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Accuracy evaluation of dynamic volume measurements performed by opto-electronic plethysmograph, by using a pulmonary simulator

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Abstract— **Opto-electronic systems (OS) are motion analysis systems, employed in different clinical applications. Opto-electronic plethysmograph (OEP) is a particular OS able to measure pulmonary volumes, starting from marker displacements, placed on the thorax.**

The aim of this work is to assess the OEP's accuracy on volume measurements, by using a volumetric respiratory simulator (RS). The RS is realized in order to simulate the human quiet breathing and an algorithm computes volume variations. Different trials have been carried out, by measuring volume through OEP and comparing with volume computed by algorithm.

Results show OEP accuracy on tidal volume measurement does not depend on thorax displacement's magnitude and it ranges from 9% to 20%.

Therefore, accuracy of OEP on dynamic volume measurements appears not to be influenced by thorax's movement magnitude.

I. Introduction

Opto-electronic systems (OS) are motion analysis systems used in different medical fields: gait analysis, human superior limb analysis, respiratory pattern analysis and similar applications. These systems are able to measure human movements without mechanical restraints and so they do not restrict free movements [1, 2, 3]. The main factors affecting accuracy of OS have to be identified in order to eventually improve diagnostic capabilities of these devices. The accuracy depends on the size of measurement field, on position and on size of markers. Other factors affecting accuracy could be due to optical distortion (imperfect lens shape, camera assembly, decentering of lens), number of cameras and cameras set-up (distance between centers of projection of the cameras, size of field of view) [4]. Finally, OS accuracy may be affected by electronic noise, shape distortion, conversion from marker images in image points, conversion from image points into numerical coordinates, obscured markers, and merge of close markers [5, 6]. The aim of calibration is to reduce these concerns, by using specific algorithms. Moreover, the calibration allows to determine the geometric and optical characteristics of the cameras [7, 8]. Sometimes, OS record small movements (from micrometers to millimeters), like thorax or facial movements, and therefore, a careful metrological analysis is required [8]. In literature several tests are proposed to validate OS accuracy. Most of them investigate markers displacement or inter-markers distance, because the OS analyzes human limb movements by measuring velocity and acceleration [9, 10, 11]. However, a few studies evaluated OS metrological characteristics on volume measurements. In [11] different solids are used to evaluate reliability, stability and precision of OS, concerning surface and volume measurements. Solids' surface and volume are measured both by OS and mathematical equations and starting from linear measurements by caliper. To the best of our knowledge, the OS accuracy of volume measurement has been assessed only by static trials.

The purpose of this work is to assess the reliability of OS volume measurements also in dynamic conditions. The opto-electronic plethysmograph (OEP) has been evaluated in this work. OEP is a particular OS, developed by Bioengineering Department of the University of Milan [12]. It is employed in clinical applications to measure pulmonary volumes by markers positions, applied on the thorax (front and back). In [13], accuracy of OEP has been evaluated, but only on linear displacements. Therefore, the aim of this study is to evaluate the accuracy of OEP on volume measurements, by using a volumetric respiratory simulator performing the thorax movements with known volume variations.

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II. Methods

A. OEP

OEP allows to measure volume of Chest Wall (CW) and of six different compartments (right and left): Rib Cage Pulmonary (RCp), Rib Cage Abdominal (RCa) and Abdomen (AB) [14]. This configuration allows to measure the tidal volume of single compartment as a function of time, and to obtain information about any asymmetries between sides in patients [15, 16]. OEP records marker's trajectories thanks to 6 cameras (800x600 pixels, C-mount compatible lens with focal length 8 mm, acquisition frequency 60 Hz), synchronized with coaxial infrared flashing light-emitting diodes (LEDs) and placed so that each marker is acquired by at least two cameras. Markers reflect the light to cameras with high brightness, so the marker position is seen as a circular spot on a background [17].

An algorithm based on the Gauss's theorem, allows to compute CW volume of the closed surface starting from marker's coordinates. The Gauss's theorem is expressed as:

$$\int_S \vec{F} \cdot \vec{n} dS = \int_V \nabla \cdot \vec{F} dV = \int_V dV = V_{CW} \qquad (1)$$

where F is an arbitrary vector with $\nabla \cdot \vec{F} = 1$, S is a closed surface, V is the volume closed by S and n is the normal unit vector on S [18]. Surfaces are triangles with markers as vertices.

B. *Dynamic volumetric respiratory simulator*

A dynamic volumetric respiratory simulator (RS) has been designed and assembled in order to reproduce the thorax movements during normal human breathing. RS has been tested by comparing RS movements with healthy subject's thorax movements. Markers have to be placed on the RS so that OEP is able to calculate the RS volume. At the same time, the RS volume is evaluated by another measurement system, to perform the comparison with OEP measures.

The main features of RS are: (1) volume known in every time and through other volume measurement system; (2) size close to human chest wall; (3) dynamic characteristics, in order to simulate the breathing; (4) no reflecting infrared rays, so that OEP cannot recognize other objects as markers.

