MODULAR MOTION TRACKING DEVICE

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ABSTRACT

Customers at a physical therapy outpatient clinic and neurology clinic have expressed the need for a portable motion tracking system capable of measuring patients' range of motion in their natural environments. Derived from these needs, the objective of this project was to create a portable device, capable of measuring the angle between two rigid bodies. The device was developed as two subsystems: a set of inertial measurement units (IMU), which measure the rotation and acceleration of the attached body, and a base unit, which provides a graphical user interface (GUI). This paper will outline the design and manufacture of the motion tracking system and the results of preliminary testing.

INTRODUCTION

The objective of this group of projects is to create a series of sensors that will measure motion of the human body during rehabilitation and clinical evaluation with a level of precision and accuracy suitable for clinical use. Prior work has been done to evaluate a series of sensors capable of performing this measurement. The finished product provides quantitative measurements of patient progress, quantitative measurements of the effectiveness of rehabilitation treatments, and provides a test bed for future motion tracking systems.

Cervical Dystonia is a disease that affects the neck muscles and in some cases the shoulders as well. Symptoms include involuntary contraction of the neck muscles which can result in abnormal movements and positions of the head and neck\(^1\) (see Figure 1). The movements can be static as well as dynamic, during which the patient would present with varying frequencies of tremors. In many patients, the symptoms can cause pain and discomfort. The device is used as an aid during treatments which can include oral medications as well as injections of botulinum toxin, which relaxes the affected muscles. Stroke patients who are trying to regain normal movement of their legs will also benefit from this device, as it can also be placed on the knee. The information gained can be used to track changes in the joint movement during therapy.

![Figure 1: Example of cervical dystonic movement](image)

Anticipating the future application of such a device for the measurement of knee flexion and measurement of head tilt in patients with cervical dystonia, the team is also tasked with fully characterizing the current clinical practices to measure these motions and relating those clinical practices to the output of the system designed with this project. While this prototype will initially be used in two local clinics to track rehabilitation progress, it will also be useful to future clinics as a device that digitally...
measures angles quickly and accurately. Its reusability and inexpensiveness make it an economical assistive device.

The budget for the prototype is $1000, with an expectation that small-scale mass production will be under $1000. This is a feasible expense for neurologists studying rehabilitation progress for patients; progress is currently measured imprecisely and in a less user-friendly manner. With the aid of the device, measurements will be able to be taken much more precisely and quickly, so clinics would have no issue justifying the costs.

**DESIGN PROCESS**

**Needs and Specifications**

Through meetings with the customer, a summary of specific needs ranked by importance was made. From the list of needs, engineering specifications were generated and displayed in Table 1. Both a marginal and an ideal value were derived for each specification. Both values are better than what the customer requested.

During initial meetings, the customer made it clear that the device needs to measure both static abnormalities and dynamic abnormalities. The static refers to the degrees of head tilt, consisting of anterocollis, posterocollis, laterocollis, and torticollis (see Figure 2).

![Figure 2: (left-right) Anterocollis, Posterocollis, Laterocollis, and Torticollis](image)

The dynamic refers to the frequency and direction of the tremors. The ideal angle that the device is able to measure is +/- 80 degrees of tilt and +/- 100 degrees of rotation. Since the device would initially be used in clinical trials and is considered in its prototype stage, portability and durability were not given high rankings. It is however important to the customer that the device will be precise and a 5-10° error was agreed on as being acceptable. Reproducible and quantitative results are also important since the results need to be reproducible each time the patient comes in as well as within patients. By interfacing with the base unit, the device will be able to give quantitative results and feedback during an average clinic visit.

