# Multi-functional Wearable Device for Heart Health and Position Assessment

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## ABSTRACT

In this paper we introduce a wearable device combining cardiological monitoring and person's position assessment. An accelerometer is used as a multi-functional sensor for both body position and heart mechanical performance measurements, known as mechanocardiography (MCG). Cardio biopotential is also simultaneously captured at body surface as electrocardiogram (ECG), for heart electric output analysis. Body positions, such as standing, sitting, lying in the directions of left, supine, right, and prone, are detected, with an accuracy rate of 97.71%. Detecting body position in synchronization with heart activity allows more in-depth monitoring of a subject's potential health conditions and hence, well-being. We introduce an integrated multi-sensor device as a possible wireless wearable system for health monitoring applications.

## 1 INTRODUCTION

### 1.1 Mechanocardiography (MCG)

In the late 19th century J. W. Gordon [1] noticed the oscillations caused by a person standing on a spring weighing-machine. Since then, scientists used numerous devices and methods to extract body motions escalated from the movement of the heart; however, it was not until the early 20th century when Starr [2] began to understand the meanings of the mechanical signal waves, later extended to ballistocardiography (BCG) and seismocardiography (SCG) studies among others. A more general umbrella term, MCG, is used to refer to those methods of recording and interpreting bodily movements arising from heart activity. At the Center for Integrative Bio-Engineering Research (CIBER) lab, Simon Fraser University, researchers have identified BCG characteristics corresponding to specific heart movements measured through tiny wearable chest sensors [3]. Below (Figure 1) shows a typical BCG waveform and reference ECG waveform. According to the BCG terminology assigned by the American Heart Association, Figure 1 is labeled with two wave complexes HIJ and LMN, representing the ventricular wave (occurring during the contraction of the muscles of the left and right ventricles of the heart) and the early diastolic wave (period of time when the heart relaxes after contraction in preparation for refilling with circulating blood) respectively. Medical practitioners can detect signs of chronic abnormalities and other related chronic diseases by analyzing the morphology of the BCG waveform [4]. The ECG waveform serves as a reference for cardiac cycle, where the R peak of the ECG indicates the beginning of a new cycle. BCG, and more generally MCG, provides a wealth of useful information for non-invasive cardiac health monitoring and potentially disease identification.

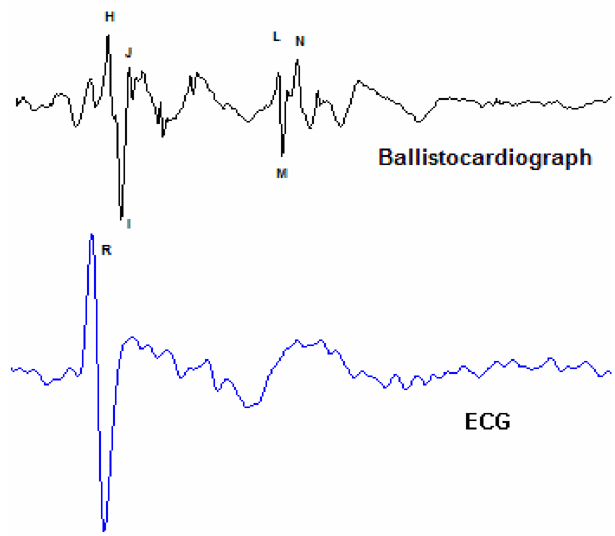


Figure 1: BCG and ECG signal of a heartbeat.
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### 1.2 Body Positioning

J. Ng (2000) [5] used accelerometers in the ultra-low frequency range to detect body postures. 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 gravity on Earth can be detected by these devices. For example, approximately 1 g force can be detected by an accelerometer with sensitive axis 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 use of an accelerometer to detect body position has been demonstrated to achieve very accurate results. 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.

## 2 INTEGRATED SYSTEM DESIGN

The multi-functional sensor introduced here integrates key elements of a MEMS 3-axis accelerometer, serving both position and MCG measurements. Two disposable ECG hydrogel electrodes are attached, one on each of the vertical sides of the accelerometer module. The accelerometer integrated system (including the accelerometer chip, 50 Hz low-pass filter, attachments for electrode connection, and wire connectors) is housed on a 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 Figure 2.

