An Improved Calculation Method for Activity Energy Expenditure by using PNS

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Abstract

In daily life, walking is one of the most energy consumed activity. There are many researches' focuses on energy expenditure estimation using GPS and 3-axis accelerometer for location tracking and activity monitoring. However, in the case of walking on a slope, GPS location tracking method and 3-axis accelerometer method are failed to estimate the energy consumption while walking on a slope. In this study, we combine the information of GPS in smart phone, the information of foot-mounted IMU and also the slope information from Google elevation database to estimate activity energy expenditure. Energy expenditure in static movement is calculated using accelerometer data. Therefore, the energy expenditure calculator is capable to calculate energy expenditure in static movement and also in dynamic movement. Experiment result shows that the increase in elevation in slope, there is an increase in activity energy expenditure. We also show there is higher energy expenditure when jumping.

Keywords: *energy expenditure, location tracking, PNS(Pedestrian Navigation System)*

1. Introduction

The existing measurement method for energy expenditure is very expensive and the measurement systems are also bulky in size. A lot of researches have also been carried out to formulate energy expenditure estimation [1-3]. Last time, people used mechanical counter to detect the number of steps in order to calculate energy expenditure. But now, using Micro Electro Mechanical System (MEMS) has become the main stream. The linear relationship between walking speed and acceleration distribution or walking frequency for accurate energy expenditure estimation has also been studied in literature [4]. In this paper, a pedestrian dead-reckoning (PDR) system has been developed using foot-mounted IMU. PNS (Pedestrian Navigation System) is a combination of the PDR and GPS system. The moving speed is calculated using PNS. The change in slope is estimated using Google Elevation API information [5]. GPS vertical error can be improved using the elevation information available in Google elevation API. We compare our energy expenditure estimation result with American College of Sports Medicine (ACSM) guidelines (2006) [1] and we suggest a new formula for energy expenditure estimation.

2. Energy Expenditure System

GPS has an error tolerance of up to 1 meter. This error is insignificant in automobile tracking but become significant in pedestrian tracking, as human foot step size is usually less than 1 meter in length. In this study, GPS position estimation is first being improved using PDR, then the resulting path is further calibrated using the height information available in Google elevation database. Activity energy expenditure estimation is calculated based on the final outcome path (GPS + PDR + elevation path).

2.1. GPS Data Processing

Global Positioning System (GPS) is a space-based global navigation satellite system [6]. GPS data include latitude, longitude, altitude, time, and signal error data. However, GPS has error due to multipath and ionosphere. Therefore, GPS receive signal with an unavoidable timing error, resulting a frequent change in signal sensitivity. The received GPS data by default included with GPS error data. We remove any GPS error data if there is more than 9 meter and above. Then, GPS data with leading time lapse of <5 seconds will be removed to reduce timing error caused by non-quality signal transmission.

2.2. GPS Data Processing

The initiative of this study is to track the pedestrian foot step using foot mounted IMU system. IMU measures the foot acceleration (Af) using equation (1).

$$A_f = \sqrt{{A_{fx}}^2 + {A_{fy}}^2 + {A_{fz}}^2} \quad (1)$$

Af is a representative parameter which includes foot acceleration, gravitational acceleration and mechanical error. Foot posture varies from time to time during walking. Swing phase is to represent mechanic noise. We divide the walking phase into two phase, namely stance phase and swing phase. When the foot is on the ground, we named it as stance phase. When the foot is away from the ground, we named it as swing phase.

