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An acceleration vector variance based method for energy expenditure estimation in real-life environment with a smartphone/smartwatch integration

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ABSTRACT

By combining embedded passive sensing technologies from both smartphone and smartwatch, it is possible to obtain a high quality detection of sedentary activities (sitting, reclining posture…), movements (walking…) and periods of more intense body movements (running…). Our research encompasses the definition of an energy-saving function for the total energy expenditure (TEE) estimation using accelerometry data. This topic is clearly at the crossroad of both computer science and medical research. The present contribution proposes an intelligent wearable system, which combines the use of two complementary devices: smartphone and smartwatch to collect accelerometry data. Together they can precisely discriminate real-world human sedentary and active behaviors and their duration and estimate energy expenditure in real time and in free-living conditions. The results of the study are expected to help subjects to handle their daily-living physical activity notably for being compliant with the physical activity international guidelines (150 min of moderate intensity activity/week). It is also expected that the physical activity feedbacks using these popular devices can prove the effectiveness of such wearable objects to promote individually-adapted healthy behavioral changes. The performance of the proposed function was evaluated by comparing the energy expenditure given by the smartphone and smartwatch with that produced by Armband®. The mean error of TEE between the proposed function and Armband® was less than 4% for an average 6 h period of daily-living activities. The main theoretical contribution is the definition of a new predictive mathematical function of energy expenditure, which competes with the non-public function used in dedicated costly devices such as Armband®. In addition, this work demonstrates the potential of wearable technologies.

1. Introduction

The chronic diseases, including obesity and diabetes, have become emergent epidemics and can be stated as the consequence of poor dietary habits and inadequacy of physical activity. The effective measure of the total energy expenditure (TEE) permits to in a waste majority of situations, of the consequence of bad dietary habits and lack of physical activity. As stressed by the researchers in Pande et al. (2013), the moderate and vigorous track daily physical activity and favor prevention of chronic diseases. Two reference methods are commonly used to provide measure of the total energy expenditure: indirect calorimetry based on gas exchange (IC) and doubly-labeled water (DLW). However, both of two methods involve costly medical material and require a controlled laboratory environment, which are not suitable to be used under the daily living conditions. Therefore, many wearable sensors-based approaches have been developed which offer an alternative solution and can be used under the daily living conditions and take advantages of sensors based accelerometers.

Smartphones become intelligent systems that permit the combined use of computer and smartphone. With the technological improvements (wireless communication, semiconductors, multi-core processor, real-time operating systems…) the performances and the size of smartphone have been continually enhanced. Thus

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the smartphone can also act as a powerful data collection platform by using the number of built-in sensors and is ready to be used for personal health monitoring in clinical and fitness trials (Duclos, Fleury, Guidoux, Lacomme, Lamaudiere, et al., 2015). Modern smartphones are programmable, have multiple embedded sensors, large high resolution touch screens, powerful processors, long battery life, large amounts of memory, ability to link wirelessly to external sensors/devices, and are considerably familiar to large segments of the population. They are also fundamentally a wireless data communication technology that facilitates data transmission from the body to a remote storage device, such as computer server, where, it can be processed and displayed in support of new types of decision support systems.

Smartphone is one of the most suitable money saving devices for TEE since people who have a smartphone do not need to purchase and carry other devices. However, academic research involving it is still scarce (Liu et al., 2014 and Ronao & Cho, 2016). By consequence, the design of an efficient and online TEE function based on smartphone accelerometers is a challenging task, which involves resolution of both accuracy measure and control of battery consummation. Only a small number of researches can be stated as online system (Khan, Siddiqi, & Lee, 2013) *i.e.* the whole process including data-collecting and TEE estimation, is performed on the device.

Lately smartwatches are the new wireless companions that have been designed to be held to the wrist. The smartphone is close to the body's center of gravity and by consequences, the smartphone accelerometers provide an estimation of the acceleration of the whole body and that is more representative of the global body activity. The smartwatch is on the extremities and by consequences would be more relevant to identification of activities where only the upper-body tends to become more active. Such remarks hold for all regular office jobs where employees work on a computer screen for long periods.

