembly.

3.2.4. System assembly

The three sensors mounted on the printed enclosure design, were connected to DF Robot 16-bit ADC module through serial communication. DF Robot 16-bit ADC module was then connected to Arduino MEGA (ATMEGA328P) via I2C communication to read the 3 potentiometer outputs. The voltage values read from the sensors were then converted to angle values using the equation derived from previously experimenting the potentiometers (Appendix C, Figure 15).

The entire sensor system was developed with a material cost of approximately AUD 80.00 (Appendix E). Therefore, this sensor system offers a much more affordable alternative to existing technologies for measuring lower back movements.

3.2.5. Validation of the system

The final system was tested and validated to assess its performance in measuring 3 DOF in rotation. The developed sensor system was placed on a flat, rigid surface and securely held to prevent any movement. Duinotech Arduino compatible 5V stepper motor with controller was used to test and verify the range of motion and stability of the enclosure in flexion/extension, lateral bending and rotation. The stepper motor shaft was rotated to known reference values to assess the accuracy and reliability of the developed sensor system in measuring flexion/extension, lateral bending and rotation.

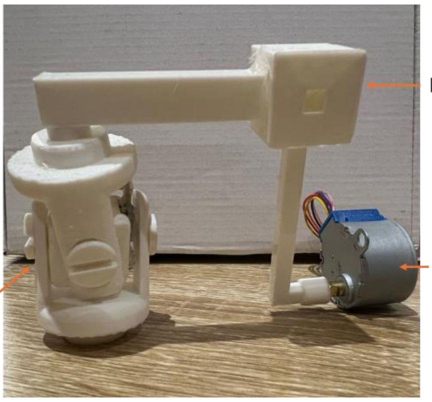

Figure 8: Validation Set-up

4. RESULTS

The results of the protocol testing, and validation of the sensor and sensor system are detailed in this section.

4.1. Results from Potentiometer Testing

4.1.1. Potentiometer Linearity

The output voltage values obtained when the potentiometer wiper was rotated 0.225° at a time (Appendix C, Figure 16) were used to determine the linearity error percentage of the sensor. Figure 10 shows that the linearity error percentage increases at higher angle values but remains below 0.5% for angles under 100°. Since the required range for measuring lower back movements is less than 50° (Appendix A, Table 2), the error is well within acceptable limits. Across the full operating region of the sensor, the linearity error percentage was observed to be less than 2%. Therefore, the chosen sensor has a high degree of linearity.

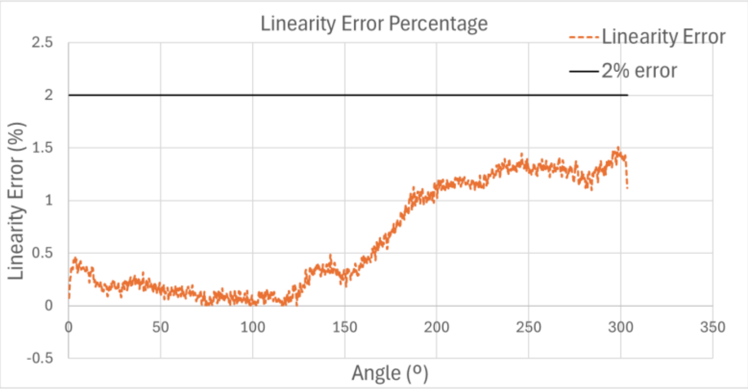

Figure 9: Linearity Error Percentage of the Sensor

4.1.2. Hysteresis

Hysteresis of the potentiometer is the difference between output voltages produced when the wiper moves in increasing and decreasing directions at a given position. Performing a hysteresis test helps to determine how consistently the potentiometer returns to the same value when the wiper moves back to a specific position. Measurements were taken at 0.225° increments, first by increasing the wiper position from 0° to 300° and then by decreasing to 0° (Appendix C, Figure 17). The results are illustrated in Figure 10.

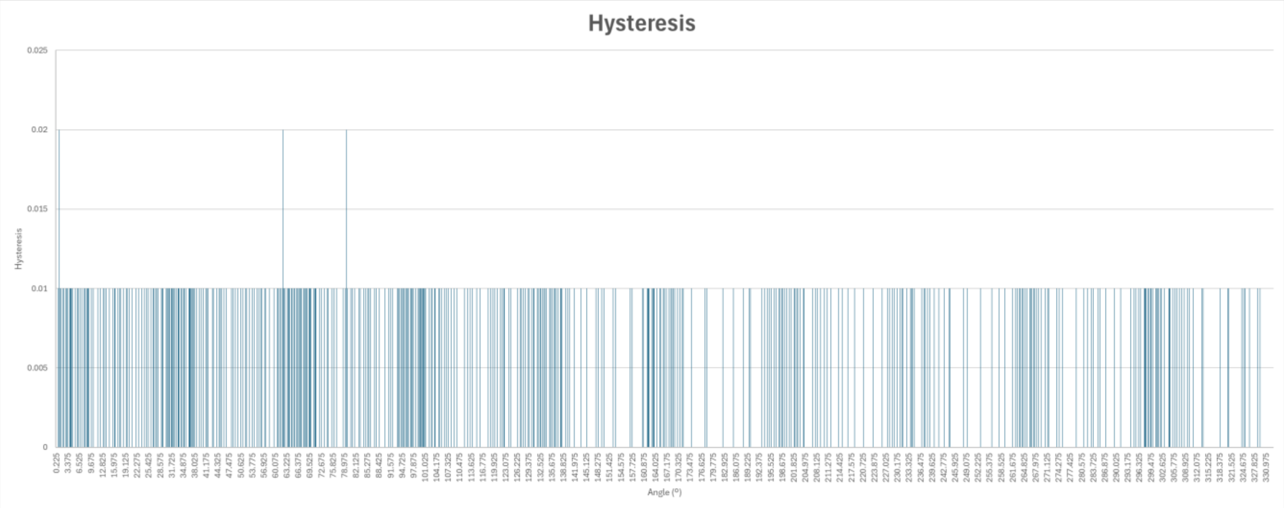

Figure 10: Hysteresis of the Sensor.