<table>
<thead>
<tr>
<th>Design Specification</th>
<th>Unit of Measure</th>
<th>Marginal Value</th>
<th>Ideal Value</th>
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<tbody>
<tr>
<td>Range of Tilt</td>
<td>Degrees</td>
<td>+/- 60</td>
<td>+/- 80</td>
</tr>
<tr>
<td>Rotational Motion</td>
<td>Degrees</td>
<td>+/- 80</td>
<td>+/- 100</td>
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<tr>
<td>Range of Dynamic Frequency</td>
<td>Hz</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Precision of Static Measurement</td>
<td>% error</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Precision of Dynamic Measurement</td>
<td>% error</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Precision of Motion Measurement</td>
<td>% error</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Displacement from attachment point on body</td>
<td>cm, degrees</td>
<td>0.5, 5</td>
<td>0, 0</td>
</tr>
<tr>
<td>Speed of attachment</td>
<td>Minutes</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Speed of Removal</td>
<td>Seconds</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Protective enclosures</td>
<td>m of drop</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Does not impede natural motion</td>
<td>Survey</td>
<td>Marginal</td>
<td>None</td>
</tr>
<tr>
<td>Minimize patient discomfort</td>
<td>Survey</td>
<td>Marginal</td>
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<tr>
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<td>kg</td>
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<tr>
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<tr>
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<td>Degrees</td>
<td>+/- 5-10</td>
<td>+/- 5</td>
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<tr>
<td>Sanitization</td>
<td>T/F</td>
<td>True</td>
<td>True</td>
</tr>
</tbody>
</table>

**Table 1: Customer Needs and Specifications**

**Issues and Risks**

Two particular risks were present over the course of designing the motion tracking system, being unable to meet customer needs and properly interfacing with the base unit subsystem.

The selected magnetometer proved to be sensitive to any ferrous material, which interfered with yaw measurements. Extensive testing and ameliorative coding helped identify and fix this issue. In addition, all possible ferrous materials were located and replaced with suitable substitutes. The magnetometer was corrected, but there is still some interference when the sensor is around ferrous materials. This risk has been accepted, and the customer is aware of this. Furthermore, one customer initially required the ability to measure the direction a patient’s head shifts, along with static head tilt measurements. This risk was accepted, and the project scope has been changed accordingly to not include measurement of head shift in this initial prototype, with the customer’s knowledge.

In case the base unit subsystem did not have working code or a graphical user interface, a working test code was developed early on in the design process. This code was used in all testing situations, including the testing of sensor precision and accuracy. To mitigate this risk, the code was developed using
Sensor Selection

Before a movement sensor was selected, the functional specifications were analyzed to see how many directions of freedom would be required. A direction of freedom (DOF) is a direction of motion of the device or person that can be quantitatively detected by the movement sensor. The customer required the following head orientation measurements: torticollis, laterocollis, and anterocollis/posterocollis and the ability to detect translation, or non-rotational, movement through space. Measuring the three axes of rotation and three axes of translation necessitated at least a six DOF sensor (one DOF for each axis of movement).

The selection of a sensor was based on several factors. First and foremost, the sensor had to meet the measurement requirements of the customer. Measuring the angle of rotation is a relatively simple task that can be accomplished with one of several sensors. A digital gyroscope could be used, which would output a signal directly related to the rotational velocity. This rotational velocity multiplied by the sampling window would provide an approximate angle that was rotated and by summing all of the angles since the start of the measurement, an approximate angle rotated could be obtained. Another option is to use an accelerometer or a tilt sensor to compare the current position to the original position in relation to gravity. This would provide a more precise measurement of the rotation. The third option is to use a digital compass, which could determine the head rotations based upon the change in comparison to the earth’s magnetic field.

Unfortunately, each of these options has a weakness. The gyroscope, while highly immune to non-rotational motion, has a tendency to drift over time and to continue rotating after the patient has stopped moving, producing inaccuracies. The accelerometer and tilt sensors produce false rotational readings if the patient accelerates their head without rotating it, as in a side to side or front to back motion. The compass is very sensitive to some metal objects or any type of magnet because the Earth’s magnetic field is quite weak. While each device alone is not accurate or reliable enough for clinical measurements, a combination of the three can work to eliminate their weaknesses. The gyroscope has a tendency to drift but can be corrected from the compass or accelerometer. The accelerometer produces inaccurate readings while a patient is moving their head or limb in a non-rotational direction, which can be compensated by the gyroscope, which is not affected by translational movement. The compass can be easily affected by a magnet, but if the accelerometers and gyroscopes do not read any change in movement, then the compass can be automatically corrected. The resulting decision was that the ideal movement sensor would have a combination of all three of the sensors, used in such a way as to utilize their strengths and negate the weaknesses of each.