In order to comply with the above cited points, the RS adopts linear actuators (maximum stroke 40 mm, maximum velocity 240 mm/s, resolution 1 μm) placed on a fixed base. Actuators move 8 panels on which markers are placed (Fig. 1). In order to establish markers' position on panels, healthy subject breathed normally for 1 minute. Therefore, displacements, velocity and acceleration of markers have been identified and markers with similar displacements are placed on the same panel. Number, dimension and slope on fixed base of panels are established accordingly to chest wall compartments' division of OEP and human thorax size. The actuator's control has been implemented through a motion multiple axes control in LabVIEW environment. Hall sensors are embedded in linear actuators such as markers' position is known at every moment. In this way, an algorithm implemented in Matlab, based on equations described in Appendix [6], allows to estimate the RS volume starting from 89 markers position.

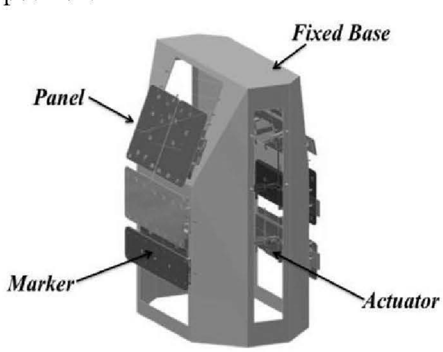

Figure 1. Schematic of respiratory simulator (RS)

C. *Experimental set-up*

In order to verify OEP metrological characteristics on volume measurements, RS volume has been estimated by both OEP and volume's computation algorithm. The RS has been placed in OEP workspace (Fig. 2); all trials were performed by maintaining the RS at same relative distances from cameras. Panels' displacements have been set equal to 3.2 mm, 5 mm, 10 mm and 20 mm. Hall sensors record panel displacements and the algorithm calculates the swept volume. Then, these measurements were compared with OEP ones.

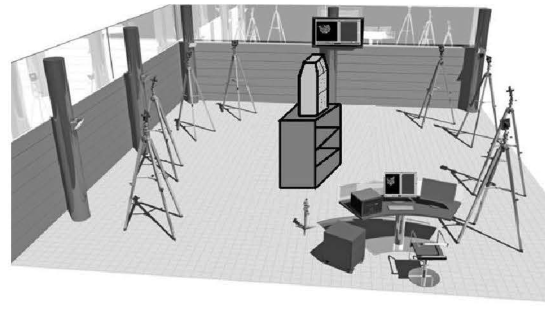

Figure 2. Experimental setup: RS is placed in OEP workspace

During a single trial, the panels' displacement is repeated 10 times. For each panel, the velocity is 24 mm/s and acceleration is 60 mm/s^2. Hall sensors record panels' displacement values and the algorithm processes these data. Therefore, the algorithm can calculate the RS total volume starting from recorded displacements. OEP records the position and displacements of 89 markers placed on RS panels and Smart Capture© software reconstructs the model of RS, by calculating the volume.

III. RESULTS

Average on 10 tidal volumes (TV) measured by OEP (TV_{OEP}) and by algorithm (TV_{Alg}), and their absolute difference defined as $\Delta = |TV_{OEP} - TV_{Alg}|$, have been calculated for each displacement (D).

TABLE I. TIDAL VOLUME MEASURED BY OEP AND COMPUTED BY ALGORITHM

D [mm]	*TV_{OEP} [L]*	*TV_{Alg} [L]*	*Δ [L]*
3.2	*0.46 ± 0.01*	*0.42 ± 0.03*	*0.04*
5	*0.72 ± 0.02*	*0.57 ± 0.03*	*0.15*
10	*1.37 ± 0.06*	*1.13 ± 0.05*	*0.24*
20	*2.56 ± 0.06*	*2.28 ± 0.03*	*0.28*

Fig. 3 highlights the differences between TV_{OEP} and TV_{Alg} for D=3.2 mm, D=5 mm, D=10 mm, and D=20 mm.

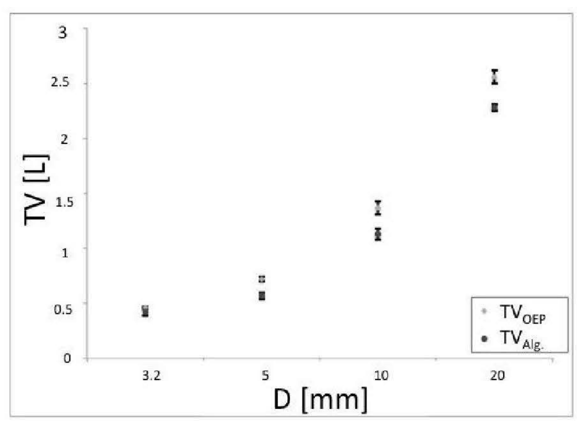

Figure 3. Comparison between tidal volumes measured by OEP and algorithm.