The results indicate that, the maximum measurable hysteresis of the sensor is 0.02 mV. This value is negligible. Therefore, the chosen sensor has high precision, and it can be ensured that this is a reliable sensor which can produce precise, consistent outputs.

4.1.3. Obtaining angle value from potentiometer

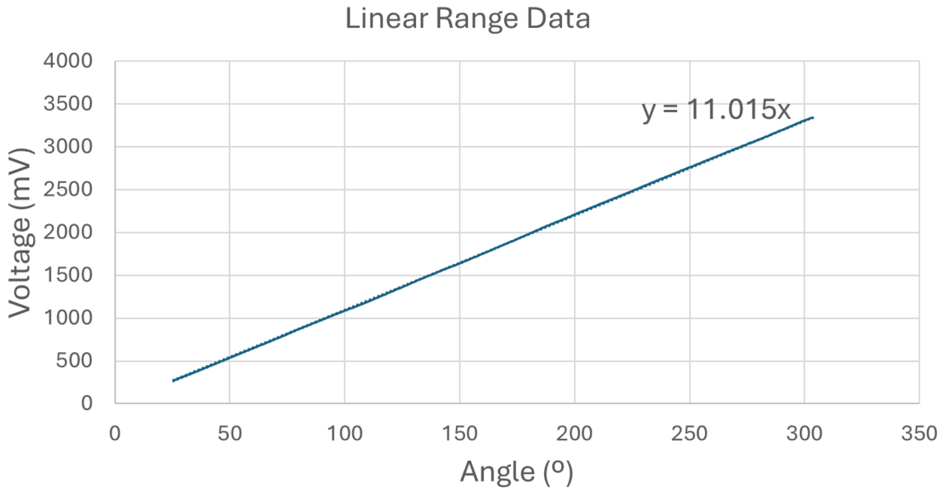

Figure 11: Linear region of the Sensor.

Based on the linearity of the sensor, an equation in the form of $y = mx$ was derived based on its output voltage values produced for known angular rotations. The gradient value (m) was calculated based on the trendline of the graph shown in Figure 11, $y = 11.015x$.

Here, y represents voltage value given in millivolts and x represents angle values (°). Therefore, following expression was derived to calculate the angle of rotation for a known voltage output (mV) of the sensor.

$$angle\ (°) = \frac{voltage\ (mV)}{11.015\ (mV/°)}$$

4.2. Validation of the sensor system

Using the set-up in 3.2.5, the dummy vertebrae was rotated about 3 axes, one axis at a time, and the sensor readings were obtained from the device. The obtained measurements were compared to the expected outputs in all axes (Figure 13, 14, 15).

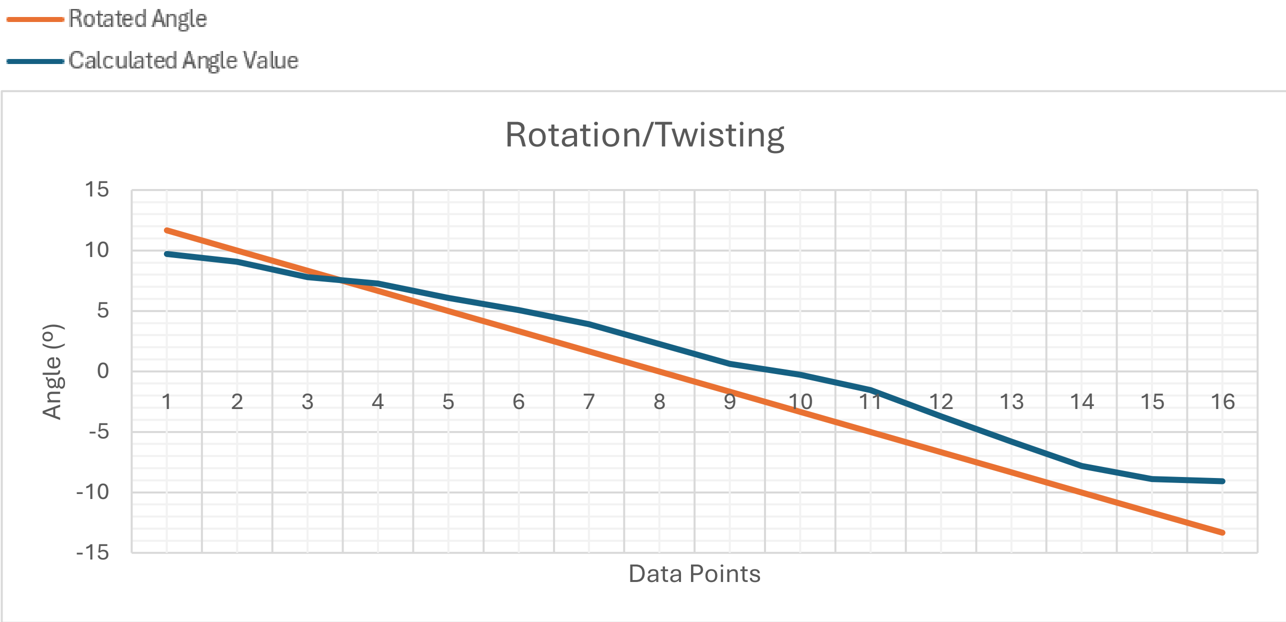

Figure 12: Rotation/Twisting measurements.

