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Instantaneous VO2 from a wearable device

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ABSTRACT

We present a method for calculating instantaneous oxygen uptake (VO2) through the use of a non-invasive and non-obtrusive (i.e. without a face mask) wearable device, together with its clinical evaluation against a standard technique based upon expired gas calorimetry. This method can be integrated with existing wearable devices, we implemented it in the "Device for Reliable Energy Expenditure Monitoring" (DREEM). The DREEM comprises a single lead electrocardiogram (ECG) device combined with a tri-axial accelerometer and is worn around the waist. Our clinical evaluation tests the developed method against a gold standard for VO2, expired gas calorimetry, using an ethically approved protocol comprising active exercise and sedentary periods. The study was performed on 42 participants from a wide sample population including healthy people, athletes and an at-risk health group including persons affected by obesity. We developed an algorithm combining heart rate (HR) and the integral of absolute acceleration (IAA), with results showing a correlation of $r = 0.93$ for instantaneous VO2, and $r = 0.97$ for 3 min mean VO2, this is a considerably improved estimation of VO2 in comparison to methods utilising HR and IAA independently.

1. Introduction

To allow for the analysis of a person's cardiovascular fitness, the volume of oxygen they utilise per minute is calculated (VO2), typically expressed as a relative rate in millilitres of oxygen per kilogram of body mass per minute (mL kg^{-1} min^{-1}). VO2 is the standard measurement of a person's metabolic rate and subsequently their physical activity as the metabolic equivalent of task (MET), where 1 MET is equivalent to a VO2 of 3.5 [1].

There have been a number of studies showing that the level of physical activity undertaken by a person is linked inversely with their risk of developing a range of chronic medical illnesses [2–4]. According to the National Heart Foundation of Australia, one in six Australians suffers from cardiovascular disease. Additionally, coronary heart disease was the leading cause in 12% of deaths in Australia in 2015 with the risk factors including obesity, physical inactivity, alcohol and smoking [5]. A clinical measurement of instantaneous VO2 allows a medical practitioner to monitor and regulate a patient's activity and treatment according to their current activity levels, with the use of regular physical exercise to reduce the risks of developing, and in the treatment of a range of chronic illnesses, including: cardiovascular disease [6], obesity [7], type 2 diabetes [8,9], emotional and psychological instability [10–12], and multiple sclerosis [13].

A lifestyle change to include increased physical activity for those who are at an elevated risk of type 2 diabetes is nearly twice as effective as the current medication therapies in preventing type 2 diabetes [14,15]. To be used as an alternative or as part of a combined treatment, clinical review of physical activity is required, with the current methods of activity assessment of physical activity limited to self-monitored reporting or consumer devices such as smart watches and wearable technologies such as the 'FitBit'. Unfortunately the accuracy of these devices for measuring MET has recently been questioned, with a number of papers [16–18] identifying significant variations in the MET measured

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by the wearable device when compared to indirect calorimetric methods.

For at-risk persons, the clinical monitoring of instantaneous VO2 is of high importance, with Negus et al. identifying the importance of considering an orthopaedic patient's instantaneous VO2 and their heart rate (HR) when developing a patient's rehabilitation program [1]. They found the estimated VO2 for exercise in rehabilitation considerably underestimated the measured VO2, with protocols designed to achieve 50% of the patient's maximum achievable VO2, instead reaching nearly 90% of the patient's maximum achievable VO2. This resulted in considerable risk of myocardial infarction for patients with undiagnosed coronary artery disease.

Further clinical applications of monitoring VO2 include use in the care and treatment of cancer patients. Knox et al. tested the hypothesis that malignancy causes increased energy expenditure in cancer patients, where they found cancer patient exhibited major aberrations in their resting metabolic rate (RMR) [19]. Although they found predictions for cancer patients could not be made on a single measurement of RMR, they did observe that patients who had significantly longer duration of disease did have elevated RMR. Prior to this, Warnold et al. [20] studied the energy balance of cancer patients and controls, finding that while there was no significant difference in energy intake, RMR was increased in cancer patients while no change was observed in the controls. With the increased energy demand of cancer patients considered, extended monitoring of their VO2 may be used in ensuring adequate nutritional intervention is applied [21].

