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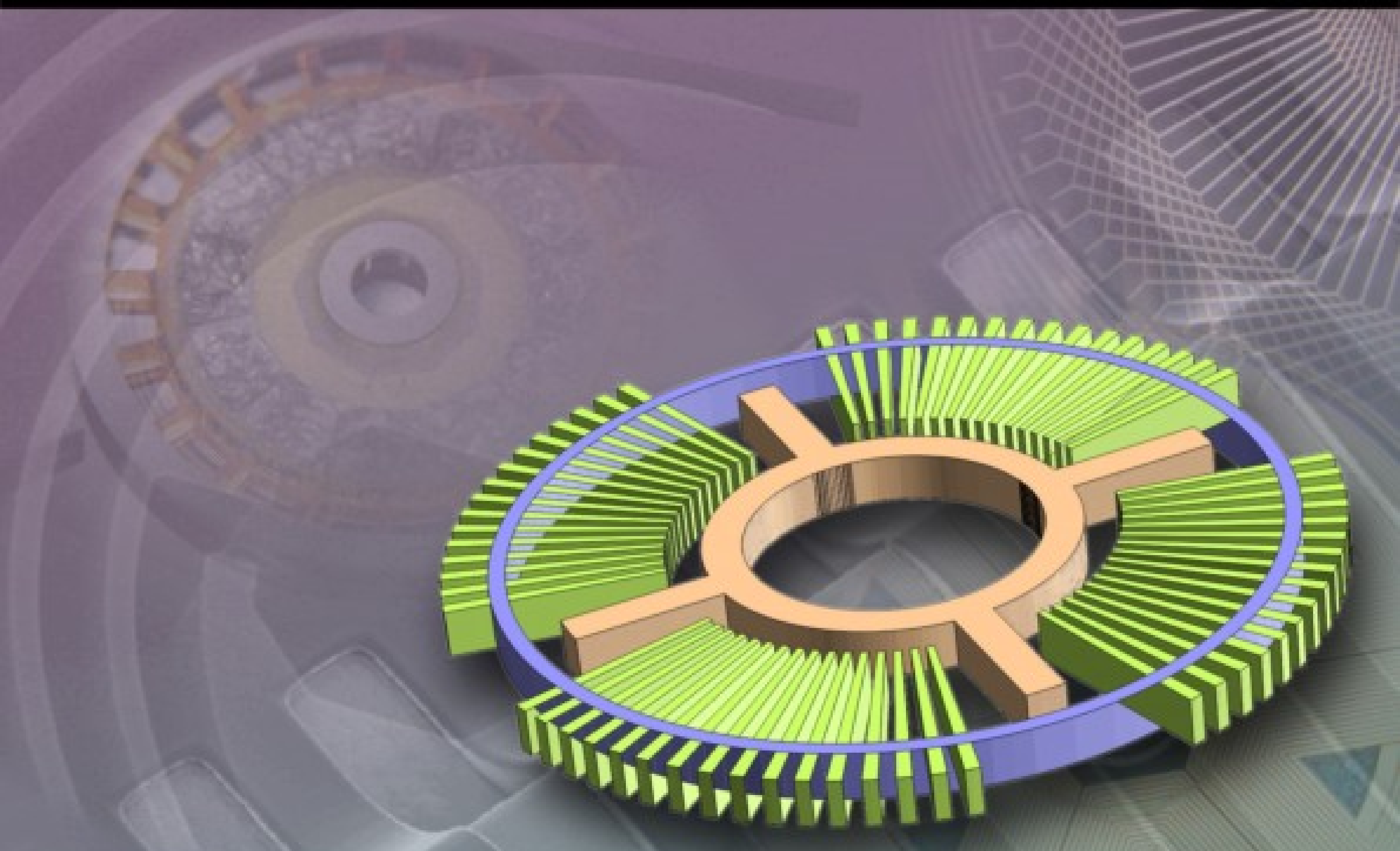

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Multi-Functional Sensor System for Heart Rate, Body Position and Movement Intensity Analysis

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Abstract: A novel multi-functional wearable sensor has been developed with multi-axis accelerometer, disposable hydro-gel electrodes, and analog filtering components. This novel sensor implementation can be used for detecting common body positions, movement intensity, and measures bio-potential signals for ECG and heart rate analysis. Based on the novel sensor principle, a prototype combines position detection, heart rate detection, and motion intensity level detection together in a handheld device that records the physiological information and wirelessly transmits the signals through Bluetooth to a mobile phone. Static body positions such as standing/sitting, lying supine, prone, and on the sides have been detected with high accuracy (97.7 %) during the subject tests. Further, an algorithm that detects body movement intensity that can potentially be applied in real-time monitoring physical activity level is proposed based on average variance values. Motion intensity results show variance values increase and exercise intensity increases for almost all of the cases. A clear relation between movement intensity level shown by an increase in frequency and/or speed of exercise increases the variance values detected in all three spatial axes. *Copyright © 2008 IFSA.*

