JCPR Journal of Clinical Physiotherapy Research Case Report

The Calculation of Motion Angles of Human Body by Inertial Sensors and Their Application in Clinical Tests

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Submitted: 2018-09-19; **Accepted**: 2018-12-26; ***DOI:*** https://doi.org/10.22037/english.v3i4.24590

Abstract

Introduction: Low back pain, knee disorders and rheumatoid arthritis are the most common musculoskeletal diseases in Iran and throughout the world. The studies conducted in the developed countries have shown that this disease has considerable effect on the functional abilities and quality of life of patients. There are a few studies about this issue in Iran. Therefore, this study aims to evaluate the effect of knee and low back pain on the functional disability and quality of life of patients resident in Tehran. **Materials and Methods:** 220 musculoskeletal disorders (knee and low back pain and rheumatoid arthritis) from one hospital in Tehran, Iran participated in the study. Persian versions of Arthritis Impact Measurement Scale 2-short form (AIMS2-SF) and Short form health survey (SF-12) were used to measure the functional disability and quality of life. AIMS2-SF questionnaire that has been designed exclusively for rheumatoid arthritis patients measures the functional disability of patients in five dimensions: physical (upper and lower limbs), symptoms, feelings and social condition. **Results:** mean age and education of patients in this study was 53(low back pain), 45 (knee pain), and 58 (RA) years old, respectively. 59% of subjects were women. Mean of physical dimensions, upper limbs, lower limbs, symptoms, feelings, and social conditions were 1.46, 1.32, 2.12, 3.65, 3.40, and 3.78 (of 10), respectively. The mean of eight dimensions of quality of life based on the SF-12 questionnaire was 43 to 64 (of 100)**. Conclusion**: The results of this study showed that the quality of life and functional abilities of musculoskeletal disorders are influenced significantly by diseases. Based on this, the increasing of physical activity and the intensive physiotherapy programs result in improvement of quality of life in these diseases.

Keywords: Human Body; Inertial Sensor; Motion Angle

Please cite this paper as: Shokuhian M, Davoodi M, Abedi M, Parnianpour M. The Calculation of Motion Angles of Human Body by Inertial Sensors and Their Application in Clinical Tests. J Clin Physio Res. 2018; 3(4): 139-143. *DOI*: https://doi.org/10.22037/english.v3i4.24590

Introduction

The health system of today's societies is struggling with a fundamental issue. Considering the advances that have occurred in the recent decade and in the field of care and treatment in societies, the inhabits of the today industrialized countries have a high average of life expectancy, but life conditions are difficult and often very complicated. Injuries which endanger human survival has improved today, but on the other hand the number of people with individual disabilities has increased.

Joint pain is one of the most common pains. There are few people who have not experienced these types of pains. One of the most important pains occurs in the neck area. Intervertebral disc dislocation or the pressure on the cervical nerves causes sensory problems in this area [1]. Physicians perform various tests to evaluate the early causes of cervical pain, which one of the most of them is the study of changes in the neck area in different directions. The diagnose of it is a difficult task due to the little changes in the motion range with eyes and without precise instrumentation. So, it is necessary to use sensors which record kinetic motion. Physicians use imaging tests and neurological tests for more evaluation or the confirmation of the diagnosis. Imaging tests consist of X-ray radiography or CT scan or MRI. In the neural function tests the EMG signals of the neck muscles are recorded and the speed and amplitude of the signals sent from the nerves are investigated. Several methods to evaluate