Second, the sensor had to be relatively small and lightweight because it will be attached to patients’ bodies and should not limit their movement or be a discomfort. The majority of patients whose gait will be measured has had a stroke and already has a difficult time moving. Anything hindering their already limited ability to walk is not beneficial to the patients. A heavy, obtrusive sensor is also not an option for cervical dystonia patients. The process that the customer uses to measure head movement requires patients to let their heads drop into their natural positions, which would be affected by a heavier sensor. The device should assist the customer rather than provide possible interference.

Finally, the device had to be inexpensive enough in order to eventually be sent home with physical therapy patients without financial worry and still be functional and easy to work with. A balance between the price and ease of use is a constant issue within industry; this last objective obviated a unique board design in favor of an already fabricated and tested solution. Designing a unique board is much cheaper, but due to the six-month time limit and relative inexperience with board layout, it was not an option. Laying out a board and selecting components typically requires several revisions before it works as expected, which was not feasible for this design process.

From these requirements, the ideal sensor was the Razor 9 Degree of Freedom sensor. This device contains a three-axis accelerometer, three-axis magnetometer, and a three-axis gyroscope connected to an ATmega328 microcontroller. The ATmega328 chip is commonly used in the Arduino boards, which have extensive community support, and several avid programmers have already generated a set of code that transforms the Razor 9 Degree of Freedom to an
Attitude Heading and Reference System (AHRS). The AHRS primarily uses the gyroscopes to detect changes in orientation (pitch, roll, and yaw) and the acceleration and magnetic sensors are used to offset the gyroscope drift. Since the Razor has all three types of sensors and a microcontroller, the board has substantial functionality and the ability to be updated to future modes of communication.

**Determining Sensor Orientation**

In order to meet the needs set forth by the customers, the outputs of the sensors on the Razor 9DOF board had to be used to determine the orientation of the sensor. The orientation of an object consists of three rotational components: pitch, roll, and yaw. The positive direction of each can be seen in Figure 3 below.

Figure 3: Illustration of positive pitch (antero/postero collis), roll (laterocollis), and yaw (torticollis) rotation

Since the two customers had different sets of requirements for the types of angles captured, two different algorithms were developed. The first was a simple algorithm to calculate knee flexion. By placing the sensor on the side of the leg, the force of gravity is mostly felt in the X and Y axes of the accelerometer (see Figure 4). In this setup, it is assumed that the X component of the accelerometer is directly in line with the length of the leg. By using simple trigonometric equations, the angle difference between the acceleration due to gravity and the direction of the leg can be obtained. By using one sensor on the top portion of the leg and another sensor on the bottom portion of the leg, the knee flexion can be obtained by taking the difference between the top and bottom angles as seen in Equations 1 and 2. The angle, θ, and the components of acceleration, $a_x$ and $a_y$, can be seen in Figure 4.

\[
\theta = \tan^{-1} \left( \frac{a_x}{a_y} \right) 
\]

\[
\text{Knee Flexion} = \theta_{\text{top}} - \theta_{\text{bottom}}
\]

Figure 4: Illustrating the values seen in Equation 1 in relation to the human leg

Since only one angle was required to determine the flexion of the knee, only one of the sensors was required. For the more complex motions of the head, which can be seen in Figure 2, an additional point of reference was required. The accelerometer can function very well as a two-dimensional inclinometer, providing the pitch and roll of a patient’s head. This can be easily accomplished by analyzing the X, Y, and Z accelerations (see Figure 5) and applying the set of equations seen below in Equations 3 and 4. These equations were developed by a manufacturer of micro-electrical-mechanical systems (MEMS) so that their customers could get full use of their products. While the accelerometer can provide accurate pitch and roll information, it is useless in determining the yaw rotation or the rotation about a patient’s spine.

Figure 5: Illustration of accelerometer axes and acceleration due to gravity

\[
\text{Pitch} = \tan^{-1} \left( \frac{a_x}{\sqrt{a_{y}^{2} + a_{z}^{2}}} \right) 
\]

\[
\text{Roll} = \tan^{-1} \left( \frac{a_y}{\sqrt{a_{x}^{2} + a_{z}^{2}}} \right) 
\]

In order to determine the missing rotation, the magnetometer was employed. The basic idea was to determine the magnetic heading of the sensor when it first initialized, and then as the sensor rotates, the yaw could be found by subtracting the current heading from the original heading. This idea was complicated...
by the fact that the magnetic heading changes based upon the tilt of the sensor, even when the sensor is not rotated about its Z-axis.