Keywords: Multi-functional sensor, Position detection, Movement intensity, Wearable sensors, Health Monitoring

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1. Introduction

1.1. ECG and Heart Rate Detection

The use of electrocardiogram (ECG or EKG) to analyze heart health has been used in the medical field for many years now. It is one of the most accurate methods of detecting heart rate. While heart rate itself is often not sufficient enough as clinical diagnostic information for cardiac related health problems, its value in personal health monitoring, stress monitoring, and acute health care is critical. The study of ECG waveforms and heart rate can help medical practitioners to detect various types of cardiac arrhythmias and other heart related diseases. Examples of state of the art ECG modules include IMEC's proprietary ultralow-power bio-potential ASIC (application specific integrated circuit), which extract ECG signals, processes through a microcontroller to obtain heart rate value, and wirelessly transmits the signals through a RF communication module [1]. Another wearable cardiac monitoring system, developed by Thulasi Bai and S. K. Srivatsa incorporates an alert system through text message on the cell phone [2]. ECG monitoring is a very active research area with a variety of implementations.

1.2. Body Position Detection

The detection of body position with the use of accelerometers has produced fairly accurate results [3]. Most industrial and micro electromechanical system (MEMS) type accelerometers today are available in versions that are sensitive to static acceleration. Thus, the static acceleration of Earth's gravity relative to the sensor's orientation can be detected by these devices. For example, approximately 1g acceleration is detected by a MEM accelerometer with its axis-of-orientation pointing towards the center of Earth. As a result, a combination of the acceleration values from a three-axis accelerometer simultaneously can determine the orientation of the sensor in the three-dimensional space. Therefore, when the sensor is attached to the upper torso of a subject, the postures, namely standing and lying on each of the four sides of the body, corresponding to the position of the sensor can be detected. The position of the human body in three-dimensional space can be detected by placing an accelerometer on a body torso, with the exception of determining the difference between standing and sitting. In such cases, two sets of sensors, one located on the torso and another located on the thigh, are required.

1.3. Combining Heart Rate and Body Position Information

The combination of heart rate and body position information recorded or monitored simultaneously can provide a valuable set of physiological and behavioral data related to the physical activity and cardiac activity. It is widely known that body posture as well as body movement intensity is closely related to the physical demand of human circulatory system. However, for example an athlete undergoing intense exercise can have a relatively high heart rate without any health risks while an elderly person lying in bed with the same high heart rate may be suffering from a heart condition. The added knowledge of the subject's body position and activity intensity provides very valuable information and creates a history for monitoring, diagnostics, or health alerts. A discrete and minimally obtrusive wearable device allowing synchronous measurement of these physiological parameters can further offer enhanced mobility, for the very first time, to the collection and monitoring of these datasets for both research and practical applications.

2. Review of State-of-the-art Devices

Human motion analysis has been primarily dominated by video cameras. The marker recognition method which captures from multiple camera views in the infrared range is the most accurate method to date. It has been used in both commercial and clinical settings. Digitized video capturing motion states and movements can be further enhanced for analysis through motion analysis software [4]. However, motion detection with multiple cameras often requires complicated setup around a limited space for the subject to move. It is therefore unsuitable for monitoring people in outdoor or mobile environments. The explosive amounts of data from cameras represent another limiting factor in the practical real-time analysis of motion.

Our studies focus on wearable and easy-to-use devices based on local, personal processing and wireless transmission. Other studies have also adapted to kinematic sensor, or accelerometers to detect and analyze motion. One example of previous related research is a wireless sensor application which detects abnormal human movements, such as seizure [5]. Another example is a kinematic sensor composed of multi-axial accelerometer and gyroscope to monitor daily physical activities in elderly people [6]. The use of sensors to detect motion instead of multi-view cameras allows more flexibility in subject's movement which is more suitable for daily, long-term monitoring. The limitation of previous studies is on the accuracy of the system. More accurate distinction of body posture and positions would require multiple sensors, mounted on various places of the body, similar to the markers used in the multiple camera method.

We propose in this paper a multi-functional wearable wireless sensor which improves the body motion and position detection by introducing combined static and dynamic analysis of motion with synchronized assessment of heart rate.

3. System Architecture

3.1. Multi-Functional Sensor Architecture

The multi-functional sensor introduced here integrates key elements of a MEMS 3-axis accelerometer serving body position detection. Disposable ECG hydro-gel electrodes are attached to the accelerometer module for acquiring bio-potential signals. The accelerometer integrated system (including the accelerometer module, 50 Hz low-pass filter, and attachments for electrode connection) is housed on a miniature printed circuit board (PCB). The multi-functional sensor consists of two inputs and four outputs. The two inputs are power and ground. Out of the four outputs, three are for the accelerometer (one for each of the x, y, and z axis) and one for the ECG, to be used as a reference signal. A system diagram of the integrated sensor is shown on Fig. 3.1.