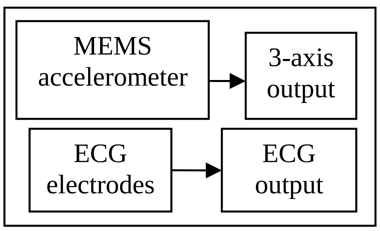


Figure 2: Multi-functional sensor

The MCG and ECG results 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 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 using MATLAB. Figure 3 below shows an overview diagram of the accelerometer data collection and processing system.

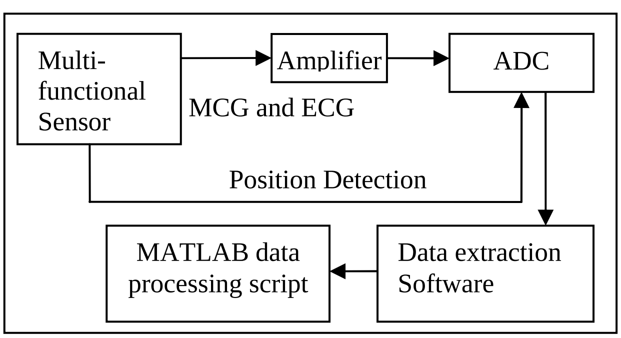


Figure 3: Sensor data extraction system/setup.

Eight channels of data are extracted from the analog-digital converter; three for each of the x, y, and z-axis of the 3-axis MCG, two for each of the ECG electrodes, and three for the 3-axis body position. The purpose of the signal processing through MATLAB is summarized below:

- Software low-pass filtering, using a Butterworth $10^{th}$ order with a cut-off frequency of 50Hz to attenuate higher frequency noise.
- Converting raw voltage output to meaningful acceleration units expressed as $mm/s^2$.
- Graphically displaying the signals for MCG morphology and body position analysis.

The integrated system can be further modified to incorporate wireless transmission by the addition of a microcontroller with Bluetooth or other wireless communication modules. Software post-processing can be done on the microcontroller. Position detection results and MCG data information can be transmitted wirelessly to a pre-configured receiving device. This entire system can then be packaged into a size small enough to be carried by users.

## 3 TESTING METHODS

The body position detection method can be summarized as follows: The sensor is attached onto the subjects' mid-region of the sternum, employing McKay's (1999) method [6]. 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 subjects are then asked to hold each position for a few seconds, in order to record MCG signals without the interruption of body movements. 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 trials to ensure data consistency. A total of five healthy (with no previous heart disease) male subjects between the ages of 20-30 are tested. The reason of selecting a specific group of people as test subjects is to minimize test variables. The expected values (in units of gravity, g) for each of the positions tested are shown in Table 1.

| **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 |

Table 1: Position values of each axis in g.



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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, -1g would be the 0g 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. For example, determining the z-axis output of 0g (z-axis parallel to the ground plane) is done by orienting the z-axis of the sensor on the side of a table as shown in the Figure 4 below.

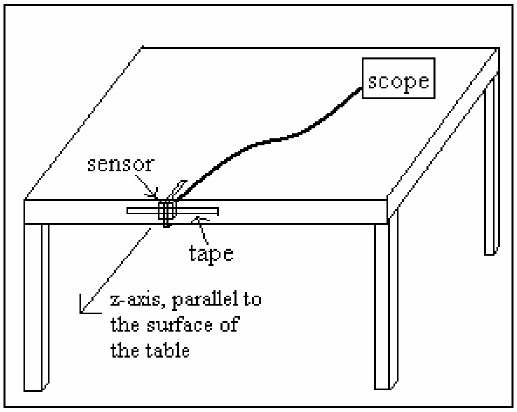


Figure 4: Method of recording 0g output of the z-axis.

The sensor's output voltage offset values corresponding to various g forces are measured, and results shown below in Table 2:

| | 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 |

Table 2: Sensor output voltages corresponding to various *g* forces measured;

The two threshold values, lower threshold (LT) and higher threshold (HT) are taken at + 45° and – 45° with respect to 0g. 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 -1g is detected.
2. If output is between LT and HT value, 0g is detected.
3. If output is above HT value, 1g is detected.

# 4 RESULTS AND ANALYSIS

The new multi-functional sensor was assessed for cardiological measurements first. The MCG results of the subjects are recorded and processed in MATLAB. A 1.5-second segment of a subject's three-axis MCG with ECG reference is extracted and shown in Figure 5 below.

