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# The Hardware of Portable and Wireless Physical Activity Recorder with Triaxial MEMS Accelerometer for Short-Term and High Intensity Physical Activities

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**Abstract:** The present study describes the development of a tri-axial accelerometer Physical Activity Monitoring system (PAMs) for the assessment of daily physical activity amplitude and frequency ranges and estimate energy expenditure. The PAMs is a wireless and small portable data-logger system that uses a selective and high range (±2.5 - ±10 g) tri-axial Microelectromechanical Systems (MEMS) accelerometer. In contrast with low range accelerometer data loggers in the market, PAMs has selectable sensitivity range (2.5-10 g) triaxial accelerometer capable of attachment of three external triaxial accelerometers in a 6×4×1.5 cm size and light weight (25 g). Physical activity monitoring system can be attached to the waist and external accelerometers can be strapped to the limbs to record three dimensions acceleration in multi locations. The PC software has been developed to demonstrate the recorded activities and save under personal database. Dynamic accelerations in each axis recorded on MicroSD card to be meaningful and interpretable for the researchers. It was laboratory tested for linearity and noise for the triaxial accelerometer. Noise RMS (0.1-1 k Hz) was 4.8 mVrms and power spectral density RMS (0.1-1 k Hz) was 350 µg $Hz^{-2}$. Maximum Nonlinearity was 0.2 g. Test-retest reliability was very high for dynamic tests in three axes (r values ranging from 0.89 to 0.95). Test-retest experiments showed that the offset and the sensitivity of the accelerometer were equal for each measurement direction and remained constant on three measurement days.

**Key words:** Physical activity, triaxial accelerometer, energy expenditure, data logger

## INTRODUCTION

Assessment of physical activity in a free-living environment is imperative for knowing relations between physical activity and health and effects of our interventions (Westerterp, 2009). Many techniques have been using to assess human movements including observation, questionnaires, diaries, motion sensors and physical science technologies (foot switches, gait mats, force plates, optical motion analysis). Many of these techniques have clear disadvantages for continuous analysis such as the physical activity monitoring technologies (Culhane *et al*., 2005). Quantitative measurement of the energy consumed during physical activities has generated considerable interests from various groups ranging from exercise physiologists to nutritionists and fitness centre workers (Jang *et al*., 2005). In recent years, a growing numbers of portable devices have become available in the market for physical activity monitoring (Fujiki *et al*., 2009; Meamarbashi and Burhanuddin, 2006; Welk *et al*., 2007; Westerterp, 2009; Wolinsky and Driskell, 2007) ranging from mechanical pedometers and actometers to electronic accelerometers (Bouten *et al*., 1997; Fruin and Walberg Rankin, 2004; Zhang *et al*., 2003).

A pedometer is an small, simple and noninvasive mechanical movement counter that is clipped to a belt at the waist or worn on the ankle (Corder *et al*., 2007; Fostera *et al*., 2005; Zhang *et al*., 2003). Similar devices such as wrist/ankle watches and actometers also exist (Fruin and Walberg Rankin, 2004; Zhang *et al*., 2003). The main shortcoming of pedometers is that they are not sensitive to gait differences such as stride length, which is significantly vary among person to person activities (Zhang *et al*., 2003). Because pedometers cannot assess the intensity of physical activity and can not detect vertical movements therefore accelerometers were designed (Welk *et al*., 2007).

Estimation of physical activity energy expenditure is based on measuring movement of the body's centre of mass (Troiano, 2006). There are evidences that a linear relationship does exist between body acceleration and oxygen uptake, making the accelerometer a reasonable device for measuring physical activity or energy expenditure (Kreshel, 2002). Thus, accelerometers have become the preferred choice for continuous, unobtrusive and reliable method in human movement detection varying from very high intensity movements (Meamarbashi, 2009) to low and moderate movements (Godfrey *et al*., 2008). Accelerometers are very precise, stable and capable of providing an indication of reliability and objectiveness (Welk *et al*., 2007). Accelerometers can provide information about the total amount, the frequency, the intensity and the duration of physical activities (Westerterp, 2009). Furthermore, accelerometer-based physical activity instruments can provide objective data on levels of physical activity and energy expenditure (Welk *et al*., 2007). A uniaxial accelerometer measures acceleration in the vertical plane, whereas biaxial and triaxial accelerometers are sensitive to movements in two and three dimensions. Because acceleration increases in three dimensions with faster movements, theoretically, triaxial accelerometers should accurately determine energy expenditure across a wide range of exercise intensities (King *et al*., 2004).