Several attempts at using accelerometers attached to different locations have been achieved during last years. For example, Veltink, Bussmann, de Vries, Martens, & Van Lummel (1996) performed a number of experiments that used two or three uniaxial accelerometers to distinguish several activities, including standing, sitting, lying down, walking, ascending stairs, descending stairs, and cycling. The researchers in Aminian et al. (1999) studied whether activities (lying down, sitting, standing, and walking) can be recognized more efficiently using two accelerometers.

Previous researches proved there is a great of interest in combining several accelerometers to obtain a high quality detection of activities, since some activities can be better identify with a sensor located at the body and some activities are better identified by sensor located at extremities. Smartphones have demonstrated a large capability as a non-invasive device of physical activity measurements (Del Rosario, Redmond, & Lovell, 2015). For example, smartwatch accelerometry is used to detect and diagnose tremor (Wile, Ranawaya, & Kiss, 2014). However the smartwatch has not been used for following daily-living arm movements. It can evaluate arm and wrist movements to complete the evaluation of TEE.

The approach we promote in this paper refers to the same trend of researches taking advantages of two mobile devices including a smartphone and a smartwatch. More precisely, an online predictive function for Total Energy Expenditure (TEE) estimation using smartphone and smartwatch accelerometers is proposed. This study first determined the subjects' activities from data provided by the smartphone and smartwatch accelerometer sensors and then quantified the TEE considering the subjects' sex, age, height and weight. Our research encompasses definition of a function using these accelerometers without any assumption on its initial position (X, Y and Z axes). Let us note that initial devices position is the major drawbacks of several previous published methods under controlled conditions.

A verification study of performance was also carried out. This study compares the estimated TEE to the TEE provided by a reference sensor (the SenseWear Armband®); under controlled and free-living conditions during a 6h monitoring period. The experiments were achieved respectively with 6 and 10 participants. The results show that the energy expenditure was estimated with an error of around 3% with the Armband sensor in free-living conditions. Otherwise, the energy consumption problem has received a considerable amount of attention. Since functions requiring heavy computation or high frequency are usually high energy consuming (Pande et al., 2013). To ensure low energy consumption, the proposed online function provides both an energy saver expenditure function and a data collection processes with low frequency mode.

Our contribution is:

- The definition of a new energy expenditure function tuned to addressed efficiently free-living conditions and specially dedicated to analyze moderate activities. The approach is based only on accelerometers and participants data analysis without any information on the initial smartphone position;
- An intensive statistic test is available for free download at http://www.isima.fr/~lacomme/donnees_acc. A new set of data including smartphone accelerometry, smartwatch accelerometry, Armband® accelerometry for 10 participants is available for future experimentation.

The paper is organized as follows: Section 2 presents an overview of smartphone-based approach in this topic and section 3 presents the related works on TEE estimation using smartphone accelerometers. Section 4 describes the schematic representation of the applied methodology. The experimental results are introduced in Section 5, before concluding remarks.

2. Smartphone based approach in health and research

Smartphones are relevant for delivering health information (Klasnja & Pratt, 2012) since: (1) the widespread adoption of phones with powerful capacities, (2) people have predisposition to carry their phones in all places, (3) people's connection to their phones, and (4) context awareness characteristics enabled through sensing and phone-based personal information. The smartphone is a device that is currently omnipresent with the great advantage of operates wherever there is a network environment. Additionally, due to recent advances in technologies, the number of sensor included in smartphones has strongly increased over the last years. Smartphones are now more sophisticated including accelerometers and GPS to provide geographical location and three-dimensional coordinates (Kim et al., 2013). As stressed by numerous authors, long-term monitoring using a smartphone is cordless consuming and would require periodic power supply. Nevertheless, smartphone application in medical science has received a considerable amount of attention.

Several classifications of smartphone applications domains have been introduced in recent state of the art (Daponte, De Vito, Picariello, & Riccio, 2013; Lamonaca, Poimeni, Barbé, & Grimaldi, 2015). Applications fields of smartphone in measurement systems encompass 8 main fields: (i) sport, (ii) urban, (iii) education, (iv) measurement, (v) laboratory, (vi) safety, (vii) medical, and (viii) automatic domestic equipment applications (Daponte et al., 2013). In these fields, applications take advantages of the embedded sensors of the smartphone. Medical research based on smartphone technologies hold into 4 main categories:

- Class 1. **Education applications** favoring good practices.
- Class 2. **New feedback mechanisms** favoring self-management or daily efficient connection with therapist. In such research