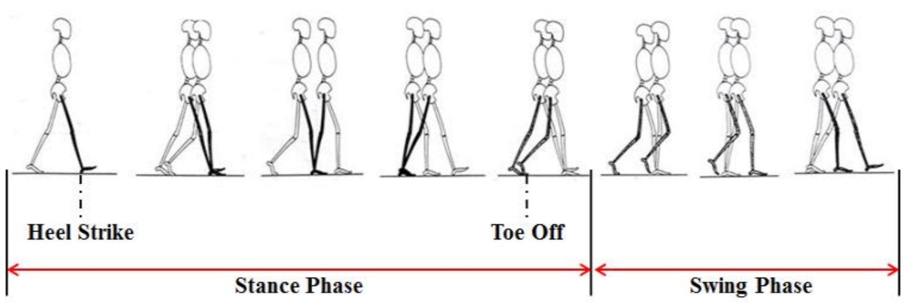


Figure 1. Graphical expression for walking phase: Stance phase and Swing Phase

The acceleration of gravity in Af is supposed to be measured at a fix 9.81m/s2 at stance phase. However due to the error incurred by motion artifact the Af is not measuring at a fixed 9.81m/s2. Figure 2 shows the Af in stance phase and swing phase, and it also shows the Af is not measuring at a fixed 9.81m/s2.

In the determination of stance phase, we measure the Af at a standing still position for 10 seconds. Within the 10 seconds, the average acceleration is 0.12m/s2, and maximum acceleration is 0.35m/s2. Considering the worse case, we let a threshold value, Thp of 0.7m/s2 to be the border line in determining stance phase. The equation of determining the Thp is shown in equation (2).

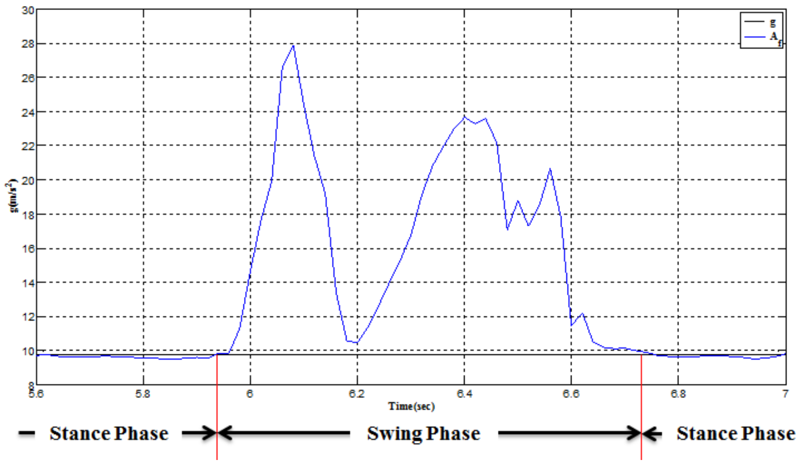
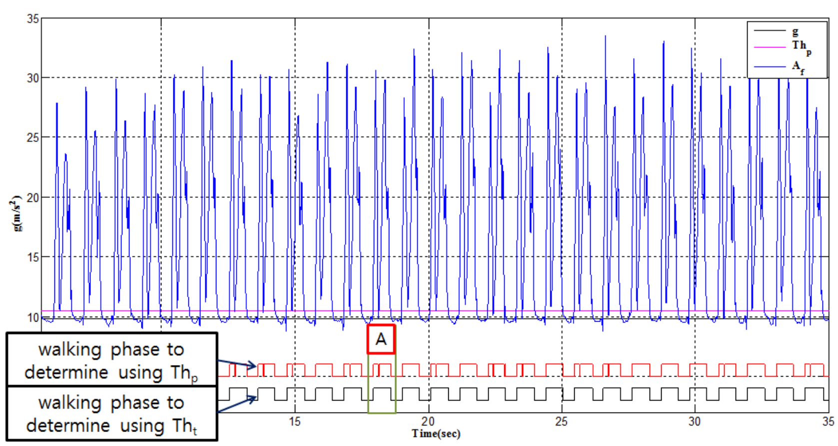