Along with weight management and risk reduction in chronic illnesses, VO2 monitoring can also be used in the clinical management of diabetic patients, where balancing food intake, energy expenditure and insulin dosage is required [22]. Unfortunately insulin management protocols rely upon an individual's self reporting of their energy intake and energy expenditure which has been shown to be highly inaccurate, with individuals significantly over reporting physical activity, due to social desirability [23]. Therefore by removing the self reporting aspect of physical activity by providing a clinically accurate instantaneous VO2 measurement with the ability to calculate cumulative VO2 for specified periods, the management of diabetic patients has the potential to be significantly improved.

2. Background

The gold standard for measuring VO2 is indirect calorimetry. VO2 measurements are calculated by devices such as the Cosmed K4b^2, which require the user to place a mask over their mouth and nose for the duration of monitoring [24]. Although indirect calorimetry using the Cosmed K4b^2 is considered a standard method, currently it is not possible for doctors to regularly monitor a patient's VO2, with Australian health data showing on average. Australians see their doctor 4 instances per year for up to 20 min each time [25]. Subsequently prediction equations are typically used for clinical assessment [26,27]. Typical uses of indirect calorimetry have been restricted to research due to the time constraints of a consultation, combined with the considerable capital investment required, and the obtrusive nature of wearing a mask.

2.1. Alternative estimation techniques

As the general public have become more aware of the importance of monitoring their activity and with the development of the smart watch, wearable technologies have become the latest trend, with each device offering a method for estimating MET. The principle behind the current wearable devices is using an estimated resting metabolic rate (RMR) for sedentary activity and during periods of activity using an accelerometer, with either:

Counts. Counting the number of times a threshold acceleration is reached per minute has been shown to correspond with the MET [28].

Integral of absolute acceleration. The integral of absolute acceleration (IAA) over 30 s periods (1) has been shown to correlate with the MET. Bouten et al. showed the IAA_{total} was 97% accurate when a subject was walking [29]. This measurement requires no calibration to the subject. In Eq. (1), a_x, a_y, a_z are the orthogonal accelerations as measured by the accelerometer in m s^{-2}. Typically, these are orientated so that a_x is the acceleration due to lateral movement, a_y is the acceleration due to antero-posterior movement, and a_z is the acceleration due to vertical movement.

$$IAA_{total} = \int_{t=0}^{30s} |a_x| dt + \int_{t=0}^{30s} |a_y| dt + \int_{t=0}^{30s} |a_z| dt \quad (1)$$

The issue with these methods is the periods of sedentary activity. Bouten et al. [29] found the IAA method to be considerably inaccurate during sedentary and static exercise with a range of 40% underestimation through to a 30% overestimation. More recently, Miyatake et al. have looked at using an accelerometer and gyroscope in a modified IAA application for estimating VO2 [30], showing an improved correlation during periods of walking and running. There has also been extensive research into activity classification using feature extraction from accelerometers [31,32]. For improved measurements, an increased number of accelerometers were required to be placed on the body. Liu et al. found tri-axial accelerometers on the hip, both wrists and a ventilation sensor on the chest were require to provide an improved estimation of the MET of activities [33].

As acknowledged by Bouarfa et al., the inaccuracies of these consumer devices have minimal impact but it is essential that the sensor remains unobtrusive [31]. Therefore for this paper, we have limited the design to a single triaxial accelerometer and a single lead ECG to ensure the device is unobtrusive while also achieving an accuracy level suitable for clinical use.

In this paper we propose a method for non-obtrusive clinical measurements of sedentary and active VO2 using a wearable device called the "Device for Reliable Energy Expenditure Monitoring" (DREEM). We validated this device using a prospective non-randomised pilot study with 42 participants, the study design and protocol are discussed further in Section 3.2.

3. Methods

3.1. Device design

Previous studies by the authors found the use of an independent tri-axial accelerometer to be highly inaccurate for estimating VO2 during sedentary, and static exercise periods [27], with a proposition for a modular wearable device which allowed for the addition of an ECG to improve the measurement of VO2 when required. Further to this, DREEM, an open platform portable bio-potential data logger [34] has been developed incorporating the design requirements recommended from the prior study. The DREEM is worn around the waist, and logs a single lead ECG and tri-axial accelerometer to local storage in CSV format with VO2 estimation performed on a standalone PC.

3.2. Experimental design

For this study to ensure the device is unobtrusive and wearable, we have placed the electrocardiogram (ECG) electrodes in a modified lead I position [35] with the right leg electrode placed on the