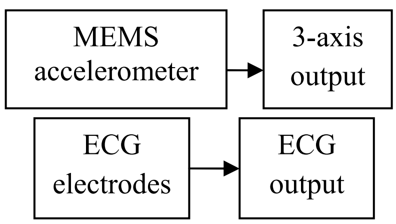

Fig. 3.1. Multi-functional sensor architecture.

The acceleration and bio-potential signals taken from the multi-functional sensor are first amplified through a custom signal conditioning circuit. The resulting signals are then inputted into the National Instrument's 9205 analog-digital converter (ADC) used to digitize the output signals. Custom-developed software implemented using National Instrument's LabVIEW then displays and records the data for post-processing. The stored results are further processed. MATLAB software is used in this stage. Fig. 3.2 shows an overview diagram of the accelerometer data collection and processing system.

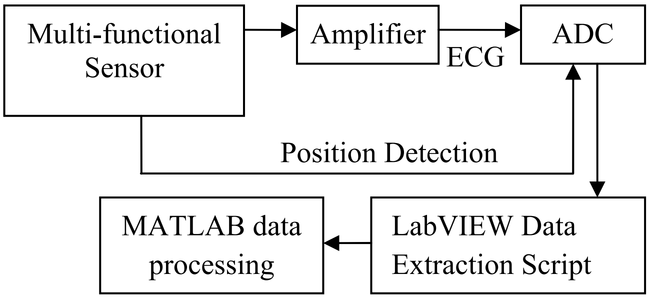

Fig. 3.2. Sensor data extraction setup.

Five channels of data are extracted from the analog-digital converter; three for each of the x, y, and z-axis of the 3-axis accelerometer and two for each of the ECG electrodes.

3.2. Application System Architecture

One prototype developed is a wearable device used to detect heart rate and monitors body position and movement intensity of the subject. It consists of a handheld device which records subjects' heart rate through ECG electrodes and detects movement intensity and body position with 3-axis accelerometer sensors, placed on the body and the leg of the subject. Heart rate and body position information is then processed through a microprocessor and transmits the information through the on board Bluetooth module to a Bluetooth enabled Symbian based mobile phone. The system block diagram of this prototype device is shown in Fig. 3.3 a. Fig. 3.3 b shows our first highly integrated implementation of the multi-functional wireless system.

This prototype device is able to detect different body positions such as standing, sitting, and lying on different sides of the body. It also processes motion sensor data by calculating the variance of the sample data, in order to determine movement intensity.

The ECG based heart rate sensor consists of the electrodes and a custom built signal conditioning circuit that converts ECG signals into pulses for preparation for the microcontroller's heart rate detection algorithm. The custom signal conditioning circuit includes filters, amplifiers, and artifact remover which minimize interference when recording ECG signals while subjects are in motion. The heart rate sensor and data validation has been reported in [7].

The accelerometer sensors consist of two 3-axis accelerometers, one mounted on top of the sternum, and another on the thigh. Below, Fig. 3.4 a is a sample setup of the device on the upper torso of a test subject. The ECG 3-electrodes are for heart rate validation of the data. One accelerometer mounted on top of the sternum is sufficient to detect many normal body positions. An additional sensor, placed on the leg as in Fig. 3.4 b can detect even more positions, such as distinguishing between standing and sitting. Fig. 3.4 b shows the setup of the addition of another sensor, mounted on the leg of the subject to allow more precise body position detection.

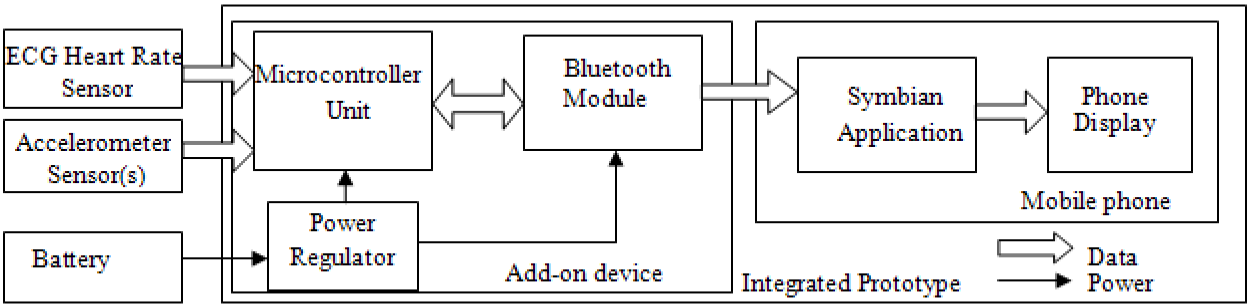

Fig. 3.3 a. Prototype System Block Diagram.