The solution to this issue was to compensate for the tilt by rotating the X, Y, and Z magnetic components by the pitch and roll angles at which the sensor was currently tilted. This effectively removed the effect of the tilt and allowed for the application of the basic magnetic heading method. The equations for providing tilt compensation were derived from rotation matrices that are commonplace in linear systems and the set of equations that were used can be seen below:

\[
m_{x}^{\text{new}} = \cos(\text{Roll}) \: m_{x} + \sin(\text{Roll}) \: \cos(\text{Pitch}) \: m_{y} - \sin(\text{Roll}) \: \cos(\text{Pitch}) \: m_{z}
\]

\[
m_{y}^{\text{new}} = \cos(\text{Pitch}) \: m_{y} + \sin(\text{Pitch}) \: m_{z}
\]

With the new magnetic components in X and Y, the heading can be determined and the original heading can be subtracted off to determine the yaw rotation that has occurred since the recording began.

**Interface Development**

Developing the interface between the sensors and the base unit consisted of two parts: selecting an appropriate digital bus protocol and then establishing a message-sending protocol. For the former, it was important to select a standardized protocol that had an appropriate level of speed, maintained signal integrity over distances of 3 to 6 feet, was simple to implement, and was commonly used. The USB protocol met all of these requirements. It is very fast, cancels out noise along the wire with minimal power consumption, and is becoming a universal standard, which facilitates future expansions to new devices, sensor types, or computers.

After the digital bus protocol was established, the messaging protocol was developed. This protocol established a set of messages that can be sent from the base unit or the sensor, including “B” to signify that data acquisition is requested, “K” to acknowledge requests, and “WRU” to request the device ID. The data that is recorded and then sent from the sensors to the base unit follows a very specific structure in order to prevent errors. First, a start character is sent, which indicates that a string of numbers is to follow. Then, the length of the data string is given. The data comes next from the gyroscopes, accelerometers, and magnetometers, and then a 16 bit checksum follows, which helps prevent errors. If an error is found, the data is tossed out and the system waits for the next set of data. This is because each set of data represents only fractions of a second and the loss of one segment will not harm the fidelity of the overall results.

**Attachment and Enclosure Selection**

The enclosure for each sensor is composed of a plastic box with the sensor securely attached to the inside of the box. On the outside of the box, there are cutouts for a start button on the head sensor and a USB cable to the base unit to provide power and transfer data on both sensors. A custom adjustable elastic head strap was made in order to attach the sensor to a patient’s head. One strap goes around the circumference of the head and one other strap runs ear to ear to hold the enclosure in place. Two custom elastic straps were also made for measuring knee flexion. One strap attaches to the calf, while the other attaches to the thigh.

The 9DOF Razor sensors are a very sensitive and delicate piece of hardware, requiring a protective enclosure to ensure they are kept safe from any accidental impacts. The first step was to determine the size of all of the components to be placed inside of the enclosure. The components included the Razor board, along with a USB connector board and a reset button to be placed inside one of the enclosures. The two enclosures are virtually identical in design, with the only difference being a reset button placed in one of the enclosures in order to zero out the readings to the base unit between the two separate Razor boards. The final enclosures that were decided upon were two electronic enclosure cases measuring 3”x2”x1” which then needed custom work in order to mount the circuitry inside. Nylon standoff and rubber washers were used to make sure that the sensitive electronics were well insulated from the attachment screws so as not to provide any false readings. In order to avoid any interference in the compass by ferrous metals, brass screws were used to hold the sensor and to close the box. The enclosure with the button is placed on the top of the head when measuring head tilt, or on the lower leg when measuring knee flexion. This is due to the fact that this particular enclosure will have a longer 6 foot USB cable attached to it as opposed to the other enclosure which will only get a 3 foot cable. The longer cable is to ensure that the enclosure will reach the top of a patient’s head or lower leg easily, while
In order to attach the enclosures to a patient securely, custom attachments needed to be created. It was decided that in order to attach the enclosures to the separate attachments for the head and legs, post-style snaps would be placed on both in order to quickly and easily attach and remove the enclosure using less than 2lb of force (see Figure 6). This also allows the enclosures to be more flexible in the future when they might need to be mounted on other parts of the human body as it provides a universal attachment method. For the head attachment, the final design was modeled after a typical headlamp found at a local hardware store. Some modifications needed to be made to the design in order to ensure that the enclosure stayed securely on top of a patient’s head during the length of the therapy session (see Figure 7).

