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WIRELESS SYSTEM FOR BREATHING ANALYSIS DURING FREE-RUNNING LOCOMOTION IN MAMMALS

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ABSTRACT

For many years, researchers have studied the interaction between breathing and locomotion. It is evident that a respiratory flow occurs with stride during locomotion in any vertebrate. Besides, the discussion was focused on the amount of air volume displaced in the lungs due to this interaction.

This paper describes a wireless system to measure the air flow and to calculate the ventilation volume during free-running mode. This is due to the fact that previous studies have been implemented on treadmill and conditioned laboratories, exerting a high stress in the animals.

The functional test of air flow system was performed in a closed sports center ($\approx 50 \times 30\ m^2$). The experiment characteristics were temperature around 20°C, without wind resistance and a stable wireless local network (WLAN). As a results, the wireless communication reaches a range over 60 m with continuous transfer of data packets and high transmission rate.

Index terms— air flow system, wireless transducer, ventilation measurement, mass flow meter.

1. INTRODUCTION

Locomotor-respiratory coupling (**LRC**) refers to phase locking of breathing and other motion activities. The most of the developed studies have focused on the action of running in different mammals (bipedal or quadrupedal). For instance, Bramble [1] developed experimental studies of the breathing cycle in horses and dogs. He explained different mechanical interactions (**MI**) in these two activities and their effects on the pulmonary ventilation [1] (inspiration and expiration). In addition, he has proposed that locomotor activity could drive all or a substantial part of ventilation in exercising animals.

A few years later, Alexander [2] developed a mathematical models based on the mechanical interactions, suggesting that this hypothesis occurs in hopping and galloping animals. Furthermore, other researchers have developed experimental studies in different animals and other human activities as cycling (e.g. Kohl [3]), rowing (e.g. Daffertshofe [4]), or flying and diving

[1]Pulmonary ventilation refers to the process of exchange of air between lungs and the ambient air.

in birds (e.g. Boggs [5, 6, 7]). All of them, showed the importance of knowing the air volume moved by stride during locomotion.

Based on this approach, the purpose of this paper is to present an implemented wireless communication system as alternative method to study respiratory flows system during locomotion in free-movement environments Finally, this project seeks to become a versatile and reliable telemetry system for future applications that improve the LRC studies in any vertebrate.

Quantification of Volume Flow During Locomotion

For several years, the discussion was focused on how much air volume is displaced due to the LRC. However, measurements of volume change provided by stride in trotting and galloping animals range from 1 to 20% of tidal volume [2] [8]. In humans that walk or run it was from 1 to 2% of tidal volume [9], or in trotting dogs it was 3-16% [10].

Many researchers implemented methods based on transducers to collect data during breathing in order to obtain quantitative results of ventilation (movement of air in and out of the lungs) during locomotion. For instance, La Fortuna [11] has used an ultrasonic flow meter in his experiment with horses to determine the effects of LRC. Simons [12] has developed studies with domestic rabbits using pneumotachometer. With the same method, Daley [13] studied LRC in humans. It is important to remark that all experiments were made on a treadmill in laboratory, causing an environmental stress in animals. Besides, such animal adaptation requires training time, it takes several months before any experimental test can be conducted.

In order to determine the air volume moved by stride, first it is necessary to measure the respiratory flow rate during locomotion. The most common transducer is a **pneumotachometer** [3]. Also, exist different kinds of transducers like a turbine, vortex, ultrasound or a thermal **mass flow meter** [4]. The main advantage of thermal mass flow meters is higher sensitivity for very low flow rates ideal for medical applications.

The remainder of the paper is organized into three sections: Section 2 explains the technical characteristics of the designed system. Section 3 describes the developed experimental test of the system performance. Finally, Section 4 presents observation and conclusion of the project.

2. SYSTEM ARCHITECTURE

The developed system is described by: (i) the electronics components of the transmitter (hardware) to control and transmit data, (ii) the wireless communication protocol between the transmitter and receiver and (iii) the transmitter mechanical housing to ensure a correct parameter measurement.

[2]Tidal Volume (TV) is the air volume inhaled or exhaled during normal breath cycle.

[3]The pneumotachometer converts the air flow through a fixed diameter tube into a proportional signal of pressure difference on either side of a central membrane.

[4]Mass flow meter measures the temperature changes of the flow as it passes through a heat source.

2.1 Hardware Design

The system is based on one mass flow meter (sensor) transducer attached with a hermetic mask. The selected sensor (Sensirion ® *SFM*3000) is a bidirectional digital flow meter designed for medical application to measure the volume flows at rates up to 200 [slm][5]. The sensor is connected by the serial bus I2C to the wireless data controller (**WDC**) and it operates at 5 *VDC* of supply voltage.