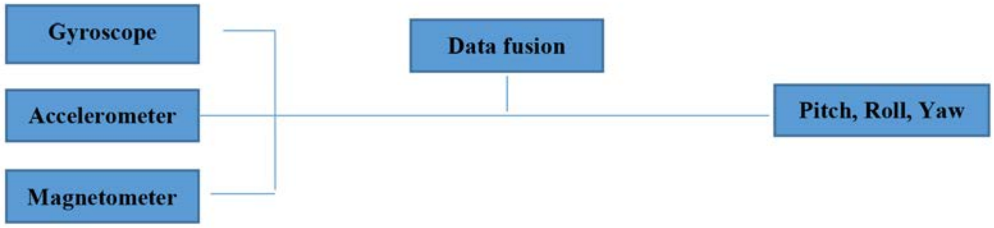

Figure 1. A schematic view of the inertial sensor

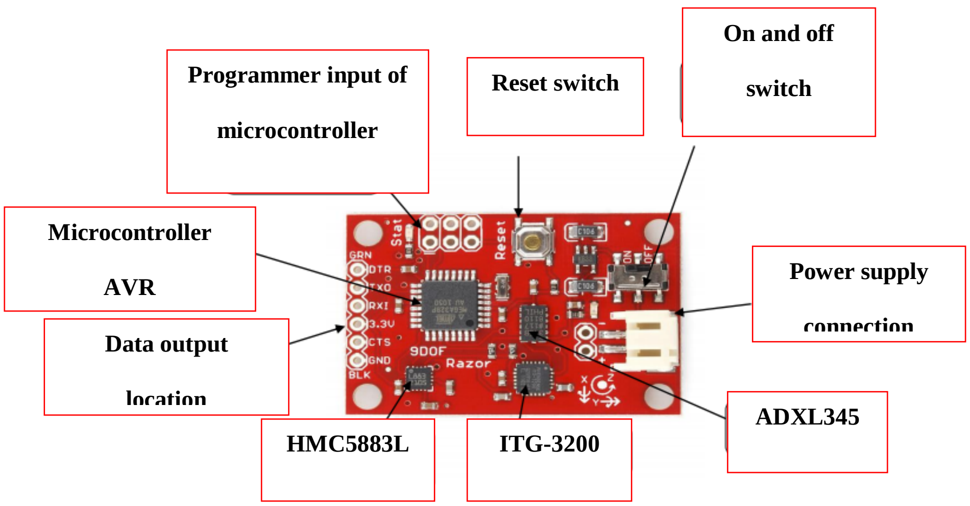

Figure 2. A view of the inertial sensor components

kinematics of the neck have been presented so far in segmental form of in general. In segmental evaluations with the use of CT scan fluoroscopy the status of the intervertebral plate and the motion between them are studied [2]. While the studies are examined to evaluate the three-dimensional motion of a neck, motion tracking is done with the use of the electromagnetic, ultrasonic techniques or the optoelectronic systems. Although the mentioned methods are precise to study the three-dimensional motion of the neck, they require laboratory environments, experienced physicians and high costs. Today with the advancement of technology in the field of MEMS sensors, wearable sensors can greatly be helpful in the process of diagnose and the evaluation of the treatment process and due to the low cost, easy application and availability of these instrument it is possible for anyone to use them to rehabilitate at home or clinical environment [3]. In this paper the function of inertial sensors and also an example of its clinical application are expressed.

Inertial sensor components

Achieving a confident and precise system in industry has always been the subject of debate. Accessing to a highly precise system always need the application of the very precise sensors. Inertial sensor is a type of sensors which are used in the aerospace, robotics, navigation, medical engineering and automotive industries. These sensors include two accelerometer and gyroscope sensors. With the use of the data of these two sensors and also the magnetometer sensor, one can extract the related data about position, speed and acceleration. In order to increase the accuracy of inertial sensors, a magnetic sensor is usually added to increase the accuracy of the calculated degree. A schematic view of this sensor is shown in figure 1.

In the inertial sensor of Sparkfun Company which has been shown in figure 2 the components include accelerometer (ADXL345), gyroscope (ITG-3200) and magnetometer (HMC5883L). These data are recorded by the microcontroller.