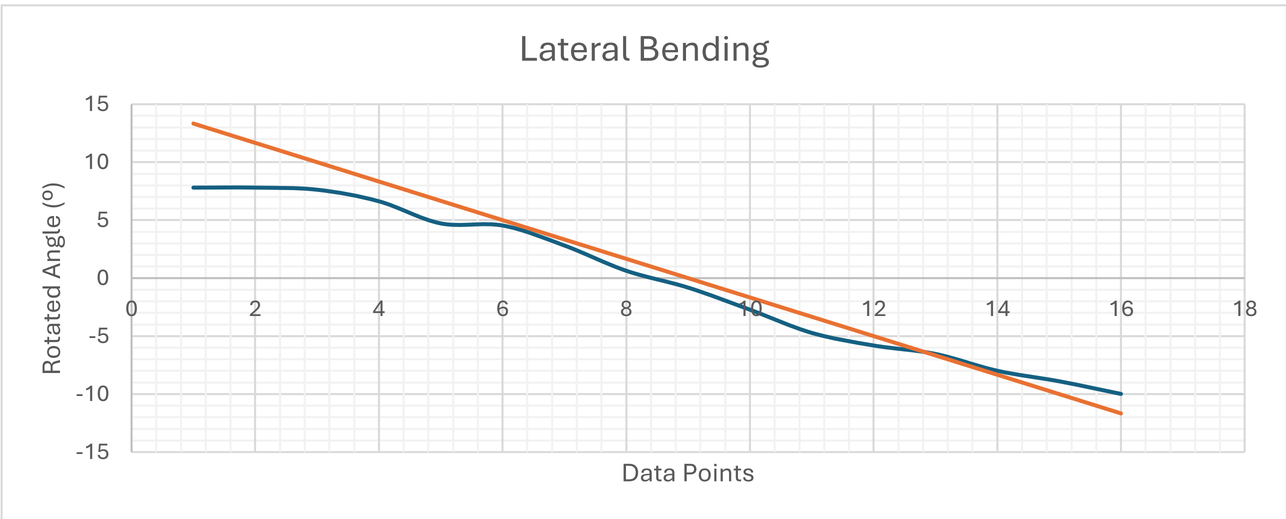

Figure 13: Lateral Bending measurements.

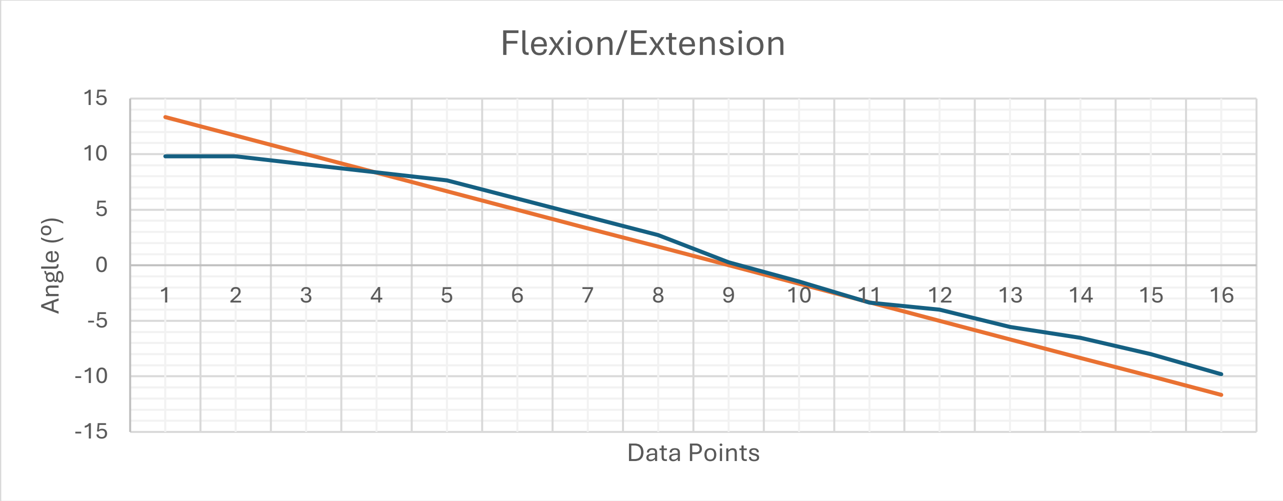

Figure 14: Flexion/Extension measurements.

From these results, it can be noticed that for lateral bending this range was from $+5° to -10°$, approximately. For flexion/extension this range was from +10° to -7°. For rotation/twisting this range was from +10° to +5°. The results generated for rotation were not so accurate. For most of its range the error for rotation is greater than 1°. This could be due to mechanical design of the part that attaches to the potentiometer wiper that measures rotation as described in section 3.2.2. (Figure 7).