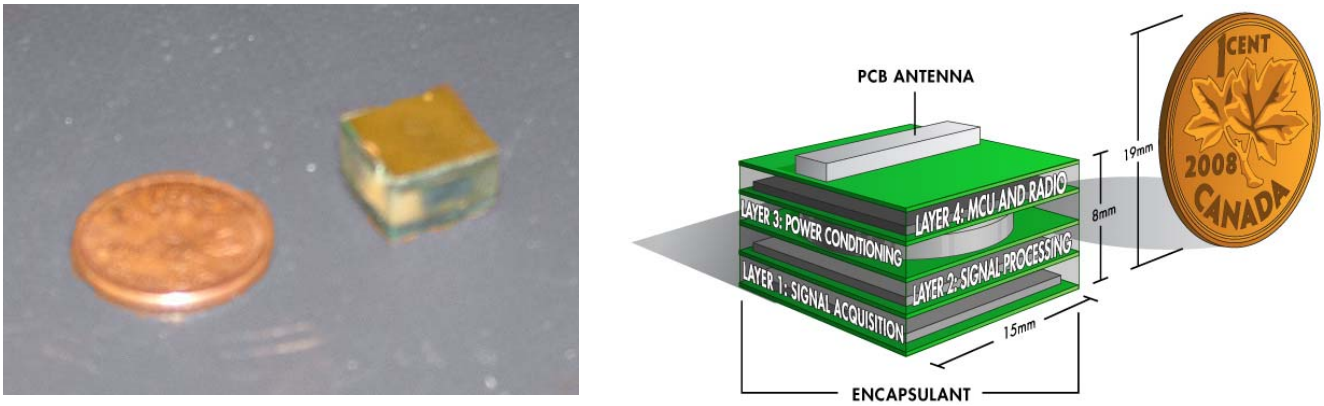

Fig. 3.3 b. Integrated implementation of our prototype multi-functional wireless sensor.

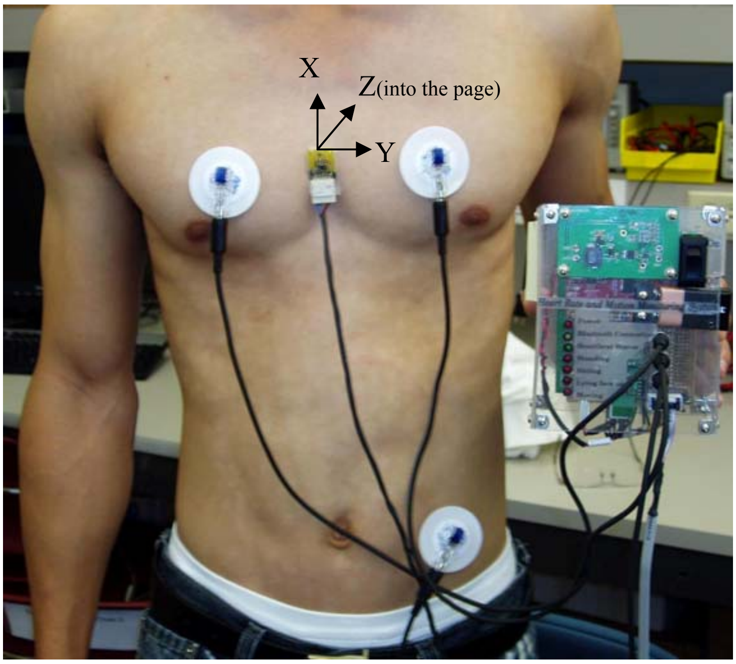

Fig. 3.4 a. Prototype Setup on upper torso.

Fig. 3.4 b. Prototype setup on leg.

4. Testing Methods and Protocols

4.1. Static Body Position Detection

The sensor is attached onto the subjects' mid-region of the sternum. Each subject is asked to perform a routine of physical stances including: standing, sitting, and lying on the left, right, supine, and prone positions. The order of body positions tested is noted down for comparison with test results. Each subject is asked to repeat the physical routines for five times to guarantee data consistency. To minimize test variables, a controlled group of five healthy (with no previous heart disease) male subjects between the ages of 20-30 are tested. The expected values (in units of gravity, g) for each of the positions tested are shown in Table 4.1.

Table 4.1. Position values of each axis in g.

Positions	**Expected g values**		
	X	**Y**	**Z**
Standing	1	0	0
Sitting	1	0	0
Lying on left side	0	-1	0
Lying supine (face up)	0	0	-1
Lying on right side	0	1	0
Lying prone (face down)	0	0	1

The low frequency output of the accelerometer indicates g values. The 0g value is defined as half the value of the sensor supply voltage, or maximum voltage depending on the sensitivity of the sensor, -1 g would be the 0 g value minus an offset voltage and 1g would be the 0g value plus an offset voltage. The voltage offset values corresponding to the g forces are found experimentally by recording the sensor output while placing the sensor in the correct orientation. The sensor's output voltage offset values corresponding to various g forces are measured as shown in Table 4.2.