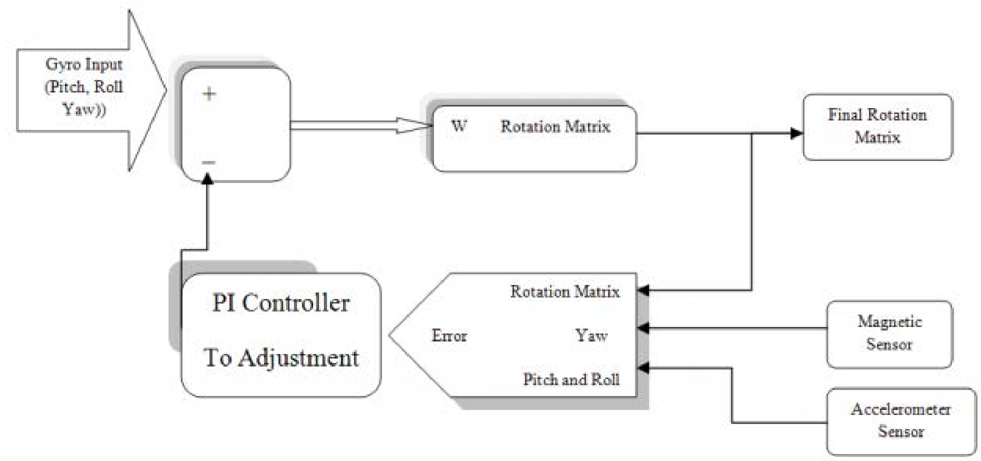

Figure 3. Block diagram of the data combination with DCM method

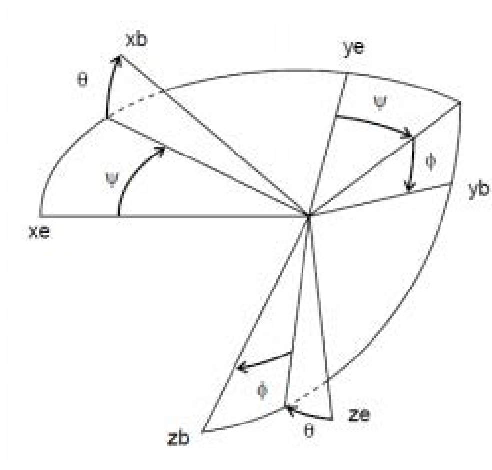

Figure 4. Coordinate systems connected to the ground and object

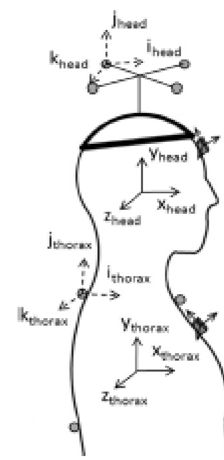

Figure .5. The position of the sensor on the forehead and chest

Combination of the inertial sensor data

Since we need kinematic parameters to analyze human motion, it is necessary to extract Euler angle with the combination of the accelerometer sensor output, gyroscope and magnetometer [4]. One of these methods is DCM which is briefly expressed. As stated in the previous chapters, it is necessary to mention that the ideal method to combine inertial data is through Kalman filter; but considering that the calculations of this method require a much higher capacity than AVR microcontroller [5-7], this method is not suitable for low capacity microcontroller.

The DCM method was used to determine the position of an air robot by Mahoney and his colleagues [8]. This method is schematically shown in the following figure. As it can be seen in the above block diagram, the gyroscope data is initially considered as the reference title. By integrating them, the matrix components of the period are determined. Then, the error of this matrix is determined with the use of the sensor data of the magnetometer and the accelerometer and finally the rotation matrix is updated and Euler angles are determined from it. This method is presented schematically in figure 3. At the end, these data are calibrated with the use of the rotating table.

Two different coordinate types, one coordinate system which is ground connected (inertial system) and the other system which is connected to sensors are shown in figure 4. The relation between these two systems is shown by Euler's angles.

The direction cosine matrix is actually used to transmit a vector from one system to the other. If P and Q are two position vectors or speed or acceleration in these two systems, they would be converted to each other by the following equations.

Table 1. Profile of the population of the subjects tested

Status	Gender	Number	Height Mean (SD)	Weight Mean (SD)	Age Mean (SD)
Healthy	Male	7	178 (5)	72 (8)	23 (1)
Patient	Male	7	177.5 (2.63)	79.4 (11.53)	53.28 (14.54)

Table (2): Data obtained from the analysis of the motion range in the healthy and patient groups

Type of Motion	Status	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Mean	STD	*P*-value
Flexion-Extension	healthy	116.24	117.13	133.35	129.3	129.02	128	130.48	126.217	6.729	0.023
	patient	115.28	91.19	122.48	98.24	110	130.26	128.81	113.751	14.953	
Lateral Bending	healthy	70.58	70.12	85.92	108.63	110.21	105.76	89.36	91.511	17.211	0.043
	patient	68.6	56.79	72.93	52.14	74.81	72.39	108.56	72.317	18.176	
Rotation	healthy	88.39	85.14	111.47	92.31	99.16	103.5	97.27	96.749	9.062	0.004
	patient	72.4	82.04	73.59	72.35	90.58	75.84	88.31	79.301	7.707	

(1) $$Q = R.P$$

(2) $$R = \begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix}$$

The matrix R is the same cosine matrix which is related to Euler angle considering the following equation.

(3) $$R = \begin{bmatrix} \cos\theta\cos\psi & \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi & \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi \\ \cos\theta\sin\psi & \sin\varphi\sin\theta\sin\psi + \cos\varphi\cos\psi & \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi \\ -\sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{bmatrix}$$

Finally, Euler's angles can be extracted by the two recent equations.

(4) $$\theta = -\arcsin(r_{zx}) \\ \varphi = a\tan 2(r_{zy}, r_{zz}) \\ \psi = a\tan 2(r_{yx}, r_{xx})$$

The method of the research

Testing and recording data

The method used in these tests was the same as Duc method [3] in 2014. During testing, patients are asked to perform triple cervical motion in two states of maximum speed and maximum amplitude to some extent that they do not feel pain.

