Sensor Module for Detecting Postural Change and Falls
G. R. Jeon¹, S. J. Ahn², B. J. Shin³, S. C. Kang⁴, and J. H. Kim⁵,*

Abstract

In this study, a postural change detection sensor module (PCDSM) was developed to detect postural changes in activities of daily living (ADL) and falls. The PCDSM consists of eight mercury sensors that measure angle variations in 360° rotation and 90° tilting. From the preliminary study, the output characteristics of the PCDSM were confirmed with the angle variations of rotational motion and a tilting table. Three experiments were conducted to test rotational motion, postural changes, and falling and lying. The results confirmed that the PCDSM could effectively detect postural changes, movement patterns, and falls or non-falls.

Keywords: Falls, Activities of daily living (ADL), Postural change, Tilt sensor, Ubiquitous healthcare

1. INTRODUCTION

Along with the development of science and technology, our modern society faces a rapid increase in the elderly population. Resulting from a declining birth rate and increasing life expectancy, we are part of an aging society [1]. Consequently, various facets of the “silver industry” are booming to accommodate the needs of the elderly population, which has caused a medical paradigm shift. Dykes et al. developed a fall prevention tool kit (FPTK) [2]. Aminian et al. studied an ambulatory system for the estimation of spatio-temporal parameters during long periods of walking [3]. Yang et al. reviewed the working principles, capabilities, and various applications of accelerometry-based wearable motion detectors for monitoring and assessment of physical activity [4]. Williamson et al. studied that the gyroscope signal was integrated to an angle estimate [5]. Rueterbories et al. analyzed the existing methods for monitoring gait and detecting gait events [6]. Goldberg et al. reviewed that knee flexion velocity at toe-off plays in the stiff-knee gait associated with cerebral palsy [7]. Mansfield et al. studied the potential of accelerometry to detect gait events [8]. Moreover, with the development of electronics, information and communication technology (ICT), and biomedical engineering, the use of portable medical devices are increasing steadily.

In addition, convenient and non-invasive medical devices are gaining popularity, while research on portable medical devices and remote home healthcare systems is gaining steam. For example, in Japan, a wristwatch (BP-1, Casio, Japan) [9] that estimates blood pressure and measures the heart rate after acquiring an electrocardiogram (ECG) and a photoplethysmogram (PPG), is commonly used. Companies like Technogym (Italy) [10] and Polar (Finland) [11] have combined biomedical instruments with fitness equipment, enabling users to monitor their heart rates during activity of daily living (ADL) by attaching sensor to their chest.

In this study, a postural change detection sensor module (PCDSM) was developed for application in ubiquitous healthcare. The PCDSM can detect the rotation, the angle of movement, and the speed of movement in real time during ADL and falls without the use of a three-axis accelerometer. The PCDSM has several advantages. A PCDSM consists of a mercury switch module has a simple configuration and easy to wear compared with a three-axis accelerometer. Furthermore, a PCDSM can recognize postural changes and falls without a software program for analysis and monitoring.

After the preliminary study was performed using tilting table, the PCDSM measured the angle variation of the tilting table while...
the subject lay on it. After preliminary study, three experiments were conducted to evaluate the performance of the PCDSM. First, the PCDSM evaluated the performance when the subject moved in the forward or backward directions while stationary. Second, the PCDSM evaluated the performance when the subject rotated laterally from left to right. Third, the PCDSM evaluated the performance when the dummy falls in the forward or backward directions from standing upright to lying down ground.

2. PCDSM

2.1 Fabrication of PCDSM

The PCDSM was fabricated to detect rotational motion, the angle and speed of movement, tilt change, and falls. Fig. 1 shows the diagram and photograph of the PCDSM components. The PCDSM is composed of an enclosed cylindrical glass with two pins placed on one side. The PCDSM is operated by the following principle. When the cylinder is tilted, mercury acts like a switch as it flows from one side to the other, causing the two pins to connect (ON) or disconnect (OFF) [12,13]. Mercury was chosen specifically because it is a fluid substance that has a high electric conductivity \(10^6 \Omega^{-1}\) at 20°C and high surface tension (486.5 dyne cm\(^{-1}\) at 20°C) [14,15].

Because mercury is harmful to the human body, necessary measures for preventing mercury leakage, even in worst case scenario, were established as follows. First, cylinder was sealed after injecting the mercury in the column. Second, the printed circuit board (PCB) of the PCDSM was molded with silicon for shock mitigation in order for the mercury column to be broken by an external impact. Third, the sponge was inserted between the cases of the PCDSM and PCB.

2.2 Operating Principle of PCDSM

Fig. 2 shows the operating principle of the PCDSM when the subject is tilted from a standing upright position to the forward direction. In the illustration, S2 indicates the primary forward sensor mounted vertically on the board (as shown in Fig. 1), and S1 indicates the secondary forward sensor tilted down to an angle of 15° with respect to the primary forward sensor (S2). The operating principle of the PCDSM is as follows. When the subject is standing upright, both S2 and S1 are in the “OFF” state because the mercury does not move in S2 and S1. When the subject is tilted forward direction less than 15°, S2 is turned “ON”. When the subject is tilted to the forward direction more than 15°, S1 is turned “ON” after S2 is turned “ON”.