Table 4.2. Sensor output voltages corresponding to various *g* forces measured.

	Sensor G Force Test				
Axis	*-1G*	*LT*	*0G*	*HT*	*1G*
X	0.96V	1.16V	1.66V	2.12V	2.32V
Y	0.96V	1.16V	1.64V	2.12V	2.30V
Z	0.93V	1.10V	1.60V	2.06V	2.28V

The two threshold values, lower threshold (LT) and higher threshold (HT) are taken at + 45° and – 45° with respect to 0 g. These two values are used as a boundary condition for determining the correct g value combination corresponding to the body position. The algorithm for g value detection follows the following steps:

1. If output is less than LT value, then -1 g is detected.
2. If output is between LT and HT value, 0 g is detected.
3. If output is above HT value, 1 g is detected.

4.2. Higher Resolution Detection

The previous methods of detecting the orientation of the accelerometer have been classified into three distinct states: +1 g, 0 g, and -1 g. However, these results do not produce the most precise measurements that the accelerometers are capable of detecting. For example, using a threshold value at +45° and – 45° with respect to 0g to determine the output reading will categorize all the values ranging from – 44° to + 44° as 0 g, with the two extremes differing almost 90°. A more precise method of determining the orientation of the accelerometer axis is to measure all the output values ranging from -1 g to +1 g in 10° interval step (other intervals may also be used). This test is conducted by measuring the sensor output with a reference protractor, and recording multiple of 10 degrees, from -1 g (-90°) to +1 g (+90°), shown in Fig. 4.1.

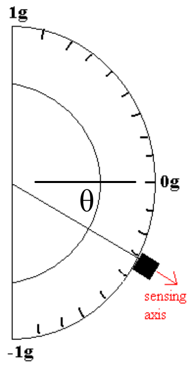

Fig. 4.1. Higher Resolution Test Measuring Technique.

4.3. Movement Intensity Test

The movement intensity detection system extracts data from the accelerometer sensor and processes within a customized script written in LabVIEW. The system architecture is shown on Fig. 4.2 and the setup used for subject's tests is on Fig. 4.3.

The 3-axis accelerometer feeds raw data to the ADC which is processed through National Instrument's custom LabVIEW script. The objective of the script is to record the 3-axis output readings, its mean and variance values taken once for every ten data samples. A total of 9 columns of data are recorded in a text file, and then analyzed through MS-Excel. The sampling rate of the data acquisition is 10 Hz, resulting the variance and mean being calculated once every second.

The setup procedure of the movement intensity test is conducted as follows: One 3-axis accelerometer sensor is placed 5 cm above the knee cap on the outer side of the right leg as shown in Fig. 4.4.

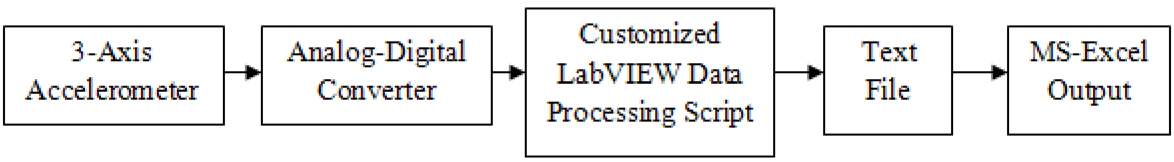

Fig. 4.2. Movement Intensity Detection System.

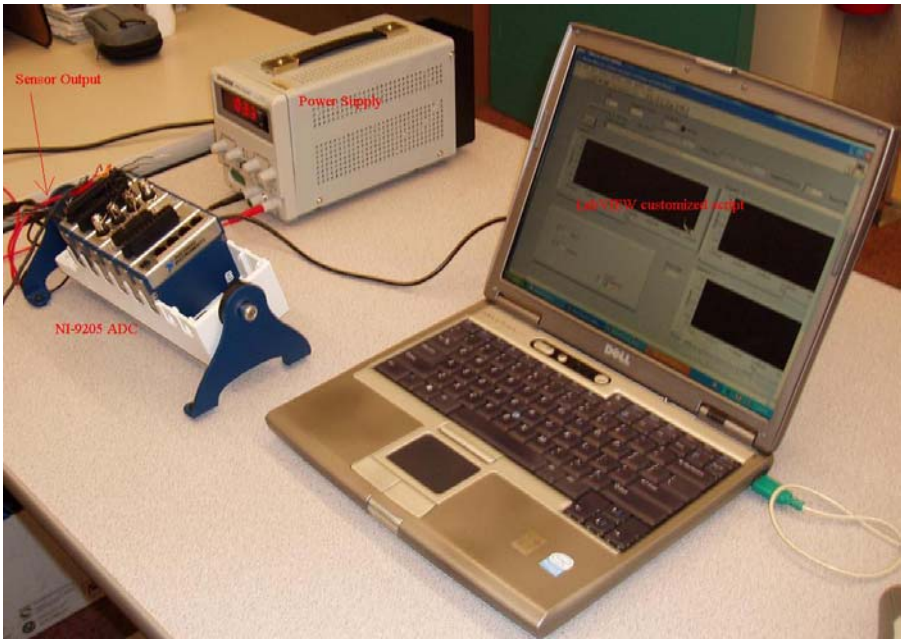

Fig. 4.3. Movement Intensity Test Setup.