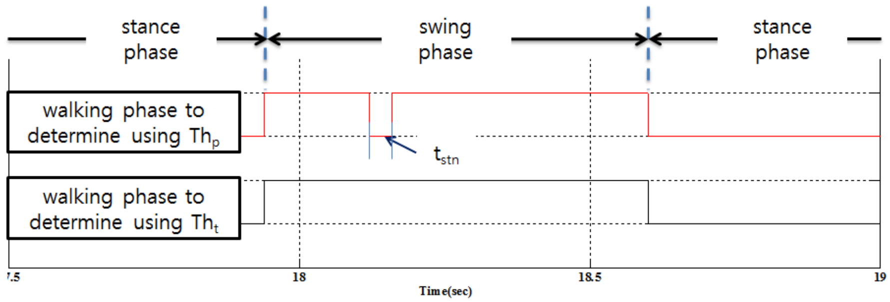
Figure 2. Acceleration of Foot in Walking (Af)

$$\mathrm{Ph_p} = \begin{cases} 0, & \text{if } \mathrm{A_f} \leq \mathrm{A_f} \pm \mathrm{Th_p} \\ 1, & \text{other} \end{cases} \qquad (2)$$

Stance phase and swing phase can be distinguished in most of the time by using equation (2). However, there is an occasion that a short stance phase is seen to be appeared in swing phase as shown in figure 3(b). The Af in swing phase is having a randomized characteristic and at some instance of time, the value of Af may be measured below the threshold value of 0.7m/s2 and this causes a short stance phase appear in swing phase. In order to remove the short stance phase in the swing phase, we applied a 0.2s threshold Tht in post calculation. As a normal walking pace for human are 120 steps per minute, the time interval between one steps is 0.5s or more [7]. Thus, applying a 0.2s threshold is practically not affecting the normal stance phase. The updated formula of calculating Ph is shown is equation (3). After applying the 0.2s threshold (Tht), the Af calculation is refined and no short stance phase is seen in the swing phase. The result is shown in figure 3(b).



(a)



(b)

Figure 3. (a) Determine Walking Phase (b) Zoom in View of A area in (a)

We calculate the speed from foot acceleration in swing phase. The walking distance is calculated using Af in swing phase and the result is shown in the experiment section. First, we obtain heading (H) from magnetic sensor output. Then, we calculate the location of latitude and longitude base on equation (4).

$$\mathrm{Ph_p} = \begin{cases} 0, & \text{if } \mathrm{T_{stn}} \leq \mathrm{Th_t} \\ 1, & \text{other} \end{cases} \tag{3}$$

$$\mathrm{lat[i]} = \mathrm{lat[i-1]} + \left(\frac{\sin(\mathrm{D[i]} \times \mathrm{H[i]})}{\mathrm{WGS_v}}\right) \tag{4}$$

$$\mathrm{lon[i]} = \mathrm{lon[i-1]} + \left(\frac{\cos(\mathrm{D[i]} \times \mathrm{H[i]})}{\mathrm{WGS_h}}\right)$$

lat is latitude in WGS-84 coordinate, long is longitude. WGSv, is the meter conversion factor for latitude, whereas WGSh is the meter conversion factor for longitude.

2.3. GPS/PDR Integrated Location Tracking

Location tracking using GPS combine with PDR method involve complex filtering technique [8, 9]. However, complex filtering technique has its technical challenge to be practically applied within a mobile system for real time location tracking. By simple calculation, we are combing GPS and PDR to form a PNS.