For the leg attachments, leg braces were first looked into for their durability and ability to stay firmly fixed to a patient’s leg, but in the end a simple elastic band was used with Velcro for easily strapping it around the upper or lower legs of virtually any patient (see Figure 7).

The enclosures are mounted on the side of the upper and lower legs and the snaps are placed accordingly on the attachments. The elastic band when properly stretched around the upper or lower leg proved to be a very secure method of attachment as well as a very cheap and easily washable method, as that was one of the customer requirements. Rubber foam strips were also placed around the bottom of the enclosure to hold it more firmly in place when attached to the respective attachments. Repeatable placement of the attachment will be ensured by the customer’s use of standard bony landmarks to attach the device.

TESTING

Test Fixture

The testing rig provided by a previous design team required certain modifications. The original test rig could only rotate in the Z direction, and tilt in the X direction. Rotation in the X and Y directions simultaneously was not possible with the existing setup so it was expanded to allow freedom of motion in all directions. The redesign can be seen in Figure 8.

It was later discovered that certain screws as well as the revolving base on the bottom were made of ferrous materials which needed to be switched out for non-ferrous materials in order to avoid interference with the 9DOF magnetometer. Nylon screws were used since they were easily obtainable in the sizes required, and the revolving base was slightly redesigned to remove the ferrous turntable. A brass insert now takes the place of the turntable and also allows for easier use and carrying of the test fixture.

Sensor Testing

The sensors were tested for accuracy, precision, and the affects of possible outside magnetic forces. The sensors were first tested individually and then together. To test the error of a single sensor, it was tested with a short warm up time of 1 minute and, again, without a warm up time. The sensor was then tested using the test fixture to determine the accuracy at various angles. Roll, pitch and yaw were each tested separately. For each, the sensor on the test rig
was started at a zero position, flat on top of the test rig. It was then moved 30 degrees one way, stopped for two seconds, moved back to zero and stopped for two seconds, then moved the opposite direction 30 degrees and stopped for two seconds (see Figure 9). This process was repeated for the length of the test and for each measurement direction. The sensors were then tested together. Both sensors were laid flat. In the first test, only one sensor was moved and the angle between them was determined. Another test was then performed moving both sensors, and the angle was again determined between them. Sensors were also tested for accuracy using a spine motion simulator to compare sensor data.

Another test was performed while wearing the enclosure on the thigh and calf to measure knee flexion. The wearer started by standing straight, then squatted until the leg was at 80° (see Figure 10). Flexion until 80° is well above the customer’s requirement for flexion.

Attachment and Enclosure Testing
Adjustability, comfort, and strength ranked high within engineering specifications. To measure adjustability, the head strap was attached to each member of the team. Comfort was measured by having team members wear the attachment unit for a period of 15 minutes and rate comfort level subjectively. During this test, setup and removal time was also recorded, and displacement was also measured. Displacement was measured by marking the attachment of the unit at the beginning of wear and then marking the attachment of the unit before removal and measuring the difference. Strength was measured by attaching the enclosure to the wearer’s skin, then using a force gauge to apply pressure to the enclosure until it failed to stay attached.

In addition, each enclosure was weighed to ensure patient comfort and movement. Sanitation was tested by wiping the enclosures with rubbing alcohol and by washing Velcro and elastic attachments and observing any visible degradation. Finally, the dimensions of each enclosure were recorded and compared to those set by the engineering specifications.