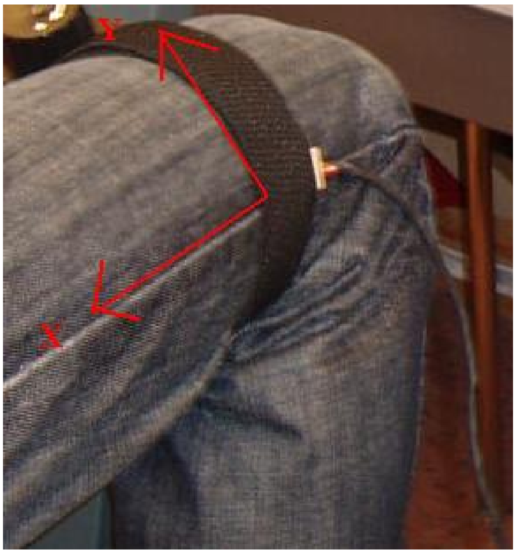

Fig. 4.4. Movement Intensity Test Sensor Location.

The following test procedures are followed during the test: Each subject was asked to perform a series of exercises on the treadmill and the exercising bike, with different intensities. The treadmill is categorized into five different intensity levels, with intensity 1 being the slowest, and intensity 5 the fastest. For the exercise bike test, the subjects are asked to try to maintain a constant cycling frequency during each 30 second recording. Subjects are asked to maintain three frequencies of 60, 80, and 100 rpm, displayed on the machine display in front of the subject. The margin of error and the human controlled frequency is ±5 rpm. The objective of these tests is to show a trend in the variance values captured. In theory, the higher the intensity of the test will show a higher variance value. Since the movement frequency increases, the data values should have a wider statistical dispersion. The following selection of exercises listed in Table 4.3 is conducted for each subject.

Table 4.3. Movement Intensity Tests.

Intensity levels	Treadmill Test		Exercise Bike
	Walking	Running	
1	✓		60 rpm
2	✓		80 rpm
3	✓		100 rpm
4		✓	
5		✓	

For each of the tests conducted according to the table above, two 30-second recordings were taken for each subject. All of the recordings are conducted using 10-Hz sampling frequency. Information recorded includes 3-axis sensor output, the mean, and variance of each of the axis, calculated once for every ten samples. The mean value is used to determine the static position of the test subject. The variance value indicates how much the output data spreads, through a give time frame. Since the variance relates to the amount of change of data, it can be related to the movement intensity, which we will observe in the results and analysis section next.

5. Results and Analysis

5.1. Higher Resolution Detection

Two of the sensors used during the tests are evaluated through the higher resolution test and the output readings against the tilt degree are plotted below (Fig. 5.1.):

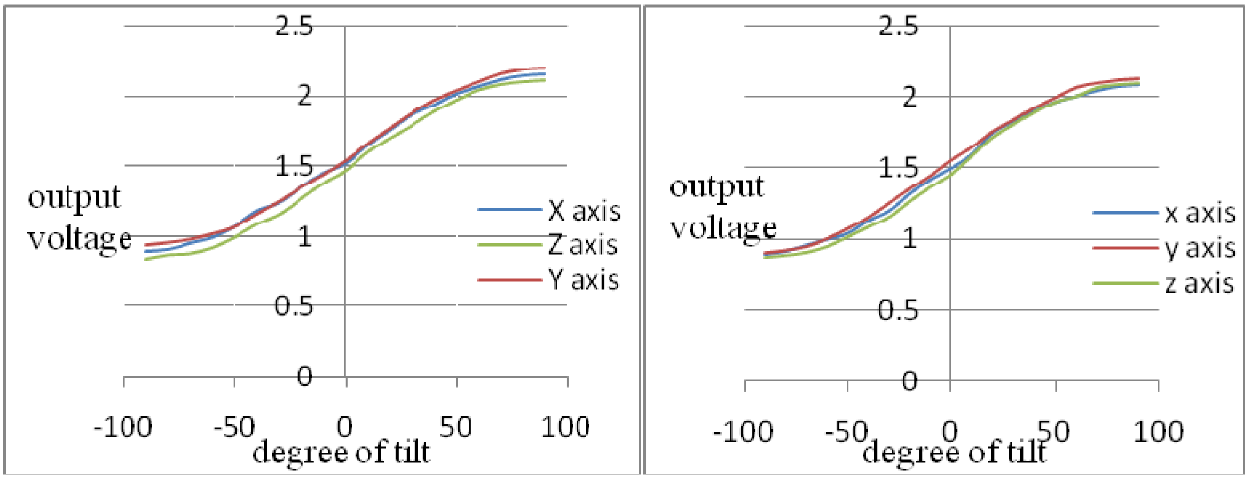

Fig. 5.1. Higher Resolution Outputs of Two Sensors.

