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# Respiratory rate assessments using a dual-accelerometer device

Sara Lapi[d], Federico Lavorini[b], Giovanni Borgioli[c], Marco Calzolai[a], Leonardo Masotti[a], Massimo Pistolesi[b], Giovanni A. Fontana[b,*]

[a] *Department of Information Engineering, University of Florence, Italy*
[b] *Department of Experimental and Clinical Medicine, University of Florence, Italy*
[c] *Department of Mathematics and Informatics "U. Dini", University of Florence, Italy*
[d] *NICReM srl, Florence, Italy*

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ABSTRACT

Monitoring of respiration-related thoracic movements may be useful to assess respiratory rate (RR) objectively. RR was measured during spontaneous breathing, voluntarily modified breathing, and exercise hyperpnoea in normal subjects via visual inspection, spirometry and a pair of accelerometers positioned on the torso. Spirometric and accelerometric values of RR recorded during relaxed breathing were (mean ± SD) 21.44 ± 1.41 bpm and 21.06 ± 2.17 bpm; during voluntarily augmented breathing, these values rose to 29.44 ± 4.61 bpm and 29.23 ± 5.33 bpm, respectively; spirometric and accelerometric RR values did not differ in any of the cases. RR assessment was unaffected by recumbence. During handgrip, spirometric (16.43 ± 3.10 bpm) and accelerometric (16.22 ± 2.76 bpm) control RR values did not differ and increased to comparable levels (24.22 ± 7.30 and 24.82 ± 5.45 bpm, respectively) by the end of exercise. At rest, visual (18.94 ± 3.45 bpm) and accelerometric (19.27 ± 3.83 bpm) RR values were compliant in normal subjects as well as in scoliotic and obese patients. Accelerometers are a reliable tool for monitoring RR, during both eupnoea and stressed breathing.

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## 1. Introduction

The respiratory rate (RR) is a vital sign that provides important information about the patient's health and it is widely accepted that an abnormal RR could indicate a variety of pathological conditions including respiratory, cardiovascular and metabolic disorders. In addition, a recent cohort study demonstrated that recordings of the RR following acute myocardial infarction provides powerful prognostic information which is independent and complementary to that of existing risk assessment, suggesting that the simple and inexpensive assessment of the RR should be considered an additional variable for risk assessment after acute myocardial infarction (Barthel et al., 2012). Conventional (visual inspection) measurement of the RR is still routinely practiced but the procedure is time consuming and labor intensive (Edmonds et al., 2002; Hooker et al., 1989). Objective methods such as measurement of the respiratory flow using a pneumotachograph or other apparatuses that require a connection to the patient's airway are obviously impractical, especially for long-term monitoring or when frequent RR assessments are needed. Earlier attempts to non-invasively monitor respiratory activity date back to the nineteen-sixties, with devices such as the magnetometers (Mead et al., 1967), the inductive plethysmograph (Tobin et al., 1983) and, more recently, the photoplethysmograph (Nakajima et al., 1996), recordings of tracheal sounds (Sierra et al., 2005) and extraction of the respiratory waveform from the conventional ECG (Phan et al., 2008). However, none of these earlier methods have proved satisfactory enough to replace the conventional method, at least in the clinical setting, as indirectly demonstrated by the fact that the routine method for RR assessment remains visual inspection (Edmonds et al., 2002; Hooker et al., 1989).

With the rapid development of electronic sensors and computer technology, novel devices are being developed to objectively assess the RR. For instance, it has recently been demonstrated that micro electro-mechanical systems (MEMS) accelerometers worn on the torso can measure inclination changes due to rotational chest-wall movements during respiratory activity and that these inclination changes can be used to measure the RR (Hung et al., 2008; Jin et al., 2009; Jourand et al., 2009; Reinvuo et al., 2006). Accelerometers are sensors that emit a signal proportional to the acceleration they undergo; acceleration, which is the variation of velocity in the unit of time, is a vector characterized by magnitude and direction. Accordingly, a single-axis accelerometer only provides the measurement of acceleration in one direction; triple-axis (tri-axial) accelerometers are three single-axis accelerometers assembled as a Euclidean framework, i.e. set as three mutually orthogonal axes.

* Corresponding author at: Department of Experimental and Clinical Medicine, University of Florence, Largo Brambilla 3, 50134 Florence, Italy.
Tel.: +39 055 7947516; fax: +39 055 4223202.
*E-mail address:* giovanni.fontana@unifi.it (G.A. Fontana).

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They therefore provide the three components (called *x*, *y*, *z*) of the acceleration within this framework. Accelerometers are sensitive to gravity, the magnitude of which largely exceeds the magnitude of the accelerations caused by quiet breathing. Thus, measuring the three components of acceleration allows us to know the tilt or inclination of the apparatus with respect to the direction of gravity (see Appendix for additional details).

Current accelerometric devices make use of a single tri-axial accelerometer, typically positioned on the abdominal wall (Bates et al., 2010). These devices have been shown to accurately detect the RR in strictly controlled conditions (Bates et al., 2010). However, it is presently unknown whether accelerometers can also reliably detect the RR when the ongoing respiratory activity is perturbed by voluntary changes in baseline respiratory activity or by conditions that are common in real life such as the hyperpnoea of exercise. It must also be recalled that in some circumstances devices equipped with a single tri-axial accelerometer may be unable, at least in theory, to detect the motion of the relevant structure. Accelerometers are not sensitive to movements involving small accelerations with respect to the gravity magnitude, as may be the case with slow translatory movements, i.e. when the three axes of the accelerometer remain parallel to each other (Bates et al., 2010). The same insensitivity results in the case of rotations around the direction of gravity, because the tilt of the device with respect to gravity remains unchanged. If we want to record chest wall motion during breathing, the above limitations can conveniently be overcome by means of a couple of tri-axial accelerometers positioned approximately at the lower rib level, on both sides of the frontal aspect of the torso. This arrangement would ensure that the signals arising from the two accelerometers during respiratory chest wall movements are in opposite directions. In addition, and perhaps more importantly, a single-accelerometer may be unsuitable to detect a respiratory signal when body movements are impeded by postural constraints, such as during ipsilateral decubitus.