5. DISCUSSION

The purpose of this study was to develop a non-invasive, affordable system that can measure intervertebral movements of the lumbar vertebrae during daily activities. Although radiographic methods are the gold standard in measuring lumbar vertebral movements due to their accuracy, their invasive nature due to harmful radiation limits their applications. Radiography methods cannot be used to monitor lower back for prolonged periods of time, which is essential for investigating and avoiding lower back pain causing postures and movements. Therefore, it is important to investigate other alternatives to measure lower back movements with similar accuracy and precision.

In this study, the capabilities of Panasonic 10mm GS position sensor was explored to measure rotational movements. The validation study for this sensor was carried out with the aid of a stepper motor, with the capability of rotating the sensor wiper to a resolution of 0.225°. It was found out that the chosen sensor has a minimal hysteresis of 0.02 mV, with a linearity error less than 2% across its operational region. This proves that the sensor can produce measurements with accuracy, repeatability (Appendix C, Figure 19), and consistency, regardless of the direction of its wiper's rotation. Unlike IMU sensors which are most commonly used in measuring lower back movements, this sensor does not show any drift of output readings for prolonged measurements. Therefore, these sensors can be considered to be ideal for achieving the goals of this project.

After testing and iterative development of multiple prototype versions (Appendix D), a final enclosure was designed to house 3 potentiometers, to measure flexion/extension, lateral bending, and rotation of vertebral bodies. The developed enclosure design comprises of 3 DOF in rotational movements with 1 DOF in translational movements. This design was inspired by the universal joint design and it was further developed to achieve the requirements of enclosure design. The enclosure was 3D printed with Polylactic Acid (PLA), with the aid of Ultimaker 2+ 3D printers. PLA showed favourable properties when compared to resin when the enclosure design was printed (Appendix D, Table 4, Figure 22). Therefore, PLA was chosen as the best suited material for the purpose of this project.

The assembled enclosure showed drawbacks due to the resistance between moving parts and inconsistencies in 3D prints. Therefore, the ranges of rotation in each degree of freedom were limited. When the sensors were attached to the assembled enclosure design, there were further restrictions for motion, due to the wired nature of the sensor. The chosen wires were less flexible and would attempt to break at soldered points when the system was rotated to higher angles. The solder pads of the sensor being very small would also contribute to this effect. Therefore, although the individual sensor had capabilities of measuring angles up to 343°, when it was integrated into the enclosure design its effective measurement range got limited to approximately from +10° to -10°.

A validation study was conducted on the complete system to evaluate its capabilities in measuring intervertebral movements. The results of the study showed that for flexion/extension and lateral bending, the system could measure orientation with an error within 1° for an approximate range of 10° of measurements. However, the results obtained for rotational/twisting movements were not satisfactory. These errors are undoubtedly due to the limitations of the range of motion of enclosure design with wires attached. However, this range is sufficient to measure flexion/extension and lateral bending of the intervertebral movements of lumbar vertebrae (Pearcy et al., 1984).

The outcomes of this study can be further improved by additional research and development. Conducting thorough validation and testing with advanced techniques such as Hexapod Robot and radiographic methods would contribute to further improve the quality of this novel device. Its capabilities can further be expanded to measure kinematics of other joints of human body. The developed biomechanics tool has huge potential in clinical and biomechanics research to analyse human body.

6. CONCLUSIONS

In this thesis, extensive research was conducted to evaluate numerous technologies in existence that measure lower back movements. This study introduced a low cost, non-invasive, portable sensor system that has capabilities of reproducing the outcomes of gold standard, radiographic techniques. The sensor used for rotational measurements, Panasonic 10mm GS position sensor, has shown great potential in measuring orientation with accuracy, consistency, and precision regardless of the direction of rotation of its wiper. This sensor was integrated with a developed enclosure design to derive a system to measure 3 DOF rotational movements of intervertebral movements of the lumbar vertebrae. The developed device has shown accuracy in measuring flexion/extension and lateral bending for a narrow range of ±10°. However, the results produced for rotational measurements were not up to standards. The device shows limitations in measuring range due to the inconsistencies in 3D printing and attachment of wires.

Although limitations exist, this novel device can overcome these limitations through future work. This work should include further development and validation testing to increase the system accuracy in measuring orientation. While these limitations exist, the developed system in this research addresses limitations in existing technologies by being affordable, portable, non-invasive, and by providing stable outputs for prolonged periods of time.

7. FUTURE WORK

It is recommended to conduct future work to increase the significance of this research and development project. Further work is required to increase the performance of the developed sensor system, to make it more reliable in measuring lower back movements.

This study has established the capabilities of Panasonic 10 mm GS Position sensors in measuring orientation. However, extended validation studies are required on the assembled system. It is recommended that validation of the system is done against a high technology orientation measuring method such as Hexapod Robot or radiographic techniques, to discover the true potentials of the developed system.

In this study, the obtained sensor readings are not translated to the centre of rotation of the vertebrae. Further research can be done on this matter to determine the variation in results.

Although this research provides a tool that is capable of measuring orientation of a joint, a further study should be conducted to evaluate how the sensor system can be further expanded to measure kinematics of other joints of the human body. The enclosure design would need to be further modified to achieve this goal.