The WDC (*ESP*32) is based on a Dual-core *Tensilica LX*6 microprocessor with integrated 802.11 a/b/g/n Wi-Fi transceiver. The data transmitted by Wi-Fi protocol is received by a laptop used as a data control center (**DCC**) (see Fig. 1). A graphic unit interface (**GUI**) is installed on the DCC to process data. All data processing was performed off-line using a commercial software package MATLAB® *R2017a*. The GUI has two main functions or operation modes: (i) data acquisition mode which allows to wirelessly receive and save the data from the sensor and (ii) post data processing mode which manages the post experimental analysis.

The whole system is powered by a lithium polymer (*LiPo*) battery of 7.4 *VDC* (1000 *mAh*). Additionally, to power the sensor and WDC a voltage regulator of 5 *VDC* (*AMS*117) was used.

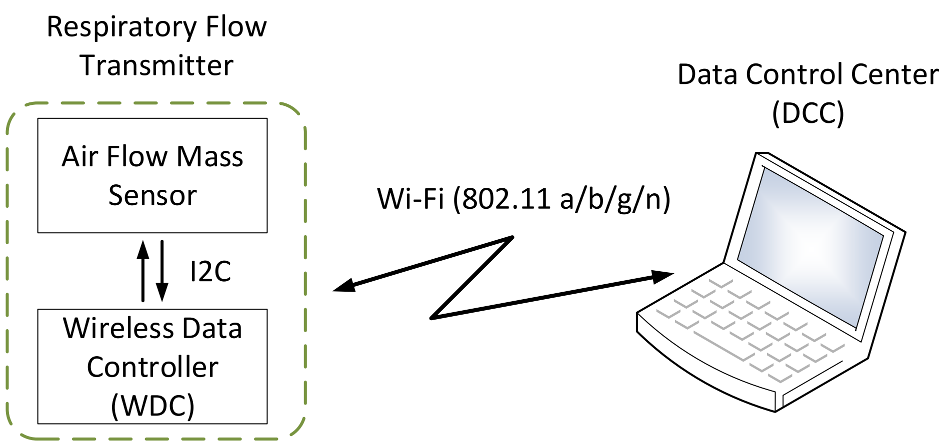

Figure 1: Respiratory flow wireless system - a transmitter and a receiver (DCC)

2.2 Wireless System Communication

The system structure is based on client-server the communication model. The respiratory flow transmitter is a client and the DCC is a server. The firmware of WDC defines the network (WLAN) settings as a name and a password to be connected. Also, the server IP-address and the hostPorts[6] were designed, which allows the data transmission between the client and the server.

The data is received and shown in real time through an implemented GUI. It saves data for post processing tasks. Finally, for data transfer of more than one peripheral device (client), it is

[5]Slm : liters per minute measured at standard temperature (0°C) and pressure (1 *atm*) [DIN 1343].

[6]A port is always associated with an IP address of a host and the protocol type of the communication. Thus it completes the destination or origination network address of a communication session.

recommendable to use different hostPorts for each device.

2.3 Volumetric Flow Measurement

The measured volumetric flow rate digital value is represented by four bytes. However the real volumetric flow rate is given by:

$$flow = \frac{measured\_value - offset\_flow}{scale\_factor\_flow} \quad , \qquad [\text{slm}] \tag{1}$$

where the constant $offset\_flow = 32000$ (DEC) and the $scale\_factor\_flow = 140\ [1/slm]$(for air) according to the sensor data-sheet [14].

According to the norm DIN 1343[7], the standard volumetric flow measurement in slm[8] is accomplished under standard conditions of temperature and pressure. The temperature is $T_n = 273,15K = 0°C$ and the pressure $P_n = 1atm = 1013,25hPa$. These reference values differ from the "room" values (environmental parameters) used in the test. The room values considered for the calculations were temperature of $T_m \approx 20°C$ and atmospheric pressure of $P_m \approx 1008hPa$. The calculated volumetric flow (V_n) expressed in L/min based on the combined gas law is described by:

$$\frac{P_n \times V_n}{T_n} = \frac{P_m \times V_m}{T_m} \tag{2}$$

$$V_n = \frac{p_m}{P_n} \times \frac{T_n}{T_m} \times V_m \quad , \qquad [\text{L}\,\text{min}^{-1}] \tag{3}$$

2.4 Transmitter Packing

The respiratory flow transmitter (sensor + WDC + battery) was attached to a designed housing of similar shape (cylindrical) like a gas filter. The complete device has the following characteristics: radio = 10cm, length = 9cm and weight $\approx 250gr$. (see Fig. 2)

This device was linked with the commercial mask (*Polimask* 330) through a standard mechanical thread (*DIN EN* 148 − 1).