Here we propose a novel approach to detect breathing-related chest wall movements by using a dual-accelerometer device with sensors positioned on opposite sides of the chest wall, so that breathing movements are sensed as relative changes in inclination between the two accelerometers (see Appendix). Therefore, the main purposes of this study are (i) to describe a novel algorithm for obtaining the RR from a couple of tri-axial accelerometers positioned on opposite sides of the chest wall; (ii) to report on the agreement between the RR values obtained in parallel by means of the visual method and the dual-accelerometer device; (iii) to compare recordings of the RR obtained with a pneumotachograph and the accelerometer during voluntary and reflex changes in the RR. An attempt was also made to assess the sensitivity of the accelerometric device by determining the chest wall displacement of subjects who were requested to take the smallest possible breath. Preliminary accounts of parts of this work have already been published (Lapi et al., 2011).

## 2. Methods

### 2.1. Participants

Twenty-two normal subjects recruited from the hospital's non-respiratory medical staff, 5 obese patients, and 4 patients with idiopathic scoliosis participated in the study. In the latter case, the Cobb's angle (Cobb, 1948) ranged between 38° and 69° (Table 1). The study adhered to the principles of the Declaration of Helsinki and was approved by the institutional Review Board; all participants were informed in detail that the investigations involved non-invasive measurements of respiratory activities but were unaware of the purposes of the study, to which they gave their consent to participate.

**Table 1**
Anthropometric and clinical characteristics of the participants.

| | Age | Sex (M/F) | BMI | Smoking habit (yes/no) | Cobb's angle (range) |
|---|---|---|---|---|---|
| Subjects | 35.5 ± 9.7 | 13/9 | 19.2 ± 1.5 | 2/20 | – |
| Obese pts | 48.8 ± 3.4 | 4/1 | 40.0 ± 2.9 | 2/3 | – |
| Scoliotic pts | 39.7 ± 3.4 | 1/3 | 19.5 ± 1.7 | 0/4 | 38–69° |

Values are means ± standard deviation unless otherwise stated; BMI, body mass index; pts, patients.

### 2.2. Spirometry

To obtain spirometric measurements of RR ($RR_{sp}$), airflow was recorded by means of a calibrated (Petusevsky et al., 1980) no. 4 heated Fleisch pneumotachograph connected to a flow transducer (HP47304; Hewlett and Packard, Palo Alto, CA); the volume signal was obtained by electronic integration of the flow signal.

### 2.3. Accelerometric device

Respiratory chest wall movements were recorded with a dual-accelerometer respiratory monitor (T100, NICReM srl, Florence, Italy). The device, developed by the Department of Information Engineering of the University of Florence (patent no. FI2007A000212, published in 2009), consists of a portable data-acquisition board connected to a pair of sensors (Fig. 1). The data-acquisition board contains a microcontroller, a 3.2″ liquid crystal display (LCD) touch screen, a power supply, analog conditioning circuits, A/D and D/A converters and a real-time clock for acquisition management. The acquisition sensors consist of two MEMS capacitive tri-axial accelerometers that were calibrated one at a time with a standard procedure to offset the output and correct any possible systematic errors due to the manufacturing process and physical structure. In order to record the chest wall movements, the sensors were mounted on two small-sized circuit boards. The acquired signal was sampled at 128 Hz and processed by a microcontroller in order to be fed to both an external device

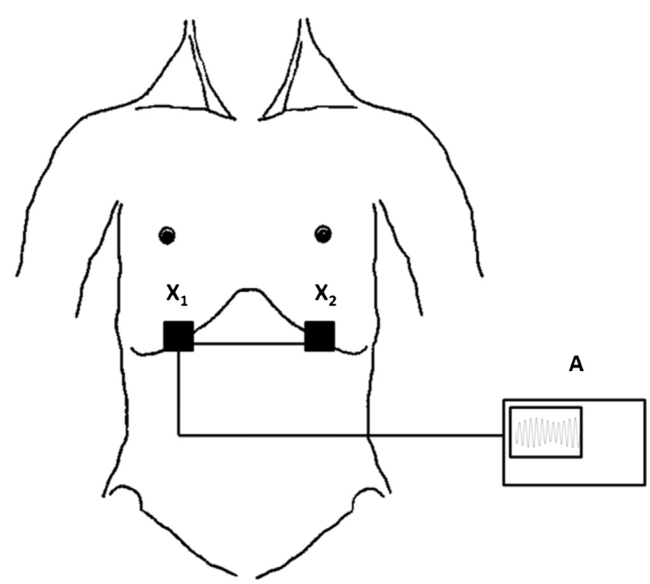


**Fig. 1.** A diagrammatic representation of the apparatus for accelerometric recordings of chest wall displacement. $X_1$ and $X_2$ are the accelerometric sensors positioned on the ventral aspect of the torso and connected to a portable central processing unit (A) through a fine electrical wire. Instantaneous respiratory rate is computed by the processing unit and displayed on the LCD screen.

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