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A DEVICE FOR EXPERIMENTAL CHARACTERIZATION OF BIOMECHANICS OF BREATHING AND COUGHING

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Abstract. *The paper addresses attention on design requirements and a novel device is presented with testing results for a breathing evaluation. Design requirements are discussed for the development of a measurement device evaluating the respiratory/breathing act that is summarized according to the three main lines as referring to the clinic of the thoracic cage, the general characteristics of the structure, and functionality of the device. The general characteristics of the device are outlined in terms of a low-cost and easily usable device by users, who can be intended as both medical operators and patients. The mechanical design is designed with an ergonomic solution for a comfortable use by a user whose respiratory act is to be measured. Therefore it is also dimensioned in geometry and weight such as to ensure easy portability as well as a simple and comfortable wearing for the required period of respiratory monitoring. A novel non-invasive system named as SENSIRIB is presented as based on an Inertial Measurement Unit device that is integrated with electronics and biomechanics elaboration software to get a portable easily wearable device that has been tested with preliminary results that are discussed as validation of the device performance.*

Keywords: *Biomechanics, Medical devices, Design, Testing, Rib motion*

1. INTRODUCTION

Breathing is a vital act to allow the body to supply itself with air and is characterized by motion acts with biomechanical aspects and physiological and chemical functions, Guyton and Halls, 2015), (Derenne *et al.*, 1978). The biomechanical aspects refer to the motion that is imposed to the thoracic cavity by the expansion and contraction of the lung tissues and these movements produce kinematic and dynamic aspects that must be coordinated for a correct functionality of the organism. Generally, the biomechanics of the respiratory act is analyzed from a descriptive and not quantitative point of view, considering only the functionality in general terms from a clinical point of view. In fact, there are few tools that allow a numerical analysis of the biomechanics of the respiratory act which from a numerical point of view is evaluated mainly by considering spirometry analysis to evaluate the volumetric expansion of the thoracic cavity. On the other hand, there are no specific tools to analyze the motion of the rib cage and in particular of the ribs but there are tools that only generally allow general assessments such as spirometry which also allows the identification of the respiratory act. Some other devices are presented in the literature as outlined in the survey (Folke *et al.*, 2003) whereas specific methods are investigated as based on optics, (Krehel *et al.*, 2014), (Ciocchetti *et al.*, 2014), and on acceleration sensing (Ono *et al.*, 2011), (Yang *et al.*, 2015) of the thorax motion.

There are few systems in use that allow the detection of the motion of the thoracic structure and in particular of the individual ribs during breathing, but no system is aimed at the specific detection and monitoring of the movement of a single rib. These devices are all aimed at analyzing breathing in terms of general parameters, as in the examples that are reported in (Folke *et al.*, 2003), (Krehel *et al.*, 2014), (Ciocchetti *et al.*, 2014), (Ono *et al.*, 2011), (Yang *et al.*, 2015). Respiratory monitoring has been of relevant attention recently in treatments fighting COVID-19 disease, (Massaroni *et al.*, 2011), (Yang *et al.*, 2015).

This paper presents a device with a measurement chain that was developed for the analysis of the biomechanics of the respiratory act. The here-in presented SENSIRIB device, as proposed in (Ceccarelli 2021), allows to evaluate the kinematic characteristics in terms of angular values and accelerations of the motion of the ribs for a biomechanical quantification of the respiratory act. The structure and functionality of the SENSIRIB device is introduced also considering the portability and its manageability in use, and reporting results of a first experimental validation that allows to characterize the effectiveness of the device in evaluating the biomechanical act of breathing as function of the movement of the ribs of and thoracic cavity with user-oriented operation.

2. BIOMECHANICS OF BREATHING

The biomechanics of respiration can be studied by considering the ventilatory act as related to the movements of the thorax following the expansions of the lung tissues in coordination with the activities of the muscles of the thoracic cavity, Figure 1. Respiratory cycle is a continuous alternation of inspiration and expiration. The diaphragm is the main respiratory muscle, and it determines chest cavity together with intercostal muscles. By contracting the muscles, they move chest wall skeleton and in particular ribs are subjected to significant motions as summarized in the sketch in Figure 1 b).