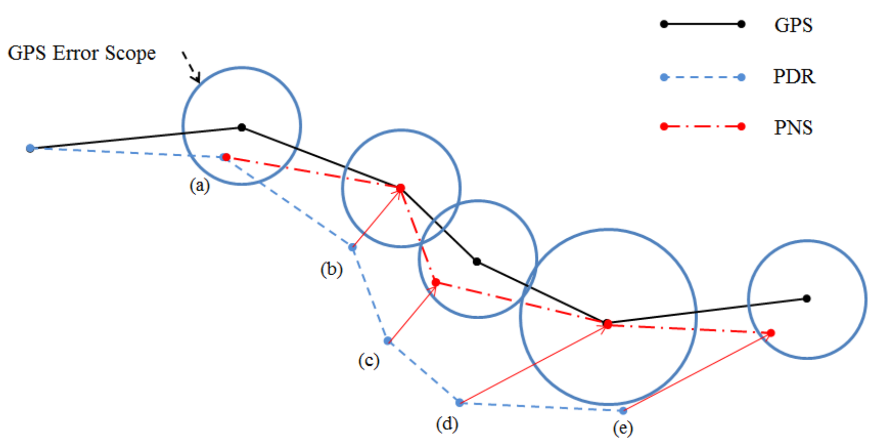


Figure 4. PDR Error Correction using GPS

If PDR path is within the error range of GPS, PDR will maintain in the path. If PDR path is fall-out of the error range of GPS, the path will match to the GPS coordinates. Figure 4 shows the graphical representation of the method.

For matching two paths, arc matching method and projection matching method were used in order. Projection matching method is to match two paths at the same starting point, then multiply the length difference between the two paths. Thus, with a simple calculation, the end point of the path is matched exactly. This is very useful in straight line estimation. However, the angle error is not taking into consideration in projection matching. When encounter a path line that contain varying vector, the path estimation error would be significant as shown in Figure 5(b)

Arc matching method is to match two paths based on the rotation of arc angle from the starting point to the end point. However, the drawback of arc matching is that, the actual end point will never be matched exactly with the estimated end point due to standard angle error. The path estimation using arc matching is shown in Figure 4(c).

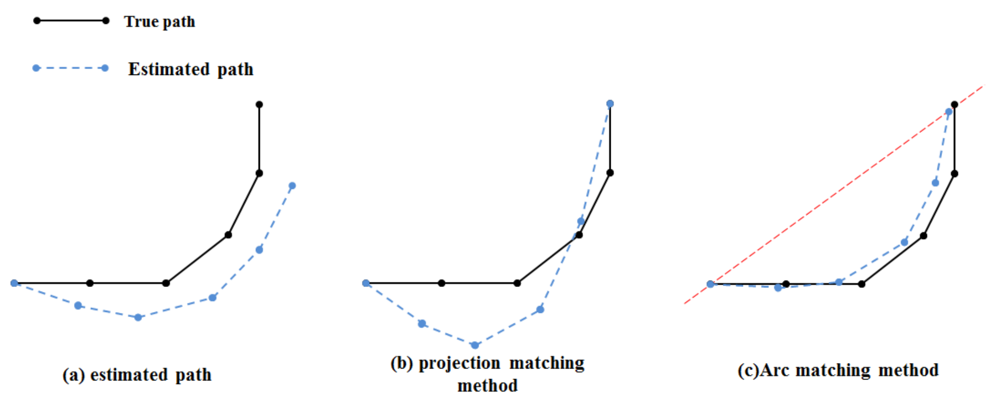


Figure 5. Path Matching Method

In order to have accurate path estimation, we suggest arc matching to be used for path angle estimation and projection matching for distance estimation. Combing the above two methods, we named it as pedestrian navigation system (PNS).

2.4. PNS/Elevation Integration Location

Previously, a lot of studies have been shown that there is a high correlation between walking energy consumption and walking on slope. We can obtain the slop data from the Google Elevation API. Google Elevation API provides elevation data for all locations on the surface of the earth including depth location on the ocean floor or height location of a mountain [5]. PDR data is a very short distance data (in cm). We calculate the PDR path by averaging the two co-ordinates between elevation data.

2.5. Activity Energy Expenditure Estimation

Energy expenditure in walking has been studied in literature [10]. ACSM suggest equation (7) for activity energy expenditure estimation. In this paper, we calculate walking speed and slope then and substitute the parameter into ACSM equation (5).

$$VO_2 = (0.1 \times S) + (1.8 \times S \times G) + 3.5 \tag{5}$$

S is speed, G is slope, and VO_2 is oxygen respiration.