Notice that when the sensor approaches the two ends, namely -90° (-1 g) and +90° (+1 g), the output becomes non-linear sine function, which is consistent with industry results [8]. The sensor output values of -1 g, 0 g, and +1 g of the higher resolution test (shown in Table 5.1) shows close resemblance to the results of the threshold g level test of Table 4.2.

Table 5.1. Higher resolution end point results.

	higher resolution g force test		
Axis	-1g	0g	+1g
x	0.89	1.52	2.16
y	0.94	1.54	2.20
z	0.85	1.47	2.11

5.2. Static Body Position Detection

The results, utilizing the static body position detection method are conducted and results are based on the LT and HT threshold method shown in Table 4.2. From the five test subjects, a total of 25 data sets are recorded. Three of the data sets recorded were discarded due to system failure such as the connectors not properly connected or a lack of power from the battery, which occurred once each for subject 1, 2, and 4. Of the remaining 22 data sets, six positions are available from the recordings. One recording captured only five positions before the 50-second time interval ended, leaving 131 body position results available for analysis. Out of 131 body positions, only three posture positions do not match the expected values shown in Table 4.1. The three errors came from lying on the right side position of a single subject. The errors are likely the result of connector cable not long enough, which might have limited the subject's movement.

The overall body position detection accuracy obtained from this experiment is 97.71%. These results obtained demonstrates the sensor system is capable of distinguishing between standing/sitting, lying on the left, supine, right, and prone positions from one 3-axis accelerometer mounted on the sternum of subject's body.

5.3. Movement Intensity Test

A total of 8 male subjects between the ages of 22-28 were selected to perform various tests on the two exercise machines. The variance data are calculated once every 10 data samples, all of the variance values are then averaged again to produce 1 value for each test. The average variance of all the test result is summarized in the Figures 5.3 and 5.4 below. The results of average variance, calculated per test are shown below, separated by individual axis. The average variance is shown on the vertical axis of the graphs below and the horizontal axis shows the test numbers.

From observing the results above, the intensity levels of the treadmill test increases as the speed of the treadmill increases. The variance values (on the vertical axis) increases as the intensity level increases for almost all of the cases. The exercise bike result also matches this trend. For both tests, the direct relationship between variance levels and movement intensity can be clearly seen.

5.4. Body Position and Heart Rate Synchronization

The ability to detect body position together with heart rate can provide useful information about the subject's health state. A test shown below where subjects undergoes a series of static and dynamic positions while monitoring the corresponding heart rate is shown in Fig. 5.5.

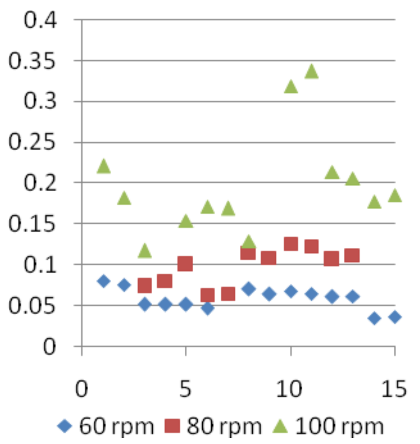

Fig. 5.3 a. Bicycle Test X axis variance.

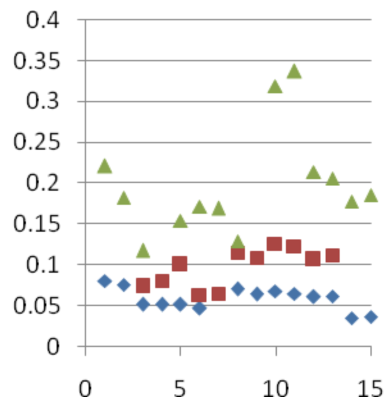

Fig. 5.3 b. Bicycle Test Y axis variance.

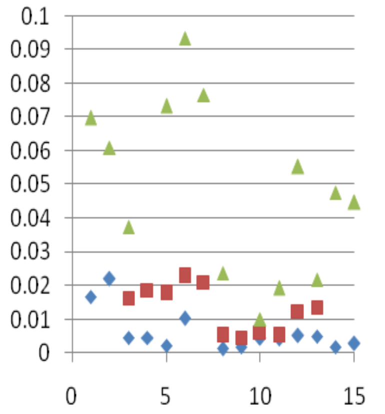

Fig. 5.3 c. Bicycle Test Z axis variance.