Additionally, the developed system should further be improved to conduct experiments and explore its potential in measuring lower back movements of humans in real world scenarios. For this purpose, methods of sensor attachment to the lower back and protocols for sensor testing needs to be developed.

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APPENDICES

APPENDIX A: LOWER BACK

Table 2: Mean value of flexion/extension and ranges of rotation and lateral bending at each intervertebral level (Pearcy et al., 1984)

Level	Axial Rotation Range (°)	Lateral Bending Range (°)	Flexion/Extension Meas (SD) (°)
L1-2	0 – 3	7 – 15	13 (5)
L2-3	1 – 3	7 – 18	14 (2)
L3-4	1 – 5	5 – 12	13 (2)
L4-5	1 – 5	1 – 9	16 (4)
L5-S1	0 – 3	1 – 6	14 (5)

APPENDIX B: SENSOR SPECIFICATIONS

Table 3: Specifications of Panasonic 10mm GS Position Sensors

Features	Low-profile, long-life sensors	
Mechanical	Rotation Torque	3 mN m max
Electrical	Linearity	±2% max
	Total Resistance	10 kΩ $\pm 30\%$
	Rating	0.05 W
Temperature	Operating Temperature	-40$°C\ to + 85°C$
Endurance	Operating life (cycles min)	1 million
Cost	Price per unit	AUD 2.32

Table 4: Comparison of different potentiometer models

Potentiometer	**Panasonic 10 mm GS Position sensors**	**Bourns Potentiometers 50K single**	**Bourns Potentiometers through hole trimmer**
Rotation Torque	3 mN m max		
Linearity	±2% max		
Total Resistance	10 kΩ $\pm 30\%$	2 kΩ	10 Ω to 2 MΩ
Rating	0.05 W	0.1 W	0.5 W
Operating Temperature	-40$°C\ to + 85°C$	-10$°C\ to + 50°C$	-55$°C\ to + 125°C$
Operating life (cycles min)	1 million	15,000	200
Price per unit	AUD 2.32	AUD 2.39	AUD 1.78

APPENDIX C: SENSOR TESTING

Test for hysteresis:

- The shaft of the motor was set to obtain the potentiometer reading 0 mV (minimum reference point).
- The shaft of the motor was rotated in clockwise direction at intervals of 0.225° and potentiometer readings were recorded continuously until maximum reference point was reached (5 V – the input voltage to potentiometer readings).
- The shaft of the motor was rotated in the anti-clockwise direction at intervals of 0.225° and potentiometer readings were recorded continuously until minimum reference point was reached.
- Voltage output of the potentiometer against the rotated shaft angle was plotted for both increasing and decreasing sweeps.
- Output voltage differences between increasing and decreasing sweeps at different angles were calculated to quantify hysteresis.

Test for linearity:

- The shaft of the motor was set to obtain 0 mV reading from potentiometer.

- The shaft of the motor was rotated in clockwise direction at intervals of 0.225° covering the full operating region of the potentiometer.
- Voltage outputs of the potentiometer against the rotated shaft angles were recorded.
- Expected linear outputs of the potentiometer for each rotated shaft angles were calculated according to the following equation:

$$expected\ linear\ output = \frac{supply\ voltage * angle\ of\ rotation}{full\ range\ of\ rotation}$$

- Linearity error percentage was calculated by comparing the measured output voltage value with expected output voltage value.

Test for stability and drift:

- The shaft of the motor was rotated to obtain a non-zero voltage value from the potentiometer.
- Output of the potentiometer was continuously measured and recorded at regular intervals, over an extended period of time.
- It was assumed that the environmental conditions such as temperature, humidity, etc. are kept constant over the measurement period.

Readings were analysed to determine any significant deviations from the baseline value.

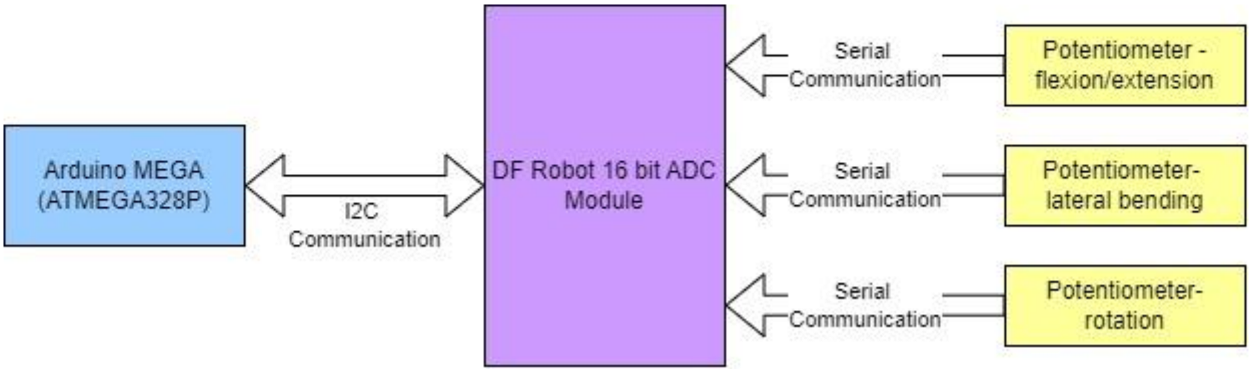

Figure 16: System hardware set-up.