The anatomy of the thoracic cavity is represented in Figure 1 a) with its essential elements consisting of the bone structure with cartilages connecting to the bore bodies of the sternum and spine together with the muscle bands. Muscle complex activates the movement of the chest and together with bone skeleton they also work a protective function of the organs contained within the chest cavity. Twelve pairs of ribs are connected with their heads to thoracic vertebrae posteriorly and with the sternum anteriorly (throughout cartilage interposition) as to compose the chest wall skeleton, Figure 1a).

The ventilatory act is characterized by kinematic aspects that are related to the movements of expansion and contraction of the rib cage with corresponding movements of the ribs, while the dynamic aspects due to forces are less evident despite the high constraint reactions that can be produced at the cartilaginous connections of the ribs on the sternum and on the vertebrae that are moreover mitigated and transmitted also through cartilage tissues. The magnitude of these forces can be generically understood also by considering the overall mass and the bone structure to which the ribs converge such as the sternum and the vertebral column. Therefore, the ventilatory act in its mechanics is mainly characterized by kinematic aspects of the expansion and ventilation motions but also by the transmission of this motion with a production of constraint reactions at the connections at the extremities of the ribs. Figure 1 b) summarizes the type of movements and related actions linked to this transmission of force that a rib or more specifically a rib segment can generally experience. In terms of movements the main motions of a rib can be recognized in the elongation movement that is also absorbed by the cartilage tissues at the extremity as well as small twists along the axis of the rib but above all, flexion motions that tend to increase the volume of the rib cage with the displacement of the ribs. Referring to these displacements, it is also possible to recognize the actions as the mechanical reactions that can be generated in terms of force at the vertebrae to which they are connected. In Figure 1 b) the main motions are represented considering the so called bucket handle motion combined with pump handle motion in the top scheme and caliper motion in the bottom scheme as those responsible for the variation of the volume of the chest cavity for the ventilation of the breathing.

The anatomy of the thoracic cavity represented in Figure 1 a) is characterized by a variety of configurations and structures of the ribs whose movement, while respecting the general characteristics indicated in the model of Figure 1 b), can be more or less significant as related to the position in the rib cage. In particular, in the development of a device that can monitor the biomechanics of ventilation through the movement of the ribs, it can be considered convenient to pay attention to the sixth rib and especially to the portion of it in which the aspect of motion can be most significant and therefore away from the points of attachment on the sternum and on the vertebrae and near the apex of the curvature of the same, as reported in the schemes of Figure 1 b).

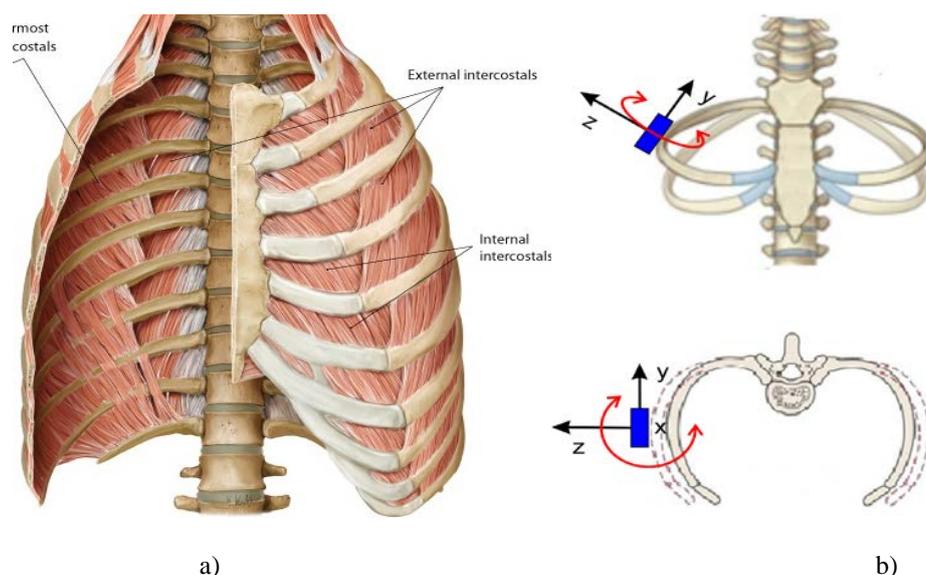


Figure 1. A scheme for biomechanics of breathing: a) the thorax anatomy; b) rib motions.

