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A Low Cost, Wireless Spinal Motion Measurement Device

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Abstract. In this study, a low cost Spinal Motion Measurement device (SMM) was created. The device consists of up to three inertial measurement units (IMUs) and two accelerometers. The IMUs are primarily used to measure the orientation and angular rate of the spine, however they can also be used on other body segments. The accelerometers are used to determine if the user is standing or sitting. The SMM uses inexpensive IMUs that are comparable in orientation accuracy to more expensive IMUs and optical motion capture in axes perpendicular to gravity. The SMM is capable of logging data at a maximum frequency of ~55Hz and has a wireless range of 15m. The SMM has shown potential to be a useful, low cost alternative for the collection of human movement data.

Keywords. Wireless, spine, motion, inexpensive

1. Introduction

Numerous different types of devices and sensors can be used to monitor the motion of an individual and their body segments. Such devices include X-ray and other radiography techniques, optical motion capture (OMC), inertial measurement unit (IMU), accelerometer, gyroscope, electro-goniometer, electro-magnetic tracking and many more.

Optical motion capture is a common method used to analyse movement in a clinical or laboratory setting [1, 2]. These systems allow for absolute and relative kinematic measurements of 3D dynamic movements [3] and are thus considered the ‘gold standard’. In addition, they are also non-invasive and can be accurate to within 1mm or less in a three metre field of view [4]. A number of limitations exist with optical motion capture however which include being relatively expensive, computationally demanding and only allowing movements in a restricted volume thus limiting their use to only clinical or laboratory settings [3, 5]. These limitations thus affect the usefulness of such systems in the ability to obtain real time results of actions in real world scenarios, thus other sensors are required.

Other sensors such as accelerometers and IMUs allow the measurement of body segment motion whilst also being less expensive than optical motion capture systems. Wong and Wong 2008 found, by comparing results to a Vicon 370 motion analysis system, that accelerometers could measure static orientation within 5°. However, accuracy and reliability was much lower in dynamic scenarios. Inertial Measurement Units (IMUs) are the combination of accelerometers and gyroscopes, typically both tri-

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axial, used to measure linear and angular motion [6, 7], and sometimes extra sensors such as magnetometers can be used to compensate for orientation drift [8, 9]. IMUs have been shown to be very accurate in static and dynamic conditions, having been reported to measure these scenarios to within ±2°[10, 11], however these devices are very expensive costing in excess of AU$3000 [10, 12].

Although not as accurate as Optical motion capture, sensors such as IMUs, accelerometers, gyroscopes and electro-goniometers are designed such that the entire sensing unit is placed on the body. This is unlike optical motion capture and electro-magnetic tracking systems where receivers are set up outside of the body to create a capture volume with either active or passive markers placed on the body. This has a major advantage as data can be collected for a movement without restrictions in the capture volume if the data is logged wirelessly. This data logging of un-restricted motion is very useful when studying scenarios that require large or a combination of movements such as sports, leisure activities and every day activities, for example the tracking of posture throughout the whole working day.

The tracking of posture has vast significance in modern, industrialized countries as it has been shown to be a major risk factor for back pain [13-15]. Back pain, and in particular pain associated with the lumbar spine, has been found to have one-year and lifetime prevalence rates of 25-50 % and 60-80 % respectively [13, 15-17] costing the individual and economy billions annually [13, 18]. This shows the significance in tracking posture in an attempt to improve it, and hence reduce the effect of back pain in terms of pain and discomfort, as well as the associated costs. The functions of the spine are to provide support, protect the spinal cord and provide muscle attachment for movement and it is therefore very important in the overall health of the individual. However, the normal function the spinal column can be hindered when an individual is suffering from back pain.

The aim of this study was to design and test an inexpensive device capable of measuring spinal posture and motion with the ability to log data wirelessly. The device should be able to measure the three-dimensional rotations, flexion-extension, lateral bending and axial rotation, of the upper and lower back relative to the hips, as well as detecting when the user is standing or sitting. The device should also have the capability of being able to measure the motion of other areas of interest on the body, such as the limbs. The significance of this research and creating such a device is two-fold. Firstly, the ability to collect a vast amount of information on the motion of body parts (three rotational axes and three angular rate axes at three different locations) with a low cost device will allow more researchers to perform studies on the motion of the spine and other areas of the human body. Secondly, the device should allow for wireless data logging up to 15m from the data logger thus creating a large capture volume.

2. Spinal Motion Measurement Device

The device created was to be capable of measuring the three rotational degrees of freedom, being flexion-extension, lateral bending and axial rotation, of the human spine such that when placed on the user it can measure their posture. Measuring posture is of importance as has been linked to be a major risk factor of back pain, and it is also used as an input to numerous biomechanical models which estimate spinal loads. Dynamic movements have been shown to increase the loads present on the spine, therefore to be useful for dynamic spinal load prediction, the deice will also measure angular rate of flexion-extension, lateral bending and axial rotation.

