

A comparative evaluation of different techniques for ambulatory monitoring of respiratory rate

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Abstract— Today a large attention is given to the development of innovative wearable or ambulatory systems able to monitor physiopathological parameters of individuals in their daily activities. The goal to progressively move the health costs from cure to prevention leads to focus on the wellness and preventive cardiofitness.

Several existing wearable systems are able to monitor cardio-respiratory signals. Although the recording of heart rate from ECG signals can be performed with high fidelity, continuous monitoring of respiratory frequency is heavily plagued by motion artifacts. In this work we report a comparative evaluation of different systems based on fabric strain gages, piezoelectric strain sensors and air flow measurements respectively, to determine their susceptibility to motion artifacts. With this aim, a set of experimental data, simultaneously acquired with these systems on a subject, are compared in order to show, by a statistical approach, the reliability of these systems during stereotypical physical exercises.

I. INTRODUCTION

The importance of wearable systems in healthcare has increased in the last years due to the fact that they became essential for the continuous monitoring of vital signs in every day activities in order to prevent illness and improve lifestyle. On the other hand, the next miniaturized low-cost technology will allow a greater number of subjects to afford the costs of these devices.

Technological advances reached, up to the present, have permitted to obtain good results from the wearable cardiac systems monitoring in terms of accuracy and repeatability, while minor attention was rally done in respiration systems developments. Actually, wearable respiration monitors commercially available are sensitive to motion artifacts due principally to the sensor slipping and, those strongly wrapped up to the body are uncomfortable.

This study was performed to compare the effects of motion on a piezoelectric-based and a piezoresistive-based respiratory signal acquisition systems respectively with the spirometer, that has been chosen as the gold standard.

II. MATERIAL AND METHODS

In particular, in this study, a piezoelectric-based system was developed. It has shown the advantages of being wearable,

enough insensitive to movement and no-contact with skin. In fact it was studied also to be applied to the firemen jacket to monitor their respiratory status.

The piezoresistive-based system used is a respiratory wearable system developed by Smartex, doted of a Portable Processor Unit (PPU) which after a preliminary filtering and digital conversion sent the signal to a remote elaborating station by Bluetooth device.

The spirometer is from Biopac, it is an air flow measurement instrument. Such instrument offers a good signal reliability, and even if it is quite uncomfortable to wear, needs a mouth piece or a mask, and its cost is very high, it is used for clinical measurement, and can be used as reference in the comparison.

A. Characteristics and working principles of the Instrumentation

- BIOPAC MP35 (www.biopac.com) for the airflow measurement; data are sampled at 100 Hz.

- Piezoelectric belt: it measures the variation of thorax expansions exploiting a piezocable, integrated in a textile belt, data are wireless transmitted through a ZigBee module; and sampled at 100 Hz.

- Piezoresistive belt: it measures the perimeter variation of thorax exploiting a fabric piezoresistive sensor; data are wireless transmitted through Bluetooth system; and sampled at 25 Hz.

All the data stored onto the remote station for analysis.

B. Protocol

We tested an athletic subject (25 aged) simultaneously recording: his ventilation by Biopac device and his thoracic variations by piezoelectric and piezoresistive systems. In particular, four physical exercises were chosen aiming at lower and upper limbs movements investigation, in order to evaluate movement artifacts consistency, and to estimate by means of statistical approach the limits of replacing air flow measurements with evaluating systems of thoracic variations.

The exercises choose are named such as basal, cycling, walking, running and elliptic test (see TABLE I). While the first four exercises are obviously understandable the last is a

particular one which upper and lower limbs movements are scheduled in.

In airflow measurement method, the subject breathed through a rubber mouthpiece connected to the Biopac system and wore a nose-clip. In thorax changes measurement, the two belts (one for piezoelectric and one for piezoresistive system) were wrapped around the thorax at the sternum level.

The subject performed the experimental exercise protocol that has been executed in a gym in Pisa, whose details are resumed in table below.

TABLE I
PROTOCOL DESCRIPTION

Type of exercise	Support machines	characteristics
Basal	-	Breath quietly standing up
Walk	LifeFitness Treadmill	Speed: 5.5 Km/h Inclination: 8%
Run	LifeFitness Treadmill	Speed: 7 Km/h Inclination: 12%
Cycle	Technogym Bicycle	RPM 90 6/12 difficulty level
Elliptic	Technogym elliptical trainer	Speed: 7 Km/h

C. Data analysis

The comparison of the acquired signal has been done both at qualitative and quantitative level. Qualitative analysis is done by comparing the temporal function obtained from the original signal, after they have been band pass filtered (0.1-1 Hz), DC filtered and normalized. Also the frequency spectrum has been compared.