Summarizing, the problem of an evaluation of the biomechanics of respiration can be faced with an analysis of the movements of the ribs or even better looking at the more mobile rib that can give significant indications of the state of the ventilatory act during respiration while monitoring the movements of a significant rib for the expansion and contraction of the rib cage as represented in the models of Figure 1 b).

3. REQUIREMENTS

The requirements that can be identified for the development of a measurement device for evaluating the respiratory/breathing act can be summarized as indicated in Figure 2 according to the three main lines that can be referred to the clinic of the thoracic cage and to the general characteristics of the structure and functionality of the device, as per the biomechanics of ventilation and operation features. In particular, for the respiratory act clinic, the device must be able to measure and monitor the respiratory act in its main aspects which, in addition to being referred to the biomechanics that is linked to the kinematics of the motion act, must also take into account the physiological conditions during the period of acquisition of the characteristics as for example considering the cardiological status and the general physiological condition referring not only to the thoracic segment. The general characteristics of the device can be expected in terms of a low-cost and easily usable device by users, who can be intended as both medical operators and patients.

Consequently, the expectations of the design and functionality of the device can be summarized as in the second part of Figure 2 in terms of the characteristics of the mechanical design, the peculiarities in the use in terms of installation and the operational purposes of the device. The mechanical design must be characterized by a device that is ergonomic for a comfortable use by a user whose respiratory act is being measured. Therefore, it should be also dimensioned in geometry and weight such as to ensure easy portability as well as a simple and comfortable wearing for the required period of respiratory monitoring. The purpose of the device in terms of functionality can be defined for an evaluation not only of the biomechanics of the respiratory act but also of the interpretative consequences at a clinical level. Therefore, the device must be completed and integrated by appropriate software that implements data processing and numerical evaluation algorithms of the acquired data to give indications both with measures of performance criteria and graphs representing the acquisitions that can allow a medical operator to formulate an adequate diagnosis of the respiratory act.

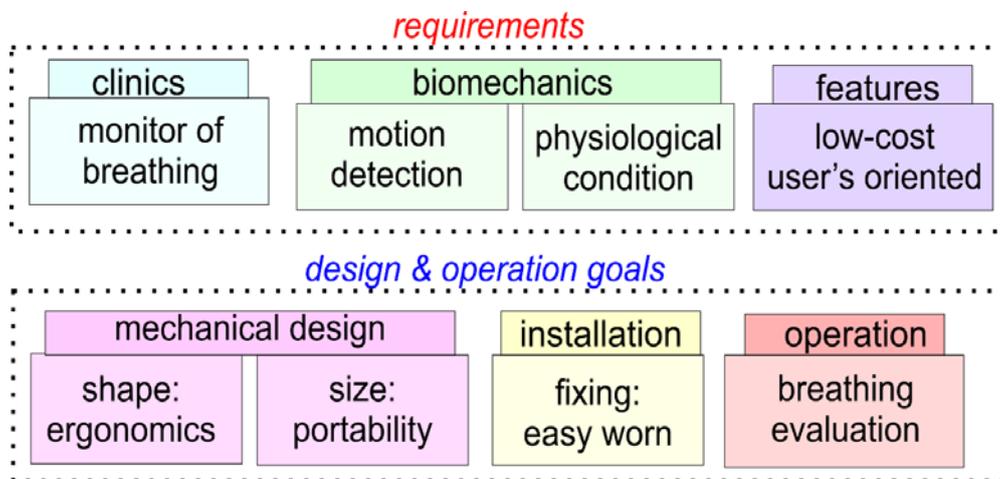


Figure 2. Requirements for design and operation of an easily wearable device for breathing biomechanics evaluation.

4. DEVICE DESIGN

The proposed SENSIRIB device is a new portable device for measuring the movement of individual human ribs for determining biomechanical characteristics of movement during respiratory acts. The device structure is characterized by small components for a portable structure with cables for data transmission that can be stored and viewed in a computer or tablet, as a display unit.