It has been shown that the loads on the spine change drastically during different stances, such as standing and sitting [19], thus it would be beneficial for the device to also have the capability of determining the stance, either standing or sitting, of the user. The device will consider standing and sitting as logical positions (either standing or sitting), and thus sensors used to detect these values do not need to be as accurate as the spine sensors. Common seating positions have the thighs at approximately 90° to the body. However it has been shown that an angle of 135° is an optimal position for comfort and muscle relaxation due to maintaining natural lumbar lordosis [20]. Thus, to incorporate numerous different sitting positions, a thigh-trunk angle threshold of 145° will be used. However, for individuals who sit with a thigh-trunk angle of 90°, by the time the 145° threshold is reached the individual would have been transitioning from sitting to standing for some time. Thus a secondary constraint will be placed to determine if a person is sitting. To be considered sitting, the thigh-trunk angle must be less than 145° and have change < X° in the previous one second to account for errors and slight movements/adjustments while sitting. X° will be determined during human testing of the device. As there is only the requirement to measure one angle of the thigh, an accelerometer will be used to determine tilt angles of each of the thighs as tracking both thighs can help determine if a person is sitting, standing or one-legged standing.

Other than being capable of measuring angles and angular rate, the device had to meet other certain criteria, such as fast, accurate, wireless data logging, as well as being portable. These criteria stem directly from the application of the product as a motion capture device for human movements, primarily spinal motion. There were six different hardware and software design iterations before the seventh and final design met the criteria. The main issues found with the failed designs were low data collection rates and large data packet drops.

The final design had each serial port of an Arduino Mega directly attached to its own IMU which allows the Arduino to read each IMU in parallel and save the data to a buffer. When the buffer contains the end bit of each data string, the data is printed to the screen. This configuration allowed for data to be collect at frequencies just above 50Hz which met the criteria for data collection rates. The issue with this configuration is only three hardware serial ports could be utilised as the first is used for displaying data and thus must be used for the BlueTooth receiver, hence limiting the device to the use of three IMUs.

2.1. Hardware

The final design iteration consisted of the following hardware:

- Up to 3 x SparkFun 9DOF Razor IMU (AU$100 ea.)
- Up to 2 x SparkFun Triple Axis ADXL377 Accelerometers (AU$13.30 ea.)
- 1 x Arduino Mega (AU$82)
- 1 x SparkFun BlueTooth Mate Gold (AU$46.80)
- 1 x 2400mAh Lithium-Polymer Battery (AU$20)
- 1 x SparkFun USB LiPoly Charger – Single Cell (AU$20)
- 1 x FTDI Basic Breakout (AU$20)

- 1 x SparkFun USB Mini-B Cable – 6 Foot (set-up and calibration only) (AU$5.30)
- 10 x USB Connector Shell – Micro-B Plug (AU$1.20 ea.)
- 11 x MicroUSB connector (AU$2.30 ea.)
- 6 x 3D printed boxes
- Various lengths of wire

Total price ~AU$560 (as of June 2016)

2.2. Specifications

The specifications of the Spinal Motion Measurement Device created in this study can be found in Table 1.

Table 1. Specifications of the Spinal Motion Measurement Device

Spinal Motion Measurement Device	
Mass	Power Box: 123g IMU: 14.1g Accelerometer: 4.8g Total: 225g
Dimensions (H x L x W)	Power Box: 25mm x 110mm x 60mm IMU: 11mm x 40mm x 33mm Accelerometer: 11mm x 23mm x 23mm
Data Logging Rate	~55Hz
Resolution	0.01°
Data logging protocol	BlueTooth
Max No. Sensors	3 x IMUs + 2 x Accelerometers
Outputs	Euler angles (IMUs): Roll, Pitch, Yaw Angular Rate (IMUs): X, Y and Z Tilt angles (Accelerometers): X and Y Time from power up
IMU	
Degrees of Freedom	9: Triple Axis Accelerometer, Triple Axis Gyroscope and Triple Axis Magnetometer
Range	±16g, ±2000°/s, ±8 Gauss
Accelerometer	
Degrees of Freedom	3: Triple Axis Accelerometer
Range	±3g
BlueTooth	
Wireless Range	15m
Baud rate	115200 bps
Battery	
Battery	2400 mAh
Recharge Rate	500 mA

3. Testing

To determine the accuracy and overall functionality of the IMU device created, it was put through a number of tests. The accuracy of the SparkFun Razor 9DOF IMU was determined by measuring the motion of a Katana Robot 450 (Neuronics, Zurich) and comparing the data to the actual motion of the Katana. The complete device was then tested on the human participants to test its functionality and accuracy when used for its intended purpose. The results of both tests were compared to various other sensors commonly used in human kinematic testing, including another, more expensive IMU. The results of this testing will be published in a journal article, thus this paper will consist of a brief summary of the results obtained.