Earlier researches have been demonstrated a significant relationship between accelerometer output and energy expenditure due to physical activity (r = 0.89). (Welk *et al*., 2007). While, accelerometers are commonly used in behavioral, clinical and epidemiological research, there are many challenges that must be overcome to improve measurement accuracy (Welk *et al*., 2007). Accelerometer data, generally expressed as the dimensionless unit, counts, are inherently neither meaningful nor interpretable (Troiano, 2006). Translating counts into a quantitative estimate of caloric expenditure or the related categorical measure of time spent in moderate or vigorous-intensity activity makes the data more useful for multiple applications (Troiano, 2006). Although, studies have been done with multiple accelerometers being worn on the trunk and extremities but most frequent placement is the waist. It is well recognized that waist-mounted accelerometers cannot accurately detect upper body movements or the effort related to lifting or carrying loads (Troiano, 2006). Although, accelerometer is sensitive to dynamic movements and insensitive to static study, the generally assumed that most of the energy expenditure throughout the day is due to walking and alike dynamic movements (Kreshel, 2002).

In many circumstances it is essential to study whole body movements (Godfrey *et al*., 2008). Different placement of accelerometer on the body, despite its apparent significance, received little consideration (Fujiki *et al*., 2009). This is best represented by placement of a sensor as close as possible to the centre of mass of the body, such as the sternum, under arm or waist (Bouten *et al*., 1997). Generally, body-fixed accelerometers for physical activity assessment are worn at waist level with amplitude range of about 6 g and up to 20 Hz (Bouten *et al*., 1997).

One of the fundamental challenges is to determine the most appropriate calibration equations and cut-off points for accelerometer data processing (Troiano, 2005; Ward *et al*., 2005). Developing accurate calibration equations with accelerometers has been challenging for several reasons. One factor is differences between in the body size that influence the movement counts associated with physical activity (Welk, 2005). Calibration equations have been shown to provide valid estimates for group level comparisons, but these equations have not been shown to be accurate for individual-level estimates (Welk, 2002).

Accelerometers have become the preferred choice for continuous, unobtrusive and reliable in human movement monitoring. Technological advancement in MEMs accelerometers, low power microcontrollers and wireless communications have enabled the design of low-cost, miniature, lightweight data loggers in the field of physical activity monitoring. New triaxial accelerometers are small sensors and minimally intrusive to normal subject movement (Midorikawa *et al*., 2007). Therefore, in the study attempted to development a small wireless data logger with triaxial accelerometer equipped with MicroSD card for the assessment of short-term and high intensity physical activities. The accelerometer range is selectable due to different intensity of activities up to 10 g and extra external accelerometers can be connected to be able in registering multi-limbs acceleration and thereafter distinguish pattern of activity and precise estimation of energy expenditure.

## MATERIALS AND METHODS

This data-acquisition unit has been designed to record three dimensional dynamic movements based on multi sensor locations to estimate physical activity. A selective measurement range (2.5-10 g) triaxial accelerometer from Free scale Semiconductor Inc. (Chandler, AZ, USA) applied to measure human body acceleration. A picopower AVR microcontroller with 2 Kbytes RAM and 1 Kbytes EEPROM (electrically erasable programmable read-only memory) was implemented in this project and connected to a high capacity MicroSD card (32MB-2 GB). Microcontroller programmed to record 3D acceleration with high resolution (0.01 m sec$^{-2}$) at 60 Hz using 8-channels 16 bits analog to digital (A/D) data converter from Texas Instrument ,Inc., into 2 Kbytes RAM and then save the average acceleration into MicroSD card via SPI (serial peripheral interface) port. A port for connection external accelerometers to A/D converter was made. Small and low power RF transmitter module was connected to the microcontroller serial port for transfer data in the online measurements mode.