The structure of the SENSIRIB device is described in Figure 3 where Figure 3a) shows the conceptual scheme of the device with its components and Figure 3 b) shows the sensing concept in detecting the rib motion using an IMU (Inertial Measuring Unit). With reference to Figure 3, the portable device SENSIRIB for measuring the movement of human ribs consists of a motion sensor (1), a signal acquisition and processing unit (2), a data display and storage unit (3), a connection cable and signal transmission (4), and a connection cable and data transmission (5), with a structure that is characterized by the fact that the components are of modest size and portable to allow the measurement of movements of a single rib human body on which the sensor (1) is positioned. The motion sensor (1) that is placed inside a small case, is

made with an IMU sensor equipped with a gyroscope and accelerometer for measuring angles and accelerations of the motion of a rib during breathing when it is placed on the human rib in skin adhesion. The signal acquisition and processing unit (2) is made with electronic components for the acquisition and processing of the signals from the IMU sensor in (1) as for example in a nanoArduino with small dimensions such that it can be placed comfortably at a distance on a belt in the human user whose rib movement is measured. The connections with signal and data transmission cables (4) and (5) are of suitable lengths for the positioning of the units (2) and (3) even at a convenient distance from a user whose movement of a rib is measured.

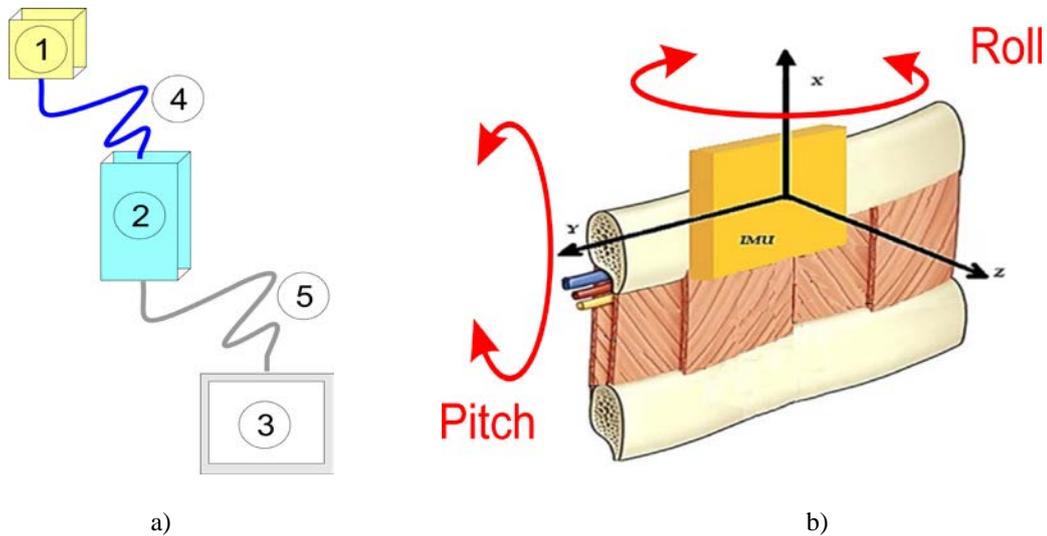


Figure 3. A conceptual design of SENSIRIB device: a) a scheme; b) IMU sensing operation.