At the beginning of the work, a questionnaire is provided to the patients in which the level of motion disabilities and patient pain are determined. VAS questionnaire is validated in Farsi and it is completely applicable to the patients. The questionnaires included information such as height, weight and age as well as the history of disease, fracture and surgery of the subjects. The group which was selected as a monitor group was conformed with the gender of the patients and it was attempted to being similar physical characteristics, but there was a significant difference in age.

Data acquisition was in such a way that one sensor puts on the forehead and the other puts on the vertebra T4 in spine. The pure motion of the neck to the upper body can be found by placing a sensor on the vertebra; because during the cervical motion, upper body motion is possible. One of the most important errors which exist in tests with the inertial sensor is the slip of the sensor on the skin. In order to solve it, sensors were put on the headband and chest band prepared and then they closed around the patient's forehead and chest. This collection is seen in figure 5.

Statistics population

Considering that age, gender, physical fitness level and individual health are effective in cervical function, attempts were made to consider these factors in the selection of samples. The statistical population in health group was selected from non-probabilistic graduated male students of Sharif University of Technology and the statistical population of the patients was selected from among the volunteers under treatment at Milad Hospital Rehabilitation Center. The condition for the healthy subjects to enter the study was considered having enough motivation, lack of muscle weakness or cervical injury. The characteristics of the two groups are presented in table 1.

Data processing

The appropriate cutoff frequency equals to 5 Hz was chosen in order to eliminate the noise of signals obtained from the sensor with the frequency analysis and low-pass fourth-order Butterworth filter was used to filter data.

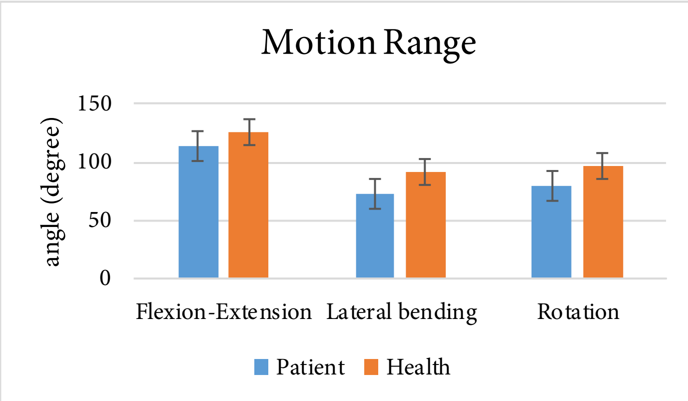

Figure 6. Mean range of motion in all three types of motion in the healthy and patient groups

The criterion of the motion range

The sensor expresses Roll, Pitch and Yaw angles to the reference coordinate system (zero system). We consider the coordinate system (1) for the sensor which places on the chest and the coordinate system (2) for the forehead sensor. And we calculate Euler's angles or in other words, the cervical motion range with the use of rotation matrix equations (equitation 5) in three modes such as Flexion-Extension, Lateral Bending and Rotation.

5) $$R_2^1 = (R_1^0)^T R_2^0$$

Results

The results of the measuring of the cervical motion range in the patients and healthy subjects are presented in table (2) and figure 6 in three motions of Flexion-Extension, Lateral Bending and Rotation. In order to study the meaningful difference level between the healthy and patients groups, variance analysis test (ANOVA) with 5% confidence level was used. Considering the values of P value in table (2) in all three types of motion, a meaningful difference between the healthy and patients groups was seen. Since during the test patients were asked to make every movement at their pain threshold and also due to the stretching of the muscles and ligaments or making pressure on the intervertebral disc and the nerves, motion range shows a considerable decrease in the patient group.

Conclusion

In this paper a measurement system is presented to record human motions in portable form. This system has features such as lightness, portability and also cheapness. This system includes inertial sensors such as accelerometer and gyroscope and in order to reduce the error in the system a magnetometer sensor has been used. The raw data of these three sensors is combined with the DCM method and the Euler's three angles will be obtained at the output. Such a system can replace with deformation sensitive clothes and expensive camera equipped systems for motion analysis. This system can be used in rehabilitating, identifying risk activities, determining the therapeutic pattern for patients and differentiating healthy subjects from patient ones in clinical centers. In a clinical use these sensors were used to detect cervical complication. As it was observed, the criterion of the motion range in the patients and healthy subjects was significantly different ($P<0.05$) and it indicates that this criterion is suitable for the diagnosis of the healthy and patients subjects; but considering that patients with a little exercise can increase their motion range, this criterion is not suitable due to the lack of involvement of speed and acceleration parameters.

Conflict of interest:
None

Funding support:
None

Authors' contributions:
All authors made substantial contributions to conception, design, acquisition, analysis and interpretation of data.

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