PC software developed to download the recorded data and compute the energy expenditure based on weight, age and sex of the subject and magnitude of dynamic acceleration in three dimensions. In the current system vertical (Z-axis) and horizontal (Y-axis) acceleration components were isolated and classifying the physical activity intensity and PC software estimating energy expenditure.

**Accelerometer validation:** With a completed working prototype, the functionality of the PAMs was first validated through various controlled experiments in the laboratory on the University of Mohaghgh Ardabili in December, 2008. Dynamic tests more frequently used to test the accelerometer in the laboratory. In this study, method or Lynch *et al.* (2001) was used. In the first validation experiment, the prototype unit is fixed with three screws on a flat static laboratory surface and recorded the acceleration data from the built-in triaxial accelerometer on MicroSD card (Lynch *et al.*, 2001) (Fig. 1, 2).

In the second experiment, the prototype is tested for performance characteristics during sinusoidal excitations. By mounting the prototype upon a single-axis shaking table, sinusoidal input excitations generated for each axis. The acceleration data was saved on MicroSD card and then processed by the custom PC software. The overall dynamic performance of each sensors axis was obtained by superimposing the measured data upon the dynamic movements of the shaking table.

The last test was a laboratory evaluation on three male and young subjects (mean age, 22±1 years; mean weight 81±2 kg) to run on a treadmill. The PAMs was attached to a custom made pouch attached to their belt and worn at waist level at the right anterior axillary line. Participants performed treadmill walking at 5, 10 and 15 km $h^{-1}$ for 10 min with a minimum of 5 min rest between each treadmill speed. During the rest interval, participants were allowed to drink water but were not permitted to eat food or drink any carbohydrate-containing beverages. No inclination was employed and trials were performed in 25°C and 55% relative humidity.

**Software:** Professional software has been developed under Delphi™ to connect with PAMs and download the data and save in personal database. Second part of software is data analysis and demonstration of the results. Here, plotted graph can be transport to other documents like PDF, Excel, JPG, GIF, BMP, HTML or text. The third section is data assessment and comparison of the personal results or between group of subjects.


Fig. 1: Triaxial accelerometer (top view)

Fig. 2: Triaxial accelerometer (bottom view)

**Data processing:** Downloaded acceleration data from the three axes of the built-in triaxial accelerometer as well as external accelerometers were converted from mV into g using the calibrations parameters of each accelerometer axis output. Each axis output smoothed and gravity (1 g) deducted from the integral of magnitude of the total acceleration vector (IAV) according to Eq. 1.

$$IAV = \int_{t=0}^{T} \sqrt{a_x^2 + a_y^2 + a_z^2}\, dt \qquad (1)$$

where, $a_x$, $a_y$ and $a_z$ are the average acceleration of X,Y and Z directions per second.

In this phase of the project the objective was determine the dynamic acceleration as the raw data to predict energy expenditure in the second phase. Therefore, the dynamic acceleration derived from IAV was compared in three different speeds of the laboratory trials on treadmill.

**Statistical analysis:** SPSS software (SPSS, Chicago, Illinois) was used for the statistical analysis (version 15.0). The level of significance was set at $p<0.05$. Results are reported as Means±SD. Simple regression was used for the laboratory tests.

## RESULTS

A light and small wireless data logger (6×4×1.5 cm, 25 g) produced. It was laboratory tested for linearity and noise for the triaxial accelerometer. Noise RMS (0.1-1 k Hz) was 4.8 mVrms and power spectral density RMS (0.1-1 k Hz) was 350 µg $Hz^{-2}$ and maximum nonlinearity was 0.2 g. Test-retest reliability was very high for dynamic tests in three axes (r values ranging from 0.89 to 0.95).

Test-retest experiments showed that the offset and the sensitivity of the accelerometer were equal for each measurement direction and remained constant on three measurement days. Nonlinearity for each axis was about ±1% FSO (full scale output). The correlation coefficients between the three different speeds of treadmill and magnitude of the total acceleration vector (IAV) were very high ($r = 0.96$; $p<0.01$).