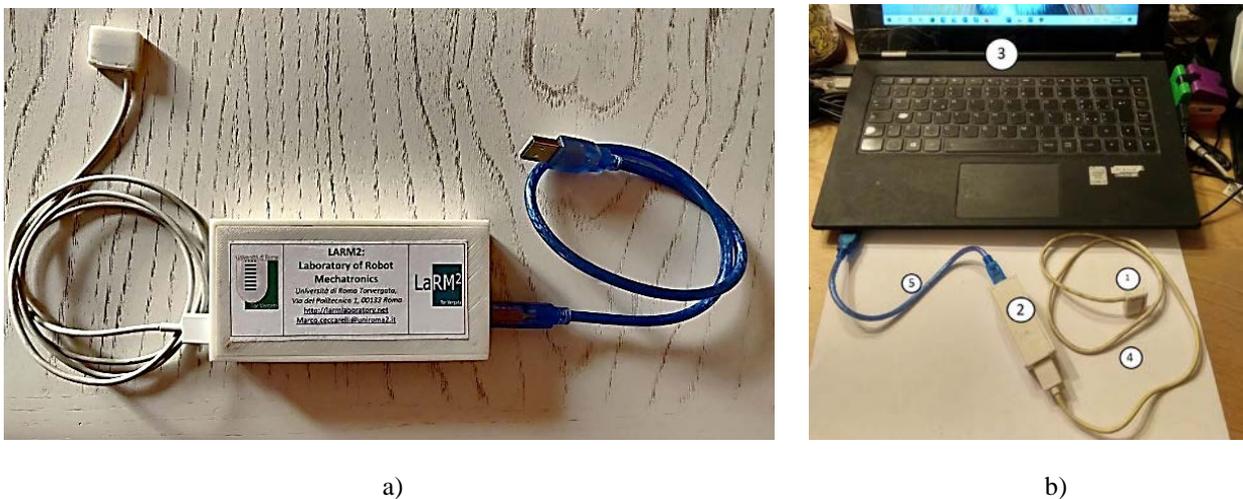


Figure 4. The built prototype of SENSIRIB device: a) the portable mechanical design; b) implementation with a laptop.

Figure 4 shows a built prototype of the device at LARM2 laboratory in Rome in the solution that has been used both to check the feasibility of the design with the planned features and to test its operation efficiency for validation in lab testing. Referring to Figure 4 a), the IMU sensor unit (1) is made with a small box of 1.2 x 1.2 x 0.4 cm having a cable (4) of about 1.2 m for connection to the box of the electronic unit (2). Unit (2) is made as a box of 10.0 x 4.0 x 3.0 cm that is provided of a cable (5) for a connection to a laptop (3) via a USB port. Figure 4 b) shows a setup with a laptop at LARM2 laboratory for testing activity.

The prototype of SENSIRIB in Figure 4 has been designed with requirements in accordance with indications in Figure 2 mainly to have a wearable device in a minimally invasive and manageable way with a laptop for adequate portability. The prototype was built according to the design scheme in Figure 3 using commercial components and structures made with 3D printing in order to obtain a device also of relative low cost and sufficiently robust for easy assembly and management. The prototype consists of a part as an interface that is installed on a subject under examination and a laptop in which the codes for acquisition and processing of the acquired data are installed. Minimal invasiveness is verified with the reduced dimensions of the extremity sensor in a 1.2 x 1.2 x 0.4 cm box structure containing the IMU sensor; the portability and a fairly simple assembly are ensured by the structure of the distributed components that are connected by

data transmission cables and are placed in a box of electronic components of 10.0 x 4.0 x 3.0 cm; the low cost is achieved by using commercial components for a total cost of less than 10 euros; the robustness is achieved by placing the components inside 3D printing manufacturing boxes of adequate dimensions and thicknesses of 0.2 cm; the device management is programmed with suitable software codes for fairly easy operation from a laptop keyboard with online display of the acquired data and subsequent processing for numerical evaluations. The prototype was produced in several units for experimental activity by operators of different abilities and cultural backgrounds, as for example in the experiments with master students in engineering or in clinical medicine, in order to verify the versatility of the device especially in its functionality even with numerical evaluation algorithms of the ventilation evaluation and a user-oriented operation without specific technical skills. The prototype was tested with satisfaction in the first text activity as reported in the next section.

5. TESTING RESULTS

The practical implementation of the device was planned considering also the clinical-medical purposes through a definition of a protocol not only for standardized use in clear sequential steps, but also for the respect of medical-ethical conditions in interaction with human users with the intention to have the consent and awareness of the investigation carried out with the use of the device SENSIRIB. The experimental validation mode of the device was designed with an application of the device in preliminary medical-clinical testing in a laboratory environment using five volunteer subjects from the student population with tests that were repeated three times to have a minimally significant statistical basis.

Figures 5 to 7 and Table 1 show the results of a characteristic test to show both the efficiency of the device and the biomechanical characterization of the ventilation act that can be carried out with the device SENSIRIB. Once the device has been set, even with calibration of the IMU sensor, in accordance with the designed protocol, the test proceeds with the application of the IMU sensor on the chest of a subject under examination, preferring the placement on the sixth rib in correspondence with the area under the axillary as shown in Figure 5 where the motion act during ventilation can be considered more evident.