Quantitative comparison is performed by a statistical analysis of the respiratory rate measured. For the measurement comparison methods, previous studies in literature show several approach: the use of comparison of mean, correlation coefficient, regression analysis, Bland-Altman plots, etc.[3-6]. Our aim was to verify the good performance of the new piezoelectric belt, in respect of the spirometer, in condition of motion artifacts. In this sense comparison of mean, correlation coefficient, Bland-Altman plots have been preferred focusing the attention on the basic question of whether several measurement methods agree sufficiently closely.

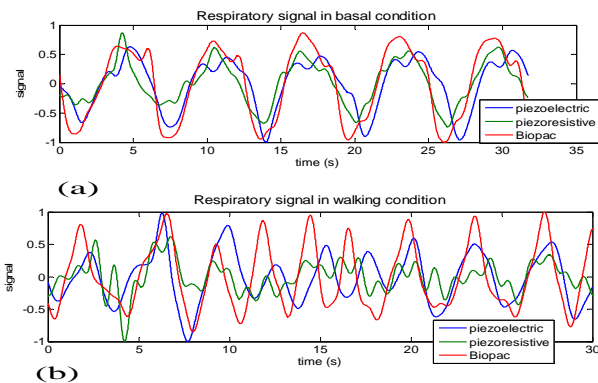


Fig. 1 Comparison of a portion of a properly filtered and normalized signal, acquired in: (a) basal and (b) walking condition

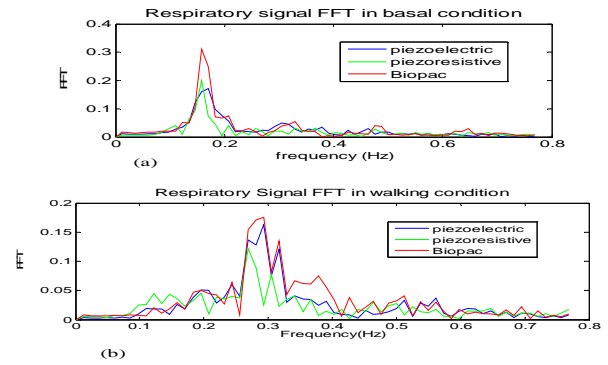


Fig. 2 Comparison of a FFT transformed respiratory signal, acquired in basal condition and walking.

III. RESULTS

From a qualitative point of view, Fig.1 (a) and (b) shows the comparison of a portion of the signal acquired, properly filtered and normalized. In these figures it can be seen as in basal condition all three kind of devices follow quite well the signal compared to the Biopac reference. Increasing the artifact level walking, the signals show a worse behavior, but the piezoelectric belt can better follow the respiratory wave. In Fig.2 (a) and (b) the frequency spectrum of the same signals is done.

In order to provide the parametrical approach we considered both separately and the whole exercise proofs.

Firstly we consider the behaviour of each systems relative to spirometer, see Fig. 3 and 4, where the first reports a samples

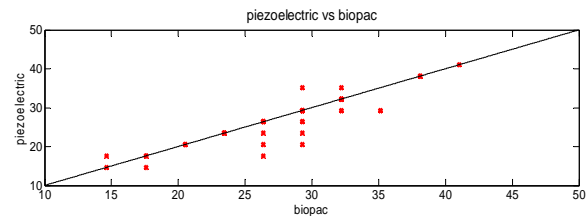


Fig.3 Comparison of piezoelectric vs spirometer in Bland -Altman

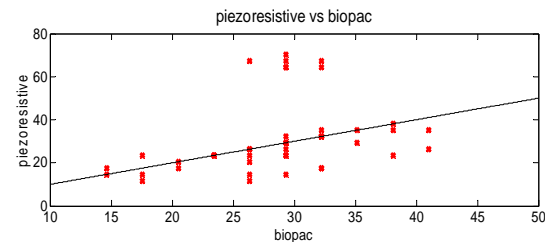


Fig.4 Comparison of piezoresistive vs spirometer in Bland -Altman plot

distribution which lies strictly closer to the net of equality than the second. But this comparison is not sufficient to assess systems agreement.

In addition, it was calculated the correlation coefficient (r) between the two methods (see Fig.5). The null hypothesis here is that the measurements by the two methods are not related. The probability is very small and we can safely conclude that the measurements are related.