RESULTS

Sensor Testing Results
The sensor was well within the customer needs and specifications for accuracy and precision (see Figure 11). There were some initial problems with the magnetometer, which in turn affected the yaw measurement drastically. Tests were done to gauge the effect of the test stand, and it was found to have a ferrous base and ferrous screws that greatly affected the magnetometer. Ferrous objects had an effect on the accelerometers starting at a distance of 7.5 cm, but to be safe, it is recommended not to put any ferrous objects within 15 cm of the enclosures. Once these components were removed, the precision was tested again. The magnetometer was still not behaving as expected but was partially corrected with an analysis of the algorithm.

Systematic sources of error affected results from the accuracy testing, including positioning the enclosures correctly on the spine motion simulator. This can account for the high range of degrees of error, specifically for pitch, in accuracy testing.

Attachment Testing Results
Both attachment methods fell within customer needs and engineering specifications. The device can

<table>
<thead>
<tr>
<th>Specification</th>
<th>Expected</th>
<th>Actual</th>
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<tbody>
<tr>
<td>Measurement</td>
<td>Tilt: ±10°</td>
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<tr>
<td></td>
<td>Rotation: ±4°</td>
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<td>Roll: within 5°</td>
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<td></td>
<td></td>
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<td>Speed of attachment/removal</td>
<td>2 minutes/5 seconds</td>
<td>28 seconds/3 seconds</td>
</tr>
</tbody>
</table>

Figure 11: Select Test Results
be easily sanitized, is comfortable, and simple to attach to patients. During one displacement trial, the wearer bumped the enclosure on a table, resulting in a failed test. However, in a real clinical situation, the test would be restarted if this were to happen. In addition, when a wearer attached the enclosure directly to skin without wearing pants, the enclosure was displaced slightly over the marginal engineering specification of .5 cm. Moreover, pants may cause the sensor to displace unintentionally. In order to mitigate this issue, it is recommended that the customer use the device on bare skin, along with a rubber material, such as medical-grade Dysom, which increases friction. The same is not necessary for the head device because patients will already be wearing head socks that make the device sanitary and creates friction to keep the attachment in place.

A normal force test was also used on the attachments with the enclosures to see how much force is needed to displace the enclosure an unacceptable amount. Force was applied in a downward direction as well as upwards and laterally. On average, it took about 1.5 lb of force to displace the enclosure far enough that it does not return to its original position. Due to the shape of the leg, more force is needed to displace it in an upwards direction than in a downwards one, about 2.5 lb.

Enclosure Testing Results

The enclosures are made out of ABS plastic with walls of 1/8 thickness. Since this is deemed to be a prototype unit, no formal testing was performed as to the impact resistance of the enclosures. Engineering judgment says that any accidental dropping or hitting of the enclosure in a small dose will be absorbed perfectly well enough to keep the sensor protected. The sensor is held within the enclosure through nylon standoffs with rubber washers adding another layer of protection from shocks. On future iterations of this device, full formal tests will be performed as to the durability of the enclosure.

The size of the enclosure came out to be 1.37”x2”x3” at the widest point for the enclosure containing the button, with the second enclosure coming in at 1.2”x2”x3”. This results in as low a profile as possible for the enclosures to ensure that they are not accidentally hit and displaced while a patient is using them.

CONCLUSIONS AND RECOMMENDATIONS

The finished product met all engineering specifications, with exception to the ability to measure a patient’s translational shift in the direction their head travels. Future iterations of the motion tracking system will look into adding measurement of shift. In addition, further tests of accuracy and precision may be performed in order to verify the system’s robustness, as well as work to eliminate the error in the yaw measurement while near ferrous materials. The final code helps to eliminate some of the errors of the yaw measurement while near ferrous materials, but would not be accurate enough to meet the customer’s needs while around any ferrous materials. While the head tilt system would be affected by the yaw inaccuracy, the knee flexion system would not be affected because it does not use yaw measurements.

The prototype met overall budget guidelines of $1000. Singularly, each system would cost $315 to reproduce. The test fixture modifications cost $100.50. Overall, $735.36 was spent, including materials that were not used in the final system. However, the individual knee flexion system was slightly over the customer’s desired budget of $300. This may be attributed to the use of Razor 9DOF sensors when less expensive sensors could have been used in a strictly knee flexion-related system. But, because one system was designed for two very different uses, this could not be avoided. In future iterations, less expensive sensors may be used solely for the modular knee flexion device.

REFERENCES


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