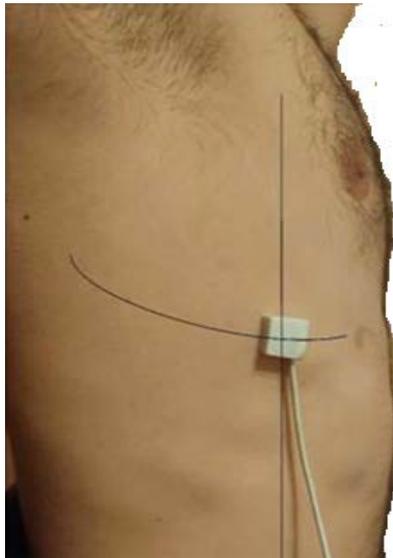


Figure 5. A setting up of the IMU sensor of SENSIRIB on the sixth rib for a test on a volunteer sixth rib.

Figures 6 and 7 show the time evolution of the main kinematic characteristics of the motion of the rib as acquired in terms of angles as indicated in Figure 3b) in accordance with the models of Figure 1 b) and in terms of the Cartesian components of the acceleration of the point of application of the IMU sensor. In addition to the mechanical characteristics, these results can also be used to evaluate and extrapolate physiological information, such as the respiratory frequency and its regularity, the depth of respiration and the regular continuity of the ventilation act. For example, from the results in Figures 6 and 7 it is possible to calculate a respiration frequency of one second per respiration cycle that is represented by inhalation with thoracic expansion as relative to the ascent ramp of the angular movements in Figure 6 a) and by an exhalation as relative to the subsequent descent ramp. Furthermore, a quasi-static phase can be noted, especially in the angular motion of the rib, probably due to the physiological act of redistribution of the air within the lung tissues.

Figure 6 a) shows a considerable angular motion of roll in a range of just over 60 degrees as relative to thoracic expansion and contraction in the inhalation and exhalation phases of the ventilatory flow with a continuous temporal course and without particular vibrations indicating a physiologically correct respiratory process.

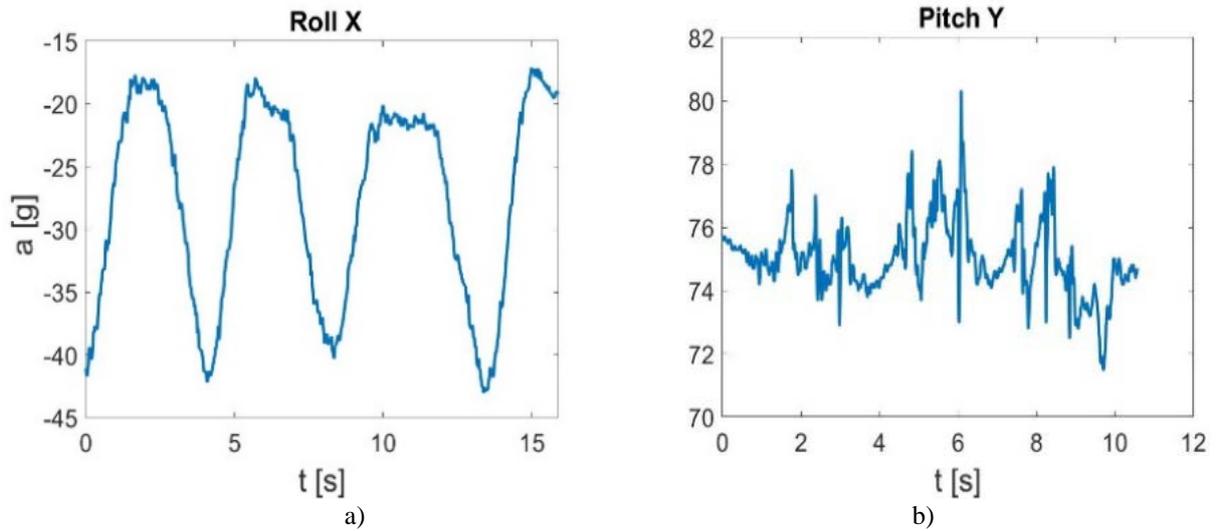


Figure 6. An example of test results of acquisition of rib motion in terms of: a) roll angle; b) pitch angle.