ACSM formula is only applicable to moving energy expenditure. In this paper, we calculate activity energy expenditure using accelerometer data. Then the calculated energy expenditure is summed with the moving energy expenditure to obtain the total energy expenditure.

In daily life, determining the movement speed could classify a person into difference activity status. Low speed mean other activity status, example is like jumping or push up. So moving speed has the relationship of inversely proportional to stationary activity.

$$\mathrm{VO}_2^{e} = \frac{1.8 \times \mathrm{S}}{\mathrm{Acc}_{cf}(1 + \mathrm{S})} \tag{6}$$

We implementing 0.1Hz fourth order Butterworth high pass filter to reduce gravity acceleration in accelerometer. Finally, we obtained Af. We have a denominator of speed+1 to prevent the resulting calculation from going to infinite during no movement (speed = 0). Acccf is the correct factor during rest activity (speed = 0) so that the output is zero. The activity energy expenditure VO2e can be calculated using equation (6).

3. Experiments and Results

3.1. Location Tracking Test Equipment

In this study, we use SHW-M110S (Samsung co.) to acquit GPS data and elevation data. F-IMU acceleration, gyro, earth magnetic data are received from the foot-mounted IMU system. SHW-M180S is an android based smart phone. It consists of Hummingbird CPU of 1 GHz operation speed, GPS, Bluetooth, and support 3G/4G internet connection. The F-IMU acceleration, gyro, earth magnetic data are transmitted to SHW-M110S wirelessly using Bluetooth transmission. In addition, the IMU sampling rate is programmable within 1 ~ 100Hz. In this study, the sampling rate of IMU is set at 50Hz. An android application to record IMU, GPS and elevation data is developed. All the data are stored in MicroSD card and analyzed using Matlab.

3.2. Straight Walking Test and Results

Three healthy college students are participated for the walking test. The college student is asked to walk in a straight line for 20m and 40m in length and walk at a constant speed. There are number of 93 times of walking test has been performed. Throughout the walking test, real step and estimated step are counted. The number of step detection accuracy is obtained by using equation (7).

$$\left(1 - \frac{|\mathrm{ST}_{est} - \mathrm{ST}_{cnt}|}{\mathrm{ST}_{cnt}}\right) \times 100 \tag{7}$$

STcnt is true number of steps and STest is estimated number of steps. Experimental result shows, the total real step count is 1978 but the estimated step count is 1980. Throughout the observation of the step count data, we found out that, there is one +4 more counts and one -2 less counts, and finally resulting the estimated step count to be 2 steps extra. Thus the successful step detection rate is 99.7%.

We calculate the distance estimation using equation (8). The calculation result from equation 8 is made to be x-axis (equation (8)) in correlation plotting with walking speed. Figure 6 shows the correlation plotting between walking speed and equation (8). Base on the correlation plotting of Figure 6, we obtained correlation factor of r = 0.9802 and proved there is strong correlation between walking speed and equation (8). Thus we are able to propose a new formula for walking distance estimation as shown in equation (9).

$$\frac{|A_{ph}| \times T_s}{T_{sw}} \quad (8)$$

$$D_n = \left(0.100157067 \times \frac{|A_{ph}| \times T_s}{T_{sw}} \& + 0.3508056050\right) \times T_{sw} \quad (9)$$