**Hardware:** Figure 3 demonstrated the final printed circuit board of the data logger designed by Protel™. Figure 4 showing complete PAMS prototype connected to a battery charger.

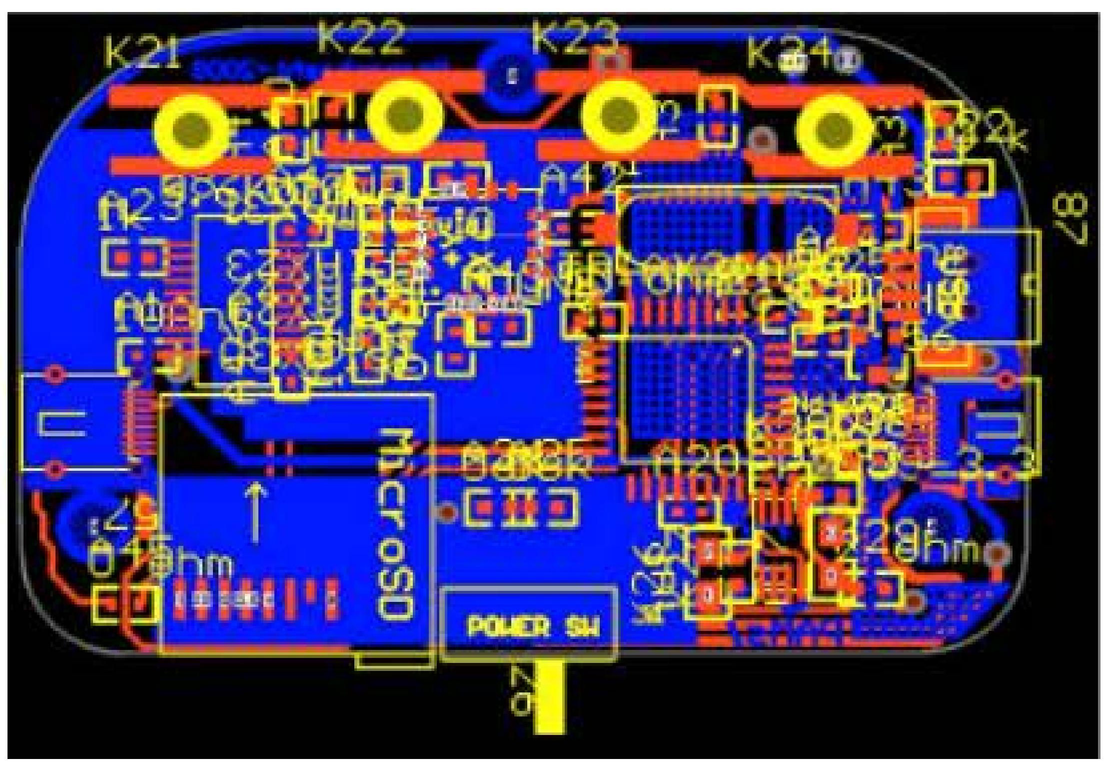


Fig. 3: The PAMs printed circuit board

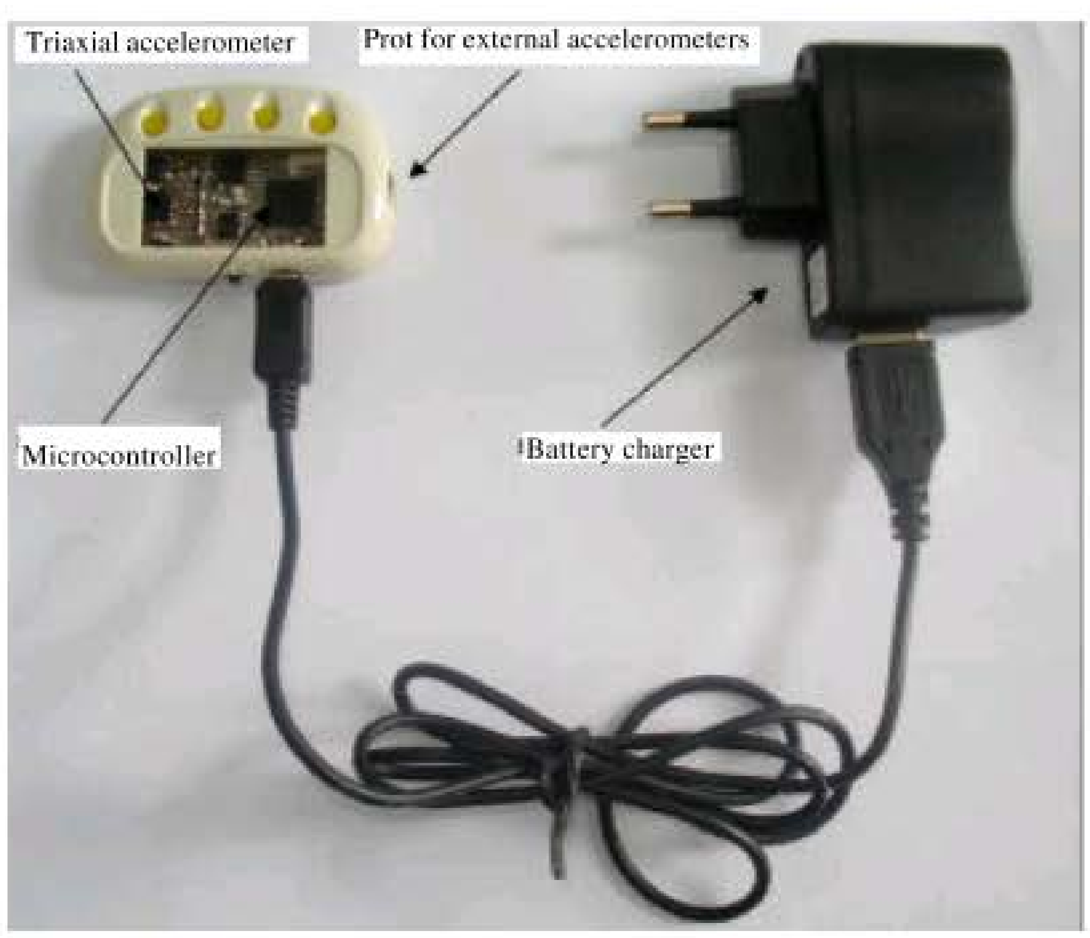


Fig. 4: PAMs prototype

After completion of the prototype, the final product was fabricated and shown in Fig. 4. Figure 4 shown the final product that can attach to the subject and external accelerometer can be connected to it. The battery is rechargeable by connect the charger to the battery charger socket.

## DISCUSSION

In this stage, this device showed very high validity and reliability to measure dynamic accelerations. The broad rang of measurement afforded opportunity to implement it in high and low intensity activities. The online and offline measurement features of this system and possibility of using external accelerometers are the advantages over current systems in the market.

## CONCLUSIONS

Accelerometry is a tool that is suitable for short and long-time monitoring of free-living subjects because it can provide objective and low cost reliable physical activity monitoring. A wide range of measures including classification of movements, assessment of physical activity level and estimation of metabolic energy expenditure can be reliably obtained by this system. The high measurement range of this product covers all the low and high intensity physical activities acceleration. Table 1 compared the features of most frequent data loggers using in the physical activity monitoring.

The higher range accelerometer, external accelerometers, high memory card capacity and wireless transmission of data during the recording are the advantages of current data logger compare with the other systems in the market. The qualitative and quantitative data provided by this system is very promising to use in athletes trainings and physical activity monitoring due to high resolution, high sampling rate and multi-locations placement of the triaxial accelerometers.

Table 1: Comparison between some physical activity monitoring data loggers

| Variables | ActiCal | MTI | RT3 | Yamax |
|---|---|---|---|---|
| Size (cm) | 2.8×2.7×1.0 | 5.1×3.8×1.5 | 7.1×5.6×2.8 | 5.1×3.8×1.9 |
| Weight (g) | 17 | 42.6 | 65.2 | 21.3 |
| Acceleration range (G) | 0.05-2.0 | ±2.13 | 0.05-2.0 | N/A |
| Frequency range (Hz) | 0.50-3.0 | 0.21-2.28 | 0.50-10 | N/A |


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