However, this high correlation does not mean that the two methods agree. The correlation coefficient in this case depends on both the variation between individuals and the variation within individuals (measurement error). The correlation coefficient therefore partly depend on the choice of subjects.

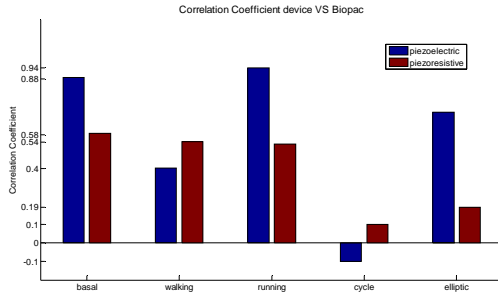


Fig.5 Correlation coefficient trend of PES and PRS vs Syrometer relative to the different physical exercises

Finally, Bland-Altman plot was used, which compares piezoelectric-based system (PES) and piezoresistive-based system (PRS) with spirometer device.

As it can be seen in Fig. 6 and 7 the comparison between the mean value of PES (mean = -0.9191) and PRS (mean = -2.2403) are reported. Even if Bland-Altman plot shows that both methods are acceptable (significance of about 95%) the distribution of samples highlight that PES mean is more closed to zero axis than PRS. Considering the Table II, it is noticed that during body movements only PES is the unique method able to follow the respiration trend.

TABLE II
MEAN ANALYSIS

MEAN ANALYSIS		
Test kind	Alpha (lim)	Device that agrees with biopac
Basal	0.9998	None
Walking	0.95	Piezoelectric
Running	0.9998	Piezoelectric
Cycle	0.9998	None
elliptic	0.96	Piezoelectric

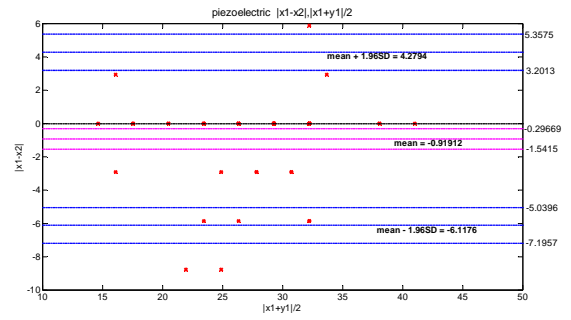


Fig.6 Comparison between piezoelectric vs spirometer system by Bland Altman plot (difference/mean)

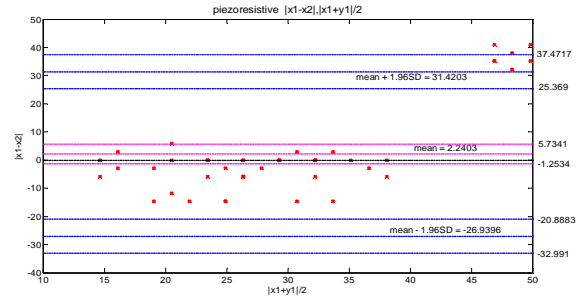


Fig.7 Comparison between piezoresistive vs spirometer system by Bland Altman plot (difference/mean)

Upper and lower limits of acceptance and interval of confidence at 95% were calculated (see Table III).

IV. CONCLUSIONS

In this study, we show a comparison of the behavior of different respiratory rate measurement systems. From a visual inspection of the normalized signal and the FFT transformed signal, we can see that in basal condition each of the instrument has a similar response, but in movement condition the sensitivity to the motion artifacts increase, especially if movements are at the thorax level; the piezoelectric belt system has shown a good robustness to such a kind of artifacts, maybe due to its configuration, which maximizes signal-to-noise ratio. This fact is validated from the whole set of statistical methods applied.

Kind of test	Piezoelectric					Piezoresistive				
	95% conf.int.			Limits of agreement		95% conf.int.			Limits of agreement	
	min	max	center	min	max	min	max	center	min	max
Basal	0.9079	0	0.9079	2.87	-2.87	1.7931	0.3255	-2.4441	6.37	-7.02
Walking	-0.026	-1.6276	3.2291	3.4365	-6.6917	-0.3804	-1.9531	3.5258	3.02	-6.92
Running	0.21165	0.7324	1.6765	2.84	-4.30	-1.946	-5.127	8.3079	6.89	-17.15
Cycle	2.0303	0	2.0303	6.42	-6.42	1.2118	-2.2786	5.7691	8.75	-13.31
Elliptic	-0.1993	-1.9531	3.7069	4.6774	-8.5836	30.3856	18.0664	5.7472	64.64	-28.51

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