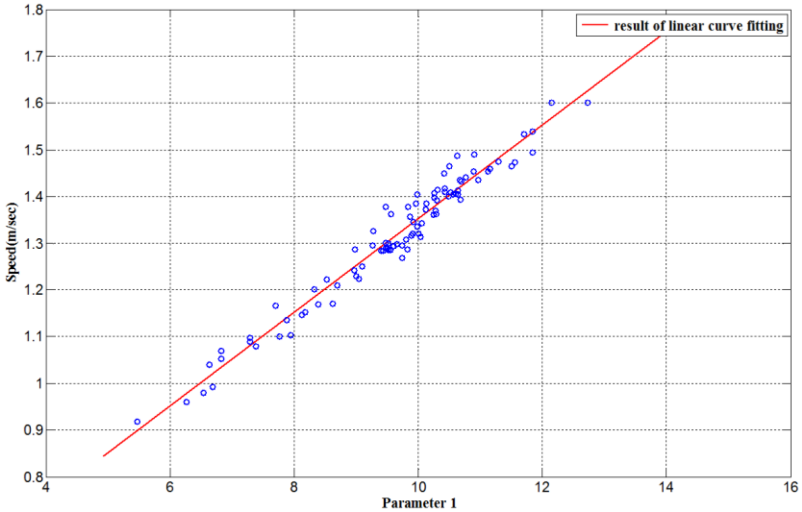


Figure 6. The Relationship between Speed and Equation (8)

3.3. Location Tracking Test and Results

The IMU system is mounted on the right-foot shoe. The shoe is worn by the test subject and the test subject is asked to hold his mobile device (smartphone) and walking around the campus of Dongseo University, South Korea. Figure 7 shows the experiment scenario after we implemented GPS and PDR in the mobile device for location tracking.

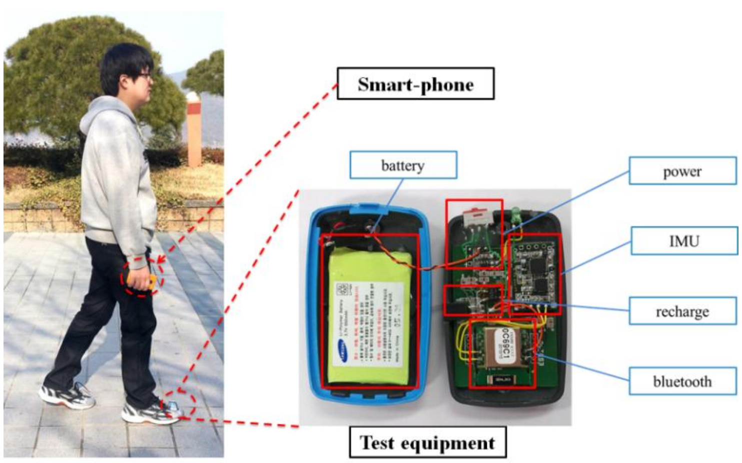


Figure 7. Walking Test and Equipment

First, we spent initialization time for more than 30 second before test start. Then we start to walk around in a 4 m radius circular for 3 minutes. Then, we perform jumping at a stationary point for another 3 minutes. After performed walk and jump test, we rest for 2 minutes in standing position. After rest, we start jumping again for 3 minutes. Lastly, we perform running for 40 seconds.

Figure 8 shows the recorded walking path (a) estimation path (b) zoom in view of black rectangle area in (a). (1), (3) section shows slope walking section, (2) section is performing a 4 m circular walk for 3 minutes, (4) section is performing the jumping test for 3 minutes and (5) section is performing the running test for about 40 seconds.

Moving path using GPS data solely do not show a straight line even though the experimenter is walking straight in physically. The moving path is being improved using PDR as shown in (b).

The recorded moving distance using only GPS data is 1,819 m and the recorded moving system for combined PNS is 1,486 m. Since the real physical measure distance is total 1,462 m, we conclude that PNS do promote a better performance in distance estimation. We added altitude information for activity energy expenditure estimation using combined PNS. Figure 9 shows the moving sector including altitude information.