3.1. Method

Three sensors were tested in this study which were the SparkFun Razor 9DOF IMU, MicroStrain 3DM-GX3-25 IMU (~AU$2900) and the OptiTrack Flex optical motion capture system.

While testing on the Katana Robot 450, the sensors were tested under three different conditions; repeated single-plane motion, repeated coupled-plane motion and random coupled-plane motion. For the two repeated test conditions, the sensors were compared in their ability to measure dynamic range of motion (ROM). The random motion test was used to determine the sensors ability to track a motion throughout its entirety.

Testing on humans was used to determine how well the device functioned in its intended application of the tracking of human motion, primarily spinal movement. The device was compared to the same sensors used in the Katana testing, however the OptiTrack system was now the reference system due to optical motion captures common use in human kinematic testing. Two participants, 1 male and 1 female, were used in this study. The optical motion capture markers were placed on the participants according to the model outlined by Preuss and Popovic [21]. The movements performed by the participants consisted of single- and coupled- plane movements and of varying speeds.

3.2. Results & Discussion

This section will give a brief summary of the results as seen in Table 2 and discussion on the usefulness of the device. Although the testing involving human participants has been performed, the data has not yet been analysed completely and thus will not feature in this section. The data from testing on the Katana Robot 450 has been analysed fully and results have been obtained.

Table 2. Results obtained from experimentation on the Katana Robot 450.

Sensor	**Single Axis ROM (RMSE)**	**Coupled Axis ROM (RMSE)**	**Random Motion (RMSE)**
SparkFun IMU	X: 2.28°	X: 1.98°	X: 2.339°
	Y: 0.57°	Y: -	Y: 0.626°
	Z: 3.97°	Z: 14.81°	Z: 10.15°
MicroStrain IMU	X: 1.40°	X: 0.78°	X: 1.822°
	Y: 1.36°	Y: -	Y: 0.685°
	Z: 0.31°	Z: 1.42°	Z: 4.420°
OptiTrack OMC	X: 1.70°	X: 0.50°	X: 3.705°
	Y: 1.80°	Y: -	Y: 2.547°
	Z: 1.96°	Z: 2.50°	Z: 0.915°

As can be seen in Table 2, the SparkFun IMU is comparable to the other sensors in accuracy when measuring motion around axes perpendicular to gravity (X and Y), however it is less accurate in measuring motion around the axis parallel to gravity (Z). Therefore if very accurate information is required from testing, it would be best practice to use optical motion capture or expensive IMUs. However, if less accurate information is required or only information on X and Y axes then it would be acceptable practice to use the SparkFun IMU or the complete Spinal Motion Measurement Device (SMM) developed in this study, for a number of reasons. Firstly, the entire SMM, which consists of three IMUs and two accelerometers, is relatively inexpensive compared to the other sensors used in this study. The SMM total price is approximately AU$560, whereas a single MicroStrain 3DM-GX3-25 IMU costs AU$2900. Not only is the SMM less expensive, but it also allows for a lot more information to be obtained due to the greater number of sensors involved. The OptiTrack motion capture system used in this study costs approximately AU$20000 which is around 36 times the price of the SMM. However, the OptiTrack system can give some information that the SMM cannot such as the exact position in 3D space of the joint or position markers.

Another advantage of the SMM over the other two sensors is the portability of device. The MicroStrain logs data via cables and thus the movements that can be analysed are restricted by the cable connecting the IMU to the data logger. The movements available for analysis using the OptiTrack motion capture system are also restricted to be within a certain capture volume (2.5m x 2.5m x 2.5m) as the cameras are not moveable during testing due to the required calibration. The SMM allows for much less restriction of motion due to its ability to log data wirelessly up to 15m from the receiver. The capture volume for the SMM essentially becomes infinite if the data receiver is also mobile, for example in the case of a smartphone.

4. Conclusion

A device was created that measured the orientation and angular rate of three different bodily segments/vertebra. The device was relatively inexpensive when compared to other sensors and it allowed wireless data logging of more than 15m from the data logger. The device is capable of logging data at frequencies above 50Hz, is portable and is comparable in accuracy to other sensors in axes perpendicular to gravity. The device has therefore shown great potential to be used in future studies as a low cost alternative for the collection of human 3D kinematic data.

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