Fig. 3 shows the response time while the subject is falling forward. When the subject is rapidly falling forward, the time taken for S2 and S1 to turn “ON” is shorter. This result suggests that the PCDSM is able to discriminate between falls and ADL with a large impact such as jumping. The operating principle of the PCDSM, when the subject is tilted backward or laterally, is the
same as in the forward direction. In addition, the PCDSM can measure the degree of the tilt (forward, backward, left, or right), enabling accurate estimation of the current postural state and the process of postural changes. Thus, the PCDSM can be used as an efficient tool for detecting emergency situations.

2.3 Preliminary Evaluation of PCDSM

To verify proper operation of the PCDSM, a preliminary study was performed using a tilting table. The angle of the tilting table was changed to 0°, 15°, 45°, and 90°, respectively with the subject lying on the tilting table. By comparing the angle of the tilting table with the sequential signal of the PCDSM, proper operation of the PCDSM was confirmed.

Fig. 4 shows the output results of the PCDSM in response to the angle variation of the tilting table. As shown in Fig. 4(a), Sensors S3, S4, S5, and S6 were turned “ON” when the subject lay flat on the tilting table. When the table was tilted to an angle of 15°, 45°, 75°, and 90° from the horizontal direction, as shown in Figs. 4(b-e), the output signals of the PCDSM were turned “OFF” in sequential order, as shown in the illustration.

3. EXPERIMENTAL RESULTS

3.1 Experimental Group

Fifteen subjects (eight males and seven females) between the ages of 24 and 32 participated in this research. The mean age of the subjects was 28 ± 4, and the average weight was 61.5 ± 7 kg. The purpose and method of this study were explained to the subjects prior to the experiment, and their consents to participate were obtained. The PCDSM was attached to the sternum of the subjects and postural changes were investigated via a variety of movements, rotations, and falls.

3.2 Detection of Rotation and Falls

The PCDSM responses were observed when the subject was tilted forward or backward and rotated in the lateral direction. Fig. 5 shows the results of the PCDSM when the subject was tilted forward or backward. When the subject was tilted forward, Sensors S2, S1, S8, S7 or S2, S1, S6, S5 were turned “ON” sequentially. And when the subject was tilted backward, Sensors S4, S3, S6, S5 or S4, S3, S8, S7 were turned “ON” sequentially.

Fig. 6 shows the results of the PCDSM when the subject was rotated left or right. When the subject was rotated to the left, Sensors S8, S7, S2, S1 or S8, S7, S4, S3 were turned “ON” sequentially. And when the subject was rotated to the right, Sensors S6, S5, S2, S1 or S6, S5, S4, S3 were turned “ON” sequentially.

Fig. 7 demonstrates the correlation between the operation procedure and the elapsed time of the PCDSM. The subject was
tilted forward or backward until he/she was lying on the ground. And the dummy fell forward or backward until it touched the ground. Fig. 7(a) and Fig. 7(b) represent the operation procedure and the elapsed time of the PCDSM when the subject was tilted forward or backward from standing upright. The mean value of the elapsed time was obtained using a stopwatch 10 times when the subject tilted forward or backward. The operation procedure of the PCDSM represents sequential operation of the PCDSM sensors when the subject was tilted forward or backward from standing upright, after the PCDSM was attached to the subject’s sternum. 

The brief descriptions of Fig. 7(a)-(d) are as follows. Fig. 7(a) represents the operation procedure and the elapsed time when the subject was tilted forward until he/she lay down on the ground. The time it took for the subject to tilt forward and lay on the ground was 3.41 s. The tilting process was as follows. While standing, the subject bent his or her knee 30°, the arm swept 45° in the forward direction, the waist tilted forward 45°, the knee bent to touch the ground, the ankle then became parallel to the ground, the waist bent to touch the ground, and both hands stretched forward. Fig. 7(b) represents the operation procedure and the elapsed time of the PCDSM when the subject was tilted backward until he/she lay on the ground. The elapsed time was 4.21 s when the subject was tilted in the backward direction from standing upright until lying on the ground. The tilting process was as follows. The subject bent his or her knee to 30° from standing upright, the knee was bent parallel to the ground at 50° and the subject squatted, the arm stretched 30° in the backward direction, the subject positioned his or her hips to touch ground, the waist bent in the backward direction to touch the ground, and both arms stretched 45° in the lateral direction to touch the ground. Fig. 7(c) represents the operation procedure and the elapsed time of the PCDSM when the dummy fell forward until it lay on the ground. The elapsed time was 1.43 s when the PCDSM Sensors S2, S1, S8, S7 or S2, S1, S6, S5 turned “ON” sequentially. Fig. 7(d) represents the operation procedure and the elapsed time of the PCDSM when the dummy fell backward until it lay on the ground. The elapsed time was 1.34 s when the PCDSM Sensors S4, S3, S6, S5 or S4, S3, S8, S7 turned “ON” sequentially. The difference in the elapsed time between Fig. 7(a) and Fig. 7(b) resulted from the directions in which the subject was tilted. The difference in the elapsed time between Fig. 7(c) and Fig. 7(d) was caused by the direction of the dummy’s fell.