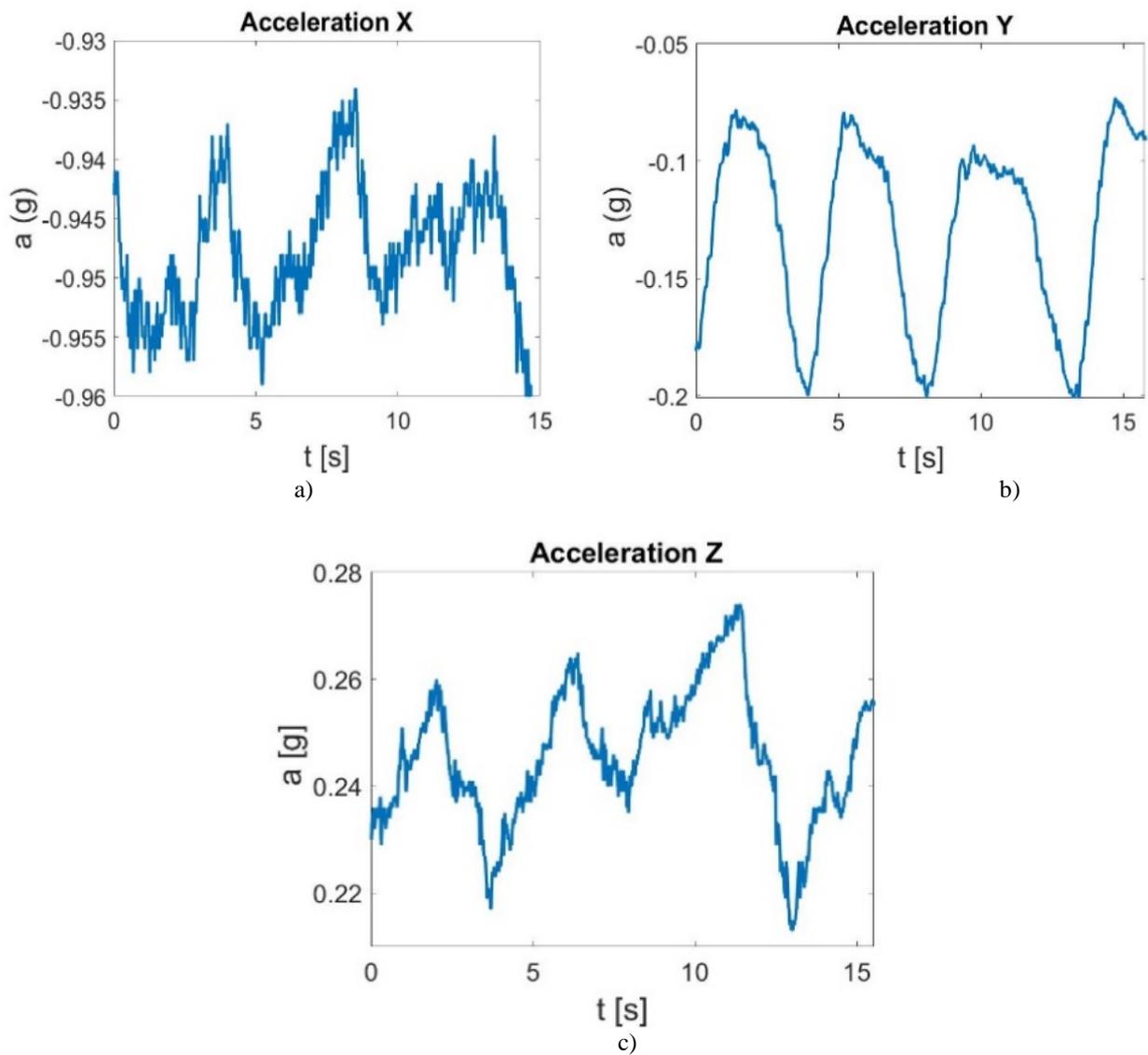


Figure 7. An example of test results of acquisition of rib motion in terms of acceleration components along: a) X-axis; b) Y-Axis; c) Z-axis.

Figure 6 b) indicates, on the other hand, that a rotational pitch motion of the rib is still significant, even if of modest size in about 6 degrees, which is related to the volumetric expansion of the rib cage with a movement especially in the diaphragmatic area being the upper part more rigidly connected with the bone structure of the shoulders and neck. The vibrations shown in the angular motion especially in Figure 6 b) may be due to the compliance of the tissue on which the IMU sensor is installed, but it can be related mainly to the physiological motion of the bone-muscular complex of a rib that is connected to the whole structure of the thoracic cavity.