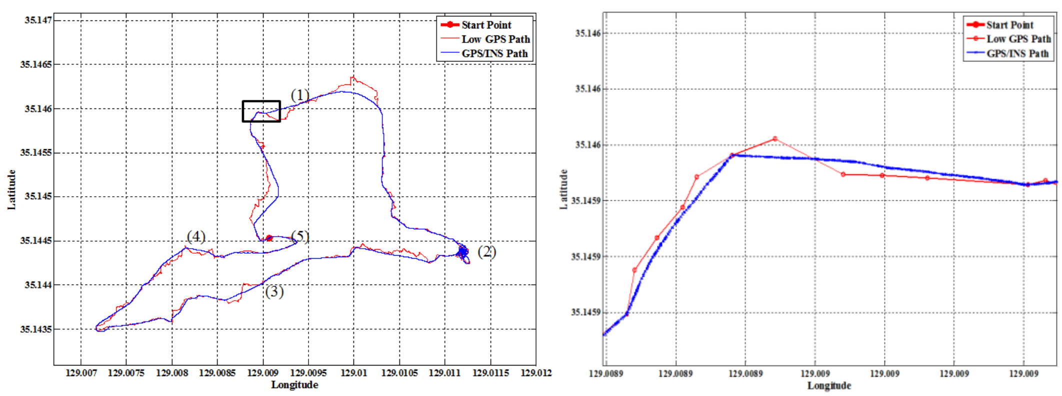


Figure 8. (a) Estimated GPS Path and Combine GPS/PDR path, (b) Improved Path using PDR

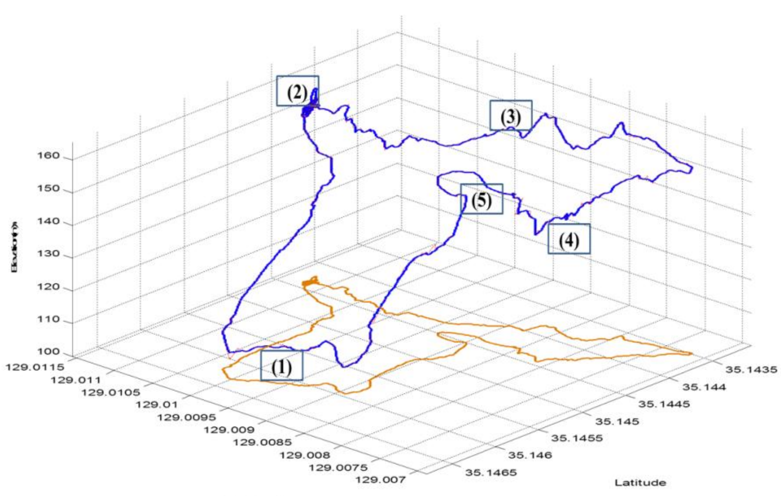


Figure 9. Path Added Elevation Value

3.4. Result of Activity Energy Expenditure Algorithm in an Outdoor Environment

Figure 10 shows the result of oxygen respiration per hour using ACSM path obtained from experiments. (1), (3) section of Figure 10 is walking on slope, (2) section is walking in circular, (4) section is jump test and (5) section is running test.