Table 1 shows the time difference when the PCDSM sensors turn “ON” and the time it takes for the dummy to fall forward or backward until it is lying on the ground. The lighting-up time difference of the PCDSM’s sensors represents the total elapsed time and the time interval between when the dummy fell
Table 1. Total elapsed time and time differences when the dummy fell forward and backward from standing to lying on the ground.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Falls Times [s]</th>
<th>Time difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forward fall</td>
<td>Backward fall</td>
</tr>
<tr>
<td>1</td>
<td>1.41</td>
<td>1.36</td>
</tr>
<tr>
<td>2</td>
<td>1.37</td>
<td>1.28</td>
</tr>
<tr>
<td>3</td>
<td>1.51</td>
<td>1.42</td>
</tr>
<tr>
<td>4</td>
<td>1.45</td>
<td>1.38</td>
</tr>
<tr>
<td>5</td>
<td>1.35</td>
<td>1.29</td>
</tr>
<tr>
<td>6</td>
<td>1.38</td>
<td>1.27</td>
</tr>
<tr>
<td>7</td>
<td>1.47</td>
<td>1.39</td>
</tr>
<tr>
<td>8</td>
<td>1.49</td>
<td>1.41</td>
</tr>
<tr>
<td>9</td>
<td>1.44</td>
<td>1.36</td>
</tr>
<tr>
<td>10</td>
<td>1.43</td>
<td>1.34</td>
</tr>
<tr>
<td>Mean</td>
<td>1.43</td>
<td>1.34</td>
</tr>
</tbody>
</table>

forward and backward from standing until lay on the ground. The difference in the total elapsed time between when Sensors S2, S1, S8, S7 were all “OFF” and were all “ON” was measured when the dummy fell forward. This difference was also measured for when Sensors S4, S3, S6, S5 all “OFF” and all “ON” when the dummy fell backward. In addition, the time difference for the increase in the acceleration interval between 45° (S8 and S7 are “OFF” in the forward direction, S6 and S5 are “OFF” in the backward direction) and 90° (S8 and S7 are “ON” in the forward direction, S6 and S5 are “ON” in the backward direction) was measured.

The average elapsed time was 1.43 s when the dummy fell forward, and the mean value of the elapsed time was 0.37 s, which was obtained by determining the average of 10 fall measurements. The elapsed time was measured from the time the PCDSM Sensors S8 and S7 went from all “OFF” to all “ON”. The average elapsed time was 1.34 s when the dummy fell backward, and the mean value of the elapsed time was 0.35 s, which was obtained by determining the average of 10 fall measurements. The elapsed time was measured when the PCDSM Sensors S6 and S5 were from all “OFF” to all “ON”.

The results from Fig. 7 and Table 1 show that there are significant differences in the elapsed time between the subject’s tilt and the dummy’s fall. In the study, the tilt experiments were performed on the subjects standing upright, and then, moving them forward and backward. Fall experiments were performed on the dummy using similar movements. The Ethics Committee of the Pusan National University Yangsan Hospital did not allow us conduct fall experiments on the subjects. Therefore, we assume that there are some limitations in our evaluation of the PCDSM’s performance and the elapsed time for subjects to fall or tilt in an ADL environment.

As demonstrated in these experiments, the elapsed time difference clearly occurs when subjects tilt or fall from standing to forward or backward. This study can help detect falls that occur frequently in the ADL environment.

4. CONCLUSIONS

In this study, the PCDSM detected posture changes, and the experiments were performed to evaluate the mechanism’s performance.

The performance of the PCDSM was evaluated when the subject was tilted forward, backward, left, or right. The performance of the PCDSM was also evaluated when the angle of the tilting table varied from 0°, 15°, 45°, 75°, to 90° so that, eventually the subjects lay horizontally on the tilting table. Furthermore, the elapsed time from when the subjects stood upright until the subject lay on the ground was also measured. Similar measurements were taken for the dummy.

As a result of these experiments, the following conclusions were derived.

1. When the subject was tilted forward, backward, left, or right, and the dummy fell forward or backward, the results of the PCDSM confirmed that the PCDSM could effectively analyze each postural change and monitor the movement pattern.

2. The PCDSM detected all postural changes accurately when the subject’s posture changed from standing upright to supine position.

3. We measured the time it took for the subjects to tilt forward or backward from an upright position to lying on the ground. The measured time was 3.41 s for a forward tilt and 4.21 s for a backward tilt. However, the measured time for the dummy was 1.43 s for a forward fall and 1.34 s for a backward fall. Thus, the PCDSM can be used to differentiate between a tilt and a fall.

The results confirmed that the PCDSM can effectively detect postural changes, movement patterns, and falls or non-falls. Therefore, the PCDSM can be utilized in the ubiquitous health and mobile health environment.

ACKNOWLEDGMENT

This work was supported by a 2-year Research Grant of Pusan National University.
REFERENCES