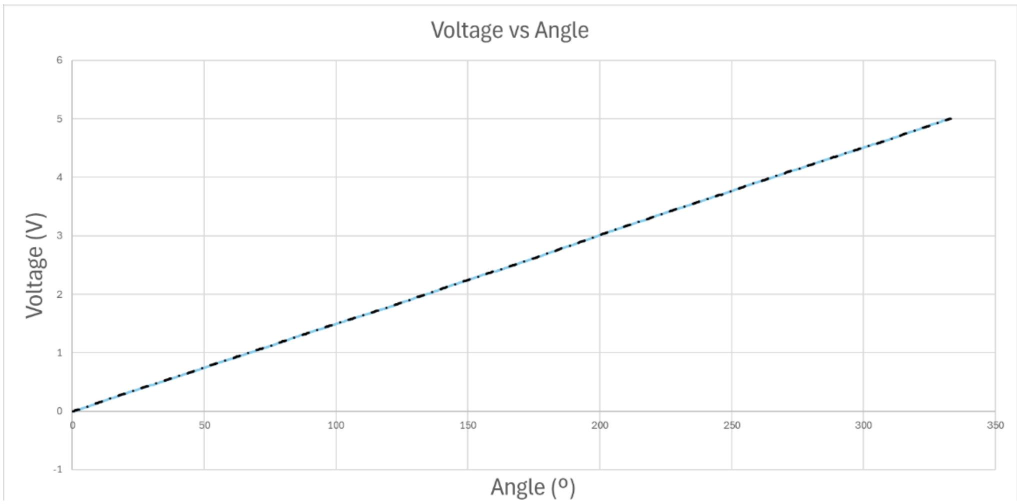

Figure 15: Test for Hysteresis.

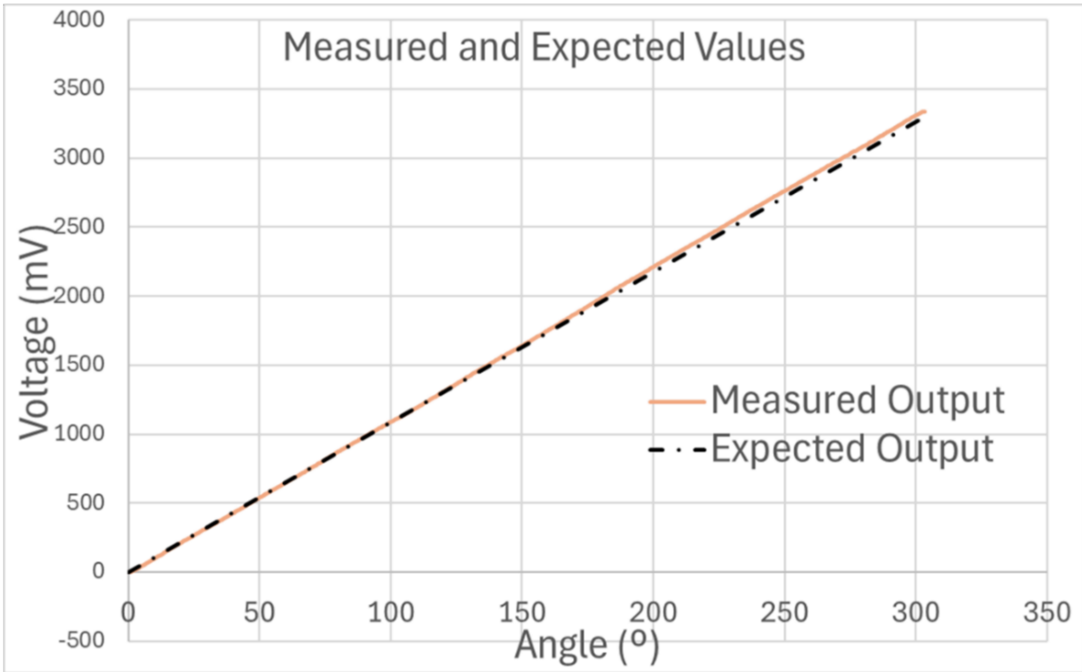

Figure 17: Test for linearity.