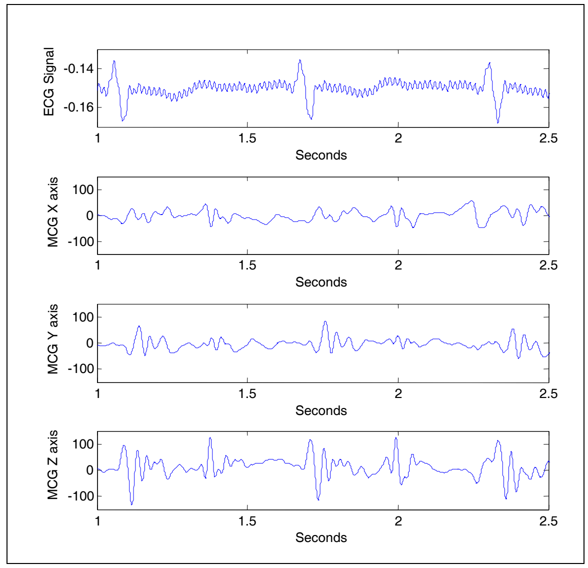


Figure 5: 1.5-second MCG and ECG plot

It can be seen in Figure 5 above that the conventional z axis of the MCG shows distinct characteristics like BCG's HIJ and LMN complexes shown in Figure 1. Also, the ECG's R peak occurs right before the 'HIJ' complex of the MCG, also similar to the reference used in Figure 1. At the same time during the MCG recordings, body positions are also detected. Table 3 shows the results from all test subjects.

| | **Body Position** | | | | | |
|---|---|---|---|---|---|---|
| | Standing | Sitting | Lying left | supine | Lying right | prone |
| **Subject 1** | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| **Subject 2** | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | null |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| **Subject 3** | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| **Subject 4** | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,-1 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,0,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,0,-1 | 0,0,1 |
| **Subject 5** | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |
| | 1,0,0 | 1,0,0 | 0,-1,0 | 0,0,-1 | 0,1,0 | 0,0,1 |

Table 3: Body position detection results.

The resulting corresponding g values displayed above are based on the threshold value method, where the decision is based on the LT and HT decision points of Table 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 (highlighted in grey in Table 3) do not match the expected values shown in Table 2. The three errors came from lying on the right side position of a single subject. Two possible explanations are:

1) Lying on the right and left side position can be difficult since human body is narrow on the sides and one arm will be under the weight of the body, which might cause discomfort that will cause the subject to adjust to positions that poorly represent the ideal side positions.

2) The signal cable used can interfere with the change of movements. The data extraction system is setup on the left of the subject. The length and regidity of the data cable does not allow much for extra movements.

A testing setup diagram is shown in Figure 6 below. The overall body position detection accuracy obtained from this experiment is 97.71%.

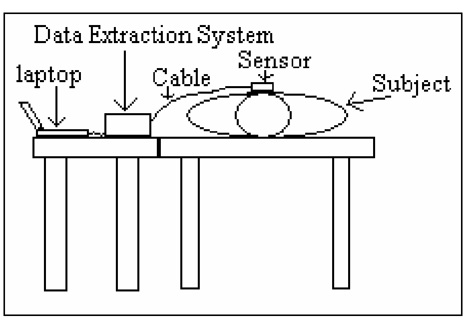


Figure 6: Setup with subject in the lying supine position.

## 5 FUTURE RESEARCH

Multiple 3-axis BCG sensors can be placed in different positions of the body to detect the existence of addition mechanical information of the heart that might have been missed during the sternum recordings. For example, an additional sensor mounted on the thigh of test subject enables the detection of sitting.

The detection of body movements such as jogging, jumping, or falling may also be achieved by applying various software processing techniques. Further research and testing are currently undergoing.

## 6 CONCLUSION

Through the recent advancements in MEMS technology, tiny accelerometer chips integrated as multifunctional smart physiology sensors for bio-medical applications open new doorways to more convenient and comfortable methods of detecting the mechanical movements of the heart and body position simultaneously. Such a multifunctional, wearable system was developed, and its performance assessed. The overall body position detection accuracy obtained from the experiments is 97.71%. This study also showed MCG valid signals can be recorded using the novel multifunctional sensor not only in the lying supine position, but also for positions such as standing, sitting, and lying in other directions. Such results suggest a potential for the multifunctional sensor for long-term patient monitoring in regular day-to-day environments, and various other health monitoring applications.

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