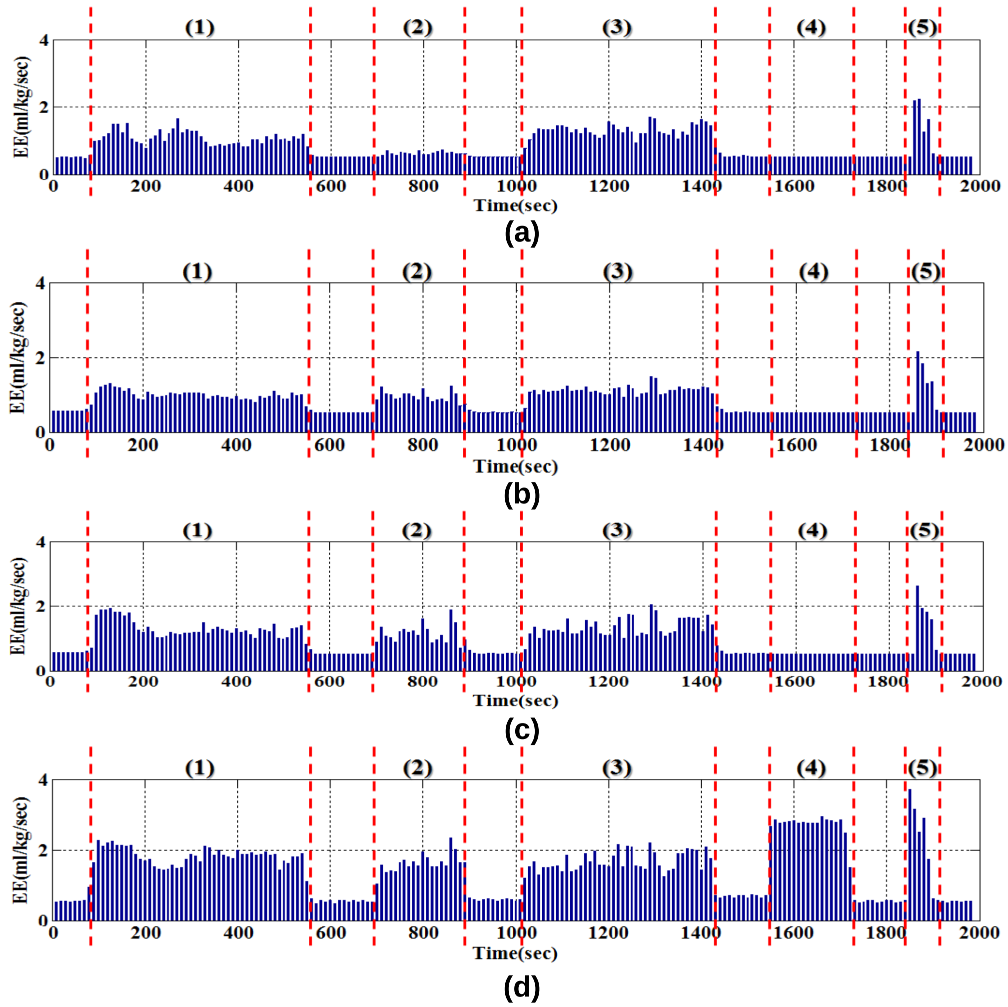


Figure 10. (a) Calculated oxygen respiration from GPS Path using ACSM, (b) Calculated oxygen respiration from integrated GPS/PDR Path using ACSM, (c) Calculated oxygen respiration from integrated GPS/PDR/Elevation Path using ACSM, (d) Proposed oxygen respiration calculation formula from integrated GPS/PDR/Elevation Path

In Figure 10 (a), (2) section shows estimated low oxygen respiration for GPS path however Figure 10 (b) (2) section in shows a higher oxygen respiration expenditure for GPS/PDR path. Also we found greatly increase in activity energy expenditure in section (1) (3) of (c), because activity on slope consumed more activity energy than on ground and the energy expenditure on slope has been shown by GPS/PDR and elevation in Figure 10 (c). Therefore slope estimation is important. However activity energy expenditure almost never appear in all section (4) in Figure 10, This is because section (4) is jumping at a static point, calculating the path do not contribute for calculating activity expenditure in static point. Figure 10 (d) shows the proposed technique of calculating GPS/PDR/Elevation/ accelerometer data. In Figure 10 (d) section (4) shows high activity energy expenditure. This shows that the proposed technique can be used to estimate the energy expenditure including static motion and dynamic motion. Adding accelerometer data to the activity energy expenditure estimation, the energy expenditure in section (1) - (5) are appeared to be high.

4. Conclusion

We concluded that activity energy expenditure is higher when we are walking on slope. GPS/PDR/elevation path shows good performance for location tracking system. But static point activity energy expenditure could not be calculated using the GPS/PDR/elevation path as shown in section (4) for Figure 10 (a), (b), (c). We calculate activity energy expenditure using equation (8) by considering the accelerometer data.

In the next study, we suggest the proposed new formula to be compared with the performance of respiratory gas analyzer. By using metabolic test system to estimate oxygen respiration, we are able to verify and validate the proposed method and confirm its performance in oxygen respiration estimation.

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