[7] Norm DIN 1343:1990-01: Reference conditions, normal conditions, normal volume, concepts and values.
[8] The equivalence of slm is given by 1 $slm \equiv 1,68875(Pa \cdot m^3)/s$ in International System of Units.

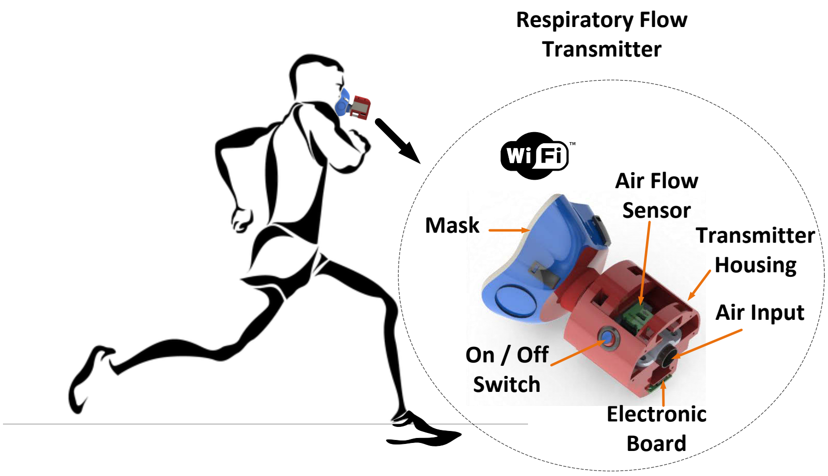

Figure 2: Description of the designed respiratory flow transmitter

3. EXPERIMENT SETUP AND RESULTS

The designed system was implemented to measure the air flow during free running mode. Participants were instructed to perform a running activity under normal conditions of ambient temperature and self-selected (preferred) running pace.

3.1 Participant Recruitment

Participants were chosen students at Ilmenau University of Technology. They were selected only if they were healthy i.e., had no physical or respiratory disabilities that might affect their movement or balance. Three healthy students aged 20-30 years were recruited to test the systems functionality.

3.2 Environment References

Participants wore the respiratory flow system located on the face, covering the nose and the mouth. The system was fastened up firmly by elastic bands behind the head. (see Fig. 3)

Figure 3: Implemented respiratory flow transmitter

Participants were instructed to run under the condition of a normal, self-selected (preferred) pace. The experimental test took a place in the closed sports center (**SC**) of the Ilmenau University of Technology. The SC area is approximately $30 \times 50m^2$. To facilitate the communication and to reach the best results in terms of system reliability, the SC wireless network was used.

The experiment area was divided in to three phases. The participant increases or decreases the speed during the first and the third phase. Furthermore, while running in a straight line the speed was constant ($\approx 5km/h$). (see Fig. 4). The purpose of these tests series was to evaluate the communication performance of the air flow sensor. The maximum transmission distance was approximately 60 m, reaching the whole workspace limited by the center area.

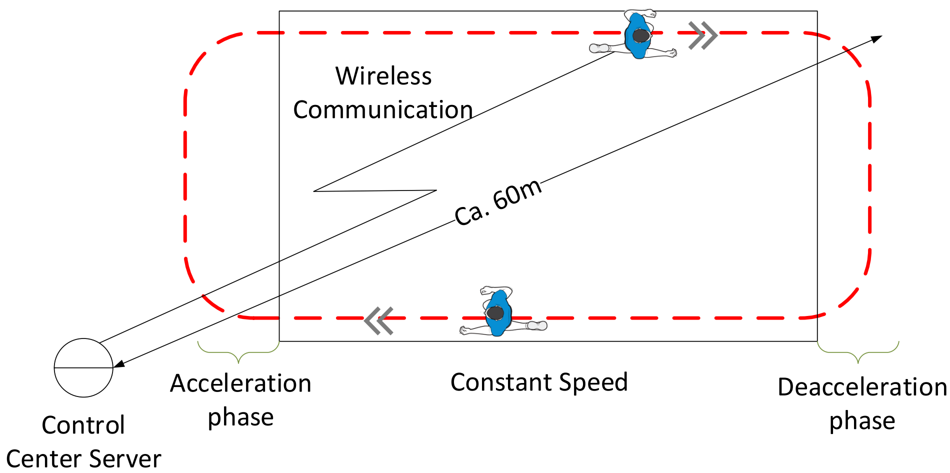

Figure 4: Free Running experimental area

Fig. 5 gives an example of the continuous flow data transfer. Besides, in the GUIs post processing interface, the tidal volume (TV) was calculated.