Figure 7 reports the results of the monitoring of the motion of the rib in terms of Cartesian components of the acceleration of the point of the rib on which the IMU sensor is installed, indicating even more clearly the kinematic characteristics of the motion of the ventilation on the monitored rib. In particular, the component x in Figure 7 a) is directed according to the vertical and it is acquired by including the value of gravity so that the net value can be computed with very modest range values of about 0.02 g relative to this direction. The accelerations along y axis, in Figure 7 b) is acquired with a range of about 0.33 g as relative to the motion of thoracic expansion and due to the angular roll displacement around the x axis. The component along the z axis in Figure 7 c) shows acquired values in a range of about 0.06 g as relative to an outward motion of the rib cage whose vibrations are very likely limited both for the rigidity of the thorax bone structure and for the damping effect of the cartilaginous connections of the ribs on the sternum.

With reference to the data summarized in Table 1, it should be noted that the reported test on a volunteer was performed in three modes, namely normal breathing, deep breathing, breathing with coughing. Each modality was repeated three times with each test duration of about 20 seconds in order to have data with sufficient statistical value. Tests were performed initially with five student individuals. The test shown with results in Figures 6 and 7 is representative of the results that are obtained and obtainable from the use of the SENSIRIB device for a numerical characterization of the respiratory act. In particular, it is possible to note the numerical values in Table 1 which characterize the different biomechanics in the three breathing modes as acquired with typical values of each mode as reported in the example only for the case of normal breathing with the results in Figures. 6 and 7.

Table 1. A summary of acquired data of testing with a volunteer subject (Ri is for normal breathing; Ti is for coughing; Mi is for deep breathing; i=1,2, 3 for repeated tests)

	<i>Ax</i>	<i>Ay</i>	<i>Az</i>	<i>Rollx</i>	<i>Pich</i>
<i>R1min</i>	-1.008	0.031	-0.052	123.1	85..9
<i>R1max</i>	-0.989	0.055	-0.033	146.2	86.9
<i>T1min</i>	-1.134	-0.095	-0.15	-179	80.3
<i>T1max</i>	-0.868	0.16	0.034	179	89.7
<i>M1min</i>	-1.038	-0.091	-0.041	-179,6	82.8
<i>M1max</i>	-0.962	0.086	0.103	177	89.2
<i>R2min</i>	-1.151	-0.168	-0.064	-173.2	79.1
<i>R2max</i>	-0.86	0.043	0.114	177	89.7
<i>T2min</i>	-1.067	-0.162	-0.045	-110.7	80.2
<i>T2max</i>	-0.935	0.01	0.065	-46.1	89.4
<i>M2min</i>	-1.026	-0.094	0.001	-89.6	84.2
<i>M2max</i>	-0.935	-0.042	0.042	-61.1	87.5
<i>R3min</i>	-1.018	-0.081	0.005	-85.5	85.3
<i>R3max</i>	-0.988	-0.039	0.031	-61.5	87.7
<i>T3min</i>	-1.274	-0.193	-0.078	-169.3	77.7
<i>T3max</i>	-0.811	0.066	0.11	172.2	89.9
<i>M3min</i>	-1.018	-0.113	-0.01	-98.4	83.5
<i>M3max</i>	-0.972	-0.05	0.031	-67.7	87.1

In summary, the motion of the rib during a normal ventilatory act is characterized by a significant angular motion of roll around the X axis and by a Y component of acceleration with values and functions that well describe the breathing dynamics and also physiological aspects. The acquisitions can be obtained such as those reported in Figs. 6 and 7 and summarized in Table 1 for the three modalities of characterization of the ventilatory act, demonstrate an efficient operation

of the SENSIRIB device which is expected to be used in the near future in larger experimental campaigns also in a clinical medical environment.

6. CONCLUSIONS

A new device named as SENSIRIB is presented for monitoring and evaluating the biomechanics of the respiratory ventilation considering the motions that occur in the ribs during breathing acts. The SENSIRIB device is designed with a few small elements in order to be easy in use and portable. The reported illustrative test demonstrates its feasibility and easy application as well as the operational efficiency for the determination and identification of biomechanical parameters essential in the characterization of motion during ventilation in breathing acts.

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