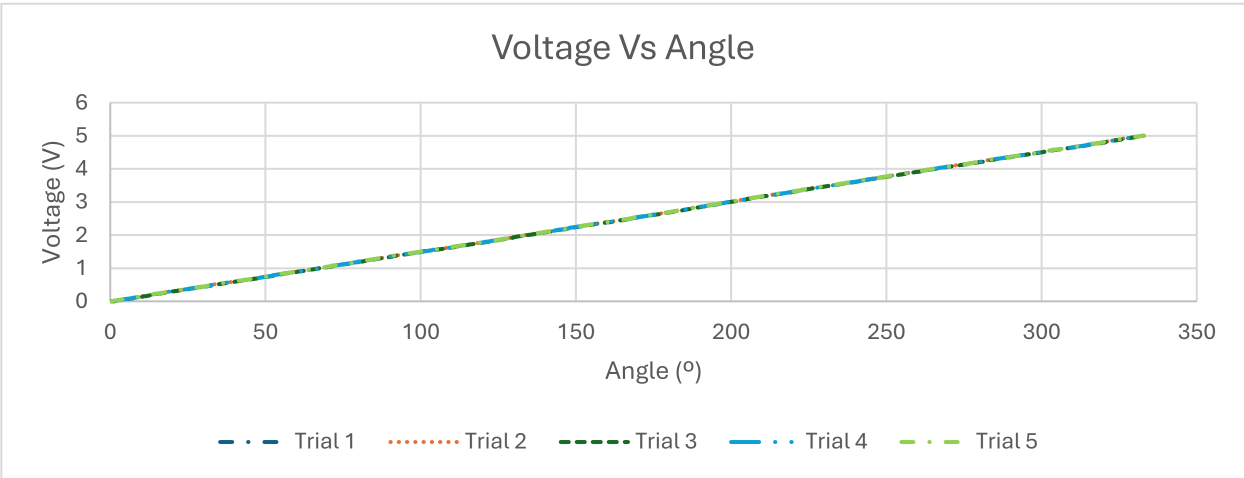

Figure 18: Test for Repeatability

APPENDIX D: ENCLOSURE DESIGN

Evolution of the enclosure design:

Prototype design – 1:

- A simple cube design with rectangular shapes with the dimensions of the potentiometer cut off from 3 faces.
- The potentiometer cannot be placed in a stable manner on the cut off surfaces.
- Has sharp edges.
- Does not support 3 DOF in rotation as rotor parts would block one another when rotating.

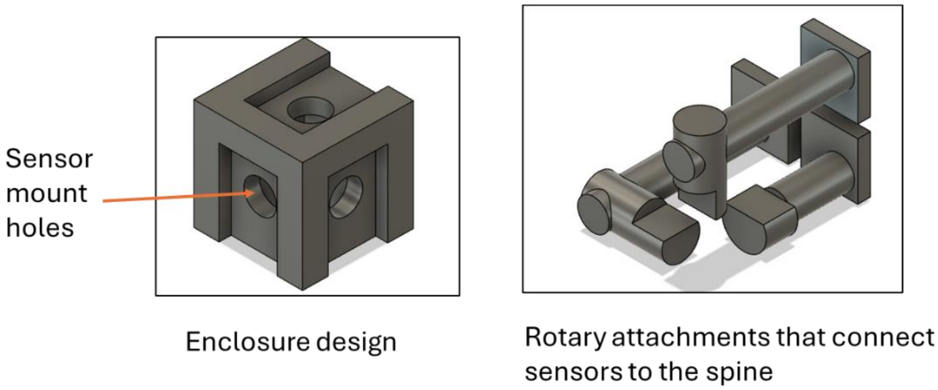

Figure 19: Prototype Design 1.

Prototype Design 2:

- Inspired from the universal joint.
- Includes a cube design, fork design and stud design.
- Cube design modified to accommodate mounting holes of the potentiometer, smoother edges. Addresses the issues of placing potentiometers in a stable manner.
- Supports 3 DOF in rotation, but does not have any freedom of movement in translations.
- The same stud is used to fix the cube design to the fork design therefore there is no stability.
- The head of the stud design would also rotate when it is inserted into the hole of the fork design. Therefore, when measuring rotational movements, the potentiometer wiper would not rotate accurately to generate accurate results.

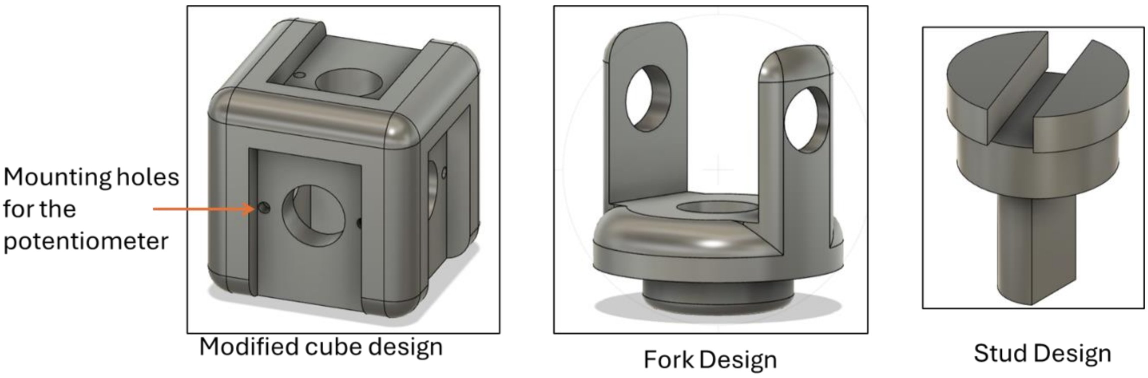

Figure 20: Protype Design 2.

Prototype Design 3:

- Described in section 3.2.2. of the thesis.
- No changes in the cube design were made.
- Fork design modified with elongated holes to accommodate an additional degree of freedom in translation.
- Another stud was designed to fix the hole of the cube design that does not carry a potentiometer. This helped to prevent the unsteadiness of the cube design when fixed to the fork design.
- The head of the fork design was modified to a square shape to avoid it from rotating with arms of the fork design. This would make sure that the potentiometer wipers are properly rotated for the movements measured.