According to Eq. 2 explained in Section 2.2, the following example illustrated how the peak volumetric flow is calculated. The environmental parameter of our location during the test were temperature of $T_m \approx 20°C$ and atmospheric pressure of $P_m \approx 1008hPa$.

$$V_n = \frac{1013,25hPa}{1008hPa} \times \frac{([273,15+20]K)}{273,15K} \times \frac{130slm}{60s} \approx 2,33 \qquad [\mathrm{L\,s^{-1}}]$$

where V_n is the normal volumetric flow rate expressed in L/s. In this example, Fig. 5 illustrates the time of one breathing cycle (inhalation and exhalation) was 1.5 sec. If we consider the ideal situation of inhalation time was 0.75s. The tidal volume (TV) calculated during running mode at $\approx 5km/h$ is $\approx 1.75L$.

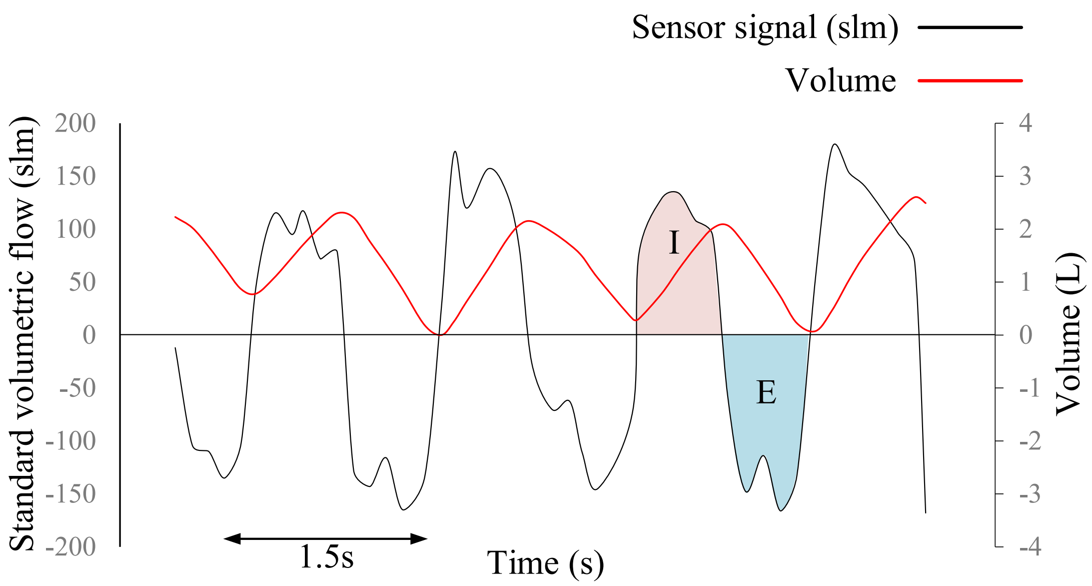

Figure 5: Continuous data acquisition of volumetric flow during free running mode. The Breathing cycle is one sequence of inhalation (I) and exhalation (E). The displaced air volume during running is the integral of volumetric flow in one breathing cycle.

4. OBSERVATION AND CONCLUSION

The functional test of the respiratory flow system was conducted in a closed sports center with controlled normal conditions as temperature and no wind resistance. The used stable WLAN increases the communication range and the packet transfer between central and peripheral devices. The system reaches a range over the 60 m with continuous data transfer. However, in an open air environment multiple access points or a router with powerful antenna should be installed to increase the wireless communication range and the stability of the transmission rate.

This system allows the addition of other peripheral devices. For instance, to compare breathing cycle in parallel of several persons. Nevertheless, it is recommended to use the saved data for post-analysis and avoid multiple signal plots "in real time" due to the increment of computing resources

During the tests, a slight swing movement from the transmitter holder was observed. We suggest that a new design of the holder has to be implemented, allowing a better distribution of the components. Thus to align the systems center of mass to the user face in order to minimize the swing movements and provide more comfort during the exercises.

Finally, we conclude that the developed system can be used and adapted to other animals, but it is necessary to previously study their anatomy and physiology. In order to adapt the mask morphology and select an appropriate flow sensor with an appropriate operation range.

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