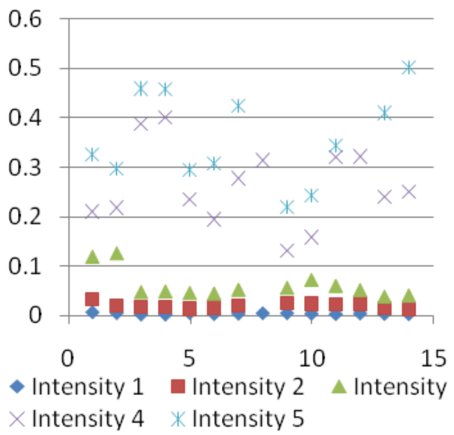

Fig. 5.4 a. Treadmill Test X axis variance.

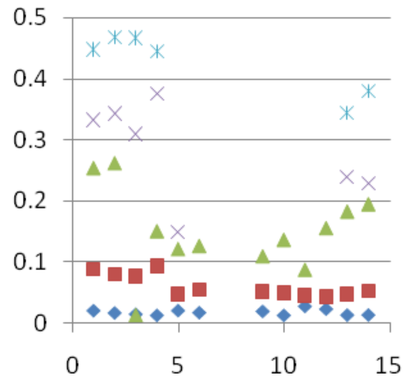

Fig. 5.4 b. Treadmill Test Y axis variance.

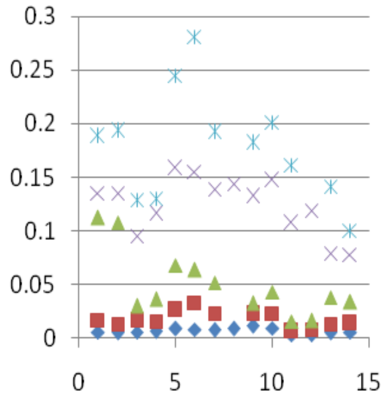

Fig. 5.4 c. Treadmill Test Z axis variance.

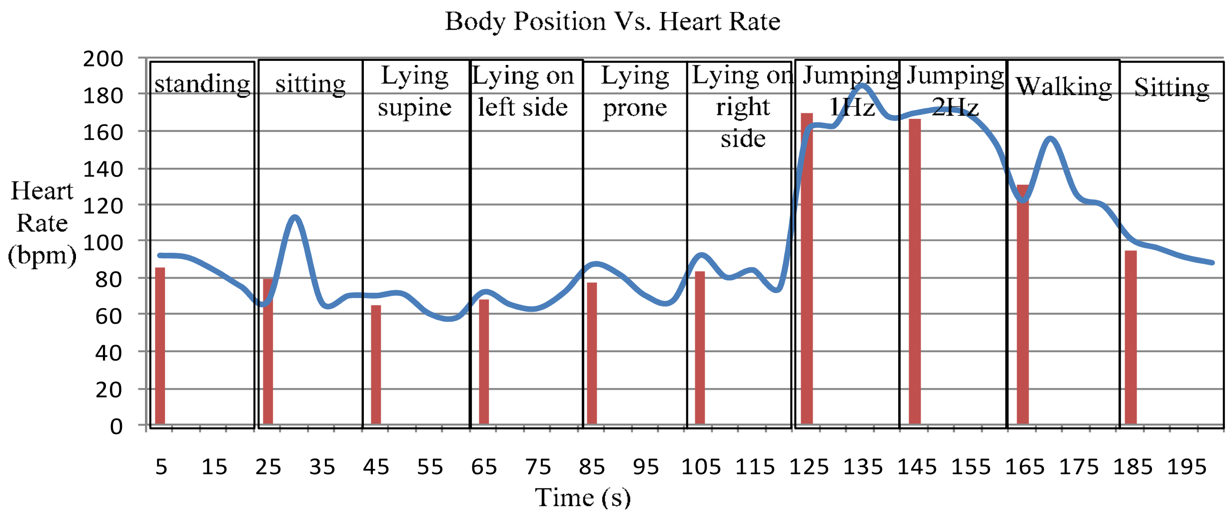

Fig. 5.5. Body Position vs. Heart Rate.

The blue curve line is the heart rate taken for every 5-second interval and the red bars are the average heart rate of each position. The abnormally high heart rate results are artifacts caused by muscle movements during exercises. For most of the positions, the start of each position shows a relatively higher heart rate which slows down as the subject's current position stabilizes. This is because the transition movement from one position to the next increases heart rate.

6. Conclusions

In this paper, body position detection and motion intensity detection, using accelerometers are evaluated. Heart rate detection, extracted from electrocardiogram signals through a customized analog signal conditioning board is implemented. Together through a prototype device introduced here, the ability to detect and record these health signs synchronously and wireless transmits them to a mobile device can form a new way of health monitoring. Novel motion intensity detection methods can also be applied to personal fitness areas. The importance of combining position detection with heart rate can provide useful information of the subject's well being.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
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