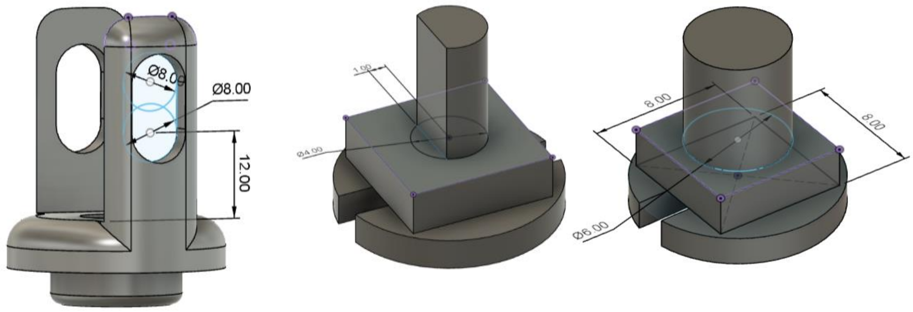

Figure 21: Prototype Design 3

Table 5: Properties of PLA and Resin 3D prints

Criteria	**Resin 3D print**	**PLA 3D print**
Resolution	High resolution, Fine details	Low resolution, visible layer lines
Surface finish	Smooth finish, minimal layer lines,	Visible layer lines, require post processing for smoothing
Strength	Brittle, less impact resistant	More flexible and impact resistant

Criteria	Resin 3D print	PLA 3D print
Post processing	Rinsing in IPA and UV curing needed	Minimal post processing, printing is complete once cooled.

PLA and Resin 3D prints

Cube Design

Stud Design

Fork Design

Figure 22: PLA and Resin 3D prints.

APPENDIX E: COST OF PRODUCTION

Table 6: Cost of one sensor unit production

Product name	Quantity	Price per unit	Price
Panasonic 10mm GS sensors	3	AUD 2.32	AUD 6.96
DF Robot 16-bit ADC module	1	AUD 15.54	AUD 15.54
Arduino UNO Board	1	AUD 34.70	AUD 34.70
3D Printing (PLA)	~30 g	~AUD 0.15 per gram	~AUD 5.00
Other expenses (cables, soldering, etc)			~AUD 15.00
Total			**~AUD 80.00**

APPENDIX F: ARDUINO CODES

<u>Stepper Motor control code:</u>

```
//Arduino Digital pins 6,7,8,9 are connected to the Motor Shield's Y direction pins
#define IN1  6
#define IN2  7
#define IN3  8 //MS1 setting
#define IN4  9 //MS2 setting (MS1 and MS2 settings HIGH,LOW decide the micro-step
resolution)
#define COMMS 10
float x = 4;
int mircoDelay = 100;
int mircoDelaySense = 0;
int state = 0;
void setup(){
  Serial.begin(115200);
  pinMode(IN1, OUTPUT);
  pinMode(IN2, OUTPUT);
  pinMode(IN3, OUTPUT);
  pinMode(IN4, OUTPUT);
  pinMode(COMMS, OUTPUT);

  //Configure to output quater step resolution
  digitalWrite(IN3, LOW); //MS1 = LOW and MS2 = HIGH gives a resolution of Quarter
step
  digitalWrite(IN4, HIGH);
  //should set up this in the hardware as well with the jumpers
}
void Step(){
    switch (state){
    case 0:
      digitalWrite(IN1, LOW);
      digitalWrite(IN2, LOW);
      delayMicroseconds(mircoDelay);
      digitalWrite(COMMS, HIGH);
      digitalWrite(COMMS, LOW);
      delayMicroseconds(mircoDelaySense);
      break;
    case 1:
      digitalWrite(IN1, LOW);
      digitalWrite(IN2, HIGH);
      delayMicroseconds(mircoDelay);
      break;
    case 2:
      digitalWrite(IN1, HIGH);
      digitalWrite(IN2, HIGH);
      delayMicroseconds(mircoDelay);
      break;
    case 3:
      digitalWrite(IN1, HIGH);
      digitalWrite(IN2, LOW);
      delayMicroseconds(mircoDelay);
      break;
  }
```

```
}
void SetDirection(){
   if (x > 0){
    state ++;
    x = x - 1;
    if (state == 4){
      state = 0;
    }
   }
   if (x < 0){
    state --;
    x = x + 1;
    if (state == -1){
      state = 3;
    }
   }

}
```

<u>Code to read raw potentiometer readings:</u>

```
#include <Wire.h>
#include <DFRobot_ADS1115.h>

DFRobot_ADS1115 ads(&Wire);

void setup(void)
{
    Serial.begin(115200);
    ads.setAddr_ADS1115(ADS1115_IIC_ADDRESS0);   // 0x48
    ads.setGain(eGAIN_TWOTHIRDS);   // 2/3x gain
    ads.setMode(eMODE_SINGLE);       // single-shot mode
    ads.setRate(eRATE_128);          // 128SPS (default)
    ads.setOSMode(eOSMODE_SINGLE);   // Set to start a single-conversion
    ads.init();
}

void loop(void)
{
    if (ads.checkADS1115())
    {
        int16_t adc0, adc1, adc2, adc3;
        adc0 = ads.readVoltage(0);
        //Serial.print("A0:");
        Serial.println(adc0);
        //Serial.print("mV,  ");
        /*adc1 = ads.readVoltage(1);
        Serial.print("A1:");
        Serial.print(adc1);
        Serial.print("mV,  ");
```

```
        adc2 = ads.readVoltage(2);
        Serial.print("A2:");
        Serial.print(adc2);
        Serial.print("mV,  ");
        adc3 = ads.readVoltage(3);
        Serial.print("A3:");
        Serial.print(adc3);
        Serial.println("mV");*/
    }
    else
    {
        Serial.println("ADS1115 Disconnected!");
    }

    delay(10);
}
```