These results show that Δ increases with the magnitude of markers displacement. In this way, the RS could be considered useful to analyse TV_{OEP} for small displacements. These results show that the RS can be used to simulate the quiet breathing, where chest wall movements do not exceed 5 mm in normal subjects. However, the problem could be solved controlling better asynchrony between panels; indeed, the panel asynchrony occurs mainly with larger displacements. In particular, during D=10 mm and D=20 mm, all panels start again with different delay after "inspiration phase", although the setting delay is equal for all. This concerns is related to different frictions between the linear guide and panels. The friction causes a delay between panels and therefore, the volume computation could result incorrect. Algorithm's volume and OEP's one versus time are represented in Fig. 4.

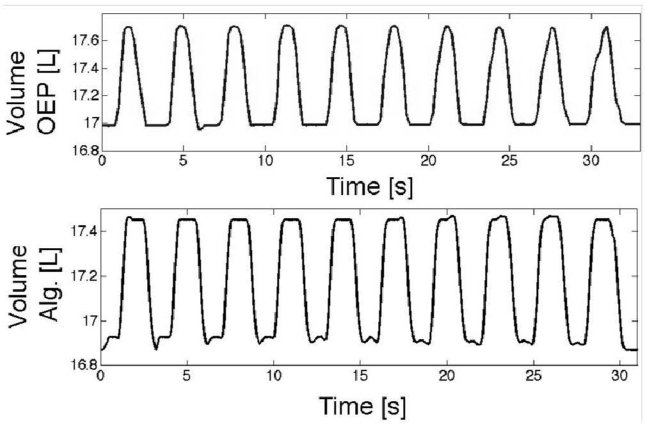

Figure 4. Algorithm's volume and OEP's one for D= 5 mm.

Fig. 4 shows that OEP overestimates the dynamic volume realized by the RS for D=5 mm. This result is obtained for all displacements.

Bland-Altman plot has been used to analyse the agreement between TV_{OEP} and TV_{Alg}, taking into account 10 respiratory acts.

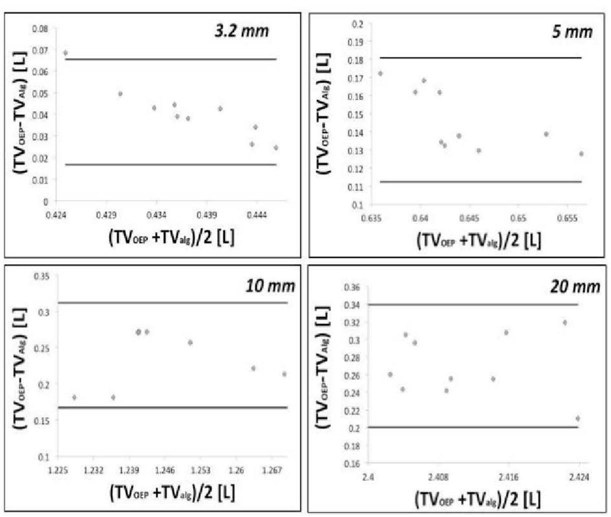

Figure 5. Bland-Altman plot for 3.2 mm, 5 mm, 10 mm and 20 mm displacement

The limit of agreements, shown in Fig. 5, are calculated as $mean \pm 1.96 \cdot std$. The measurements performed by both techniques appear to be consistent for all displacements.

Finally, the accuracy of OEP TV measurements has been evaluated as:

$$Accuracy_{TV}\ \% = \frac{TV_{OEP} - TV_{Alg}}{TV_{OEP}} \cdot 100 \qquad (2)$$

Results are shown in Table II.

TABLE II. TIDAL VOLUME ACCURACY FOR ALL DISPLACEMENTS

D [mm]	$Accuracy_{TV}$ [%]
3.2	9
5	20
10	18
20	11

Accuracy values appear not to be influenced by the magnitude of markers' displacement. The accuracy ranges from 9% to 20% and the best accuracy is obtained for 3.2 mm displacements.

IV. CONCLUSION

In this work, OEP accuracy on volume measurements has been assessed, by using a dynamic volumetric RS performing the thorax movements with known volume variations. The RS has been designed and assembled in order to simulate quiet human breathing. Comparison between TV_{OEP} and $TV_{Alg.}$ shows that OEP could be considered valid to measure tidal volume during quiet breathing because normally chest wall's displacements are not greater than 5 mm. Results show that OEP accuracy on volume measurement does not depend on panels' displacement magnitude. In [11], the OS volume accuracy is assessed in static conditions. Accuracy is well represented by a logarithmic regression (from 20% to 4%), whose trend decreases with the increase of geometric solid volumes (from 0,1 to 270 mL). The accuracy on tidal volume measurements of this study ranges from 9% to 20%, but measurements have been carried out on dynamic volumes; therefore, these results could be influenced by RS panels' asynchrony during movement. In order to improve RS performance, panel asynchrony would be reduced, modifying the LabVIEW control program. However, obtained results show that RS is appropriate to validate OEP.

Accuracy of OEP obtained on tidal volume measurements appears not to be influenced by thorax's movement magnitude. Workspace's conditions could influence the measurements' accuracy. Therefore, it is important to evaluate a priori the working environment, in order to avoid errors on volume measurements.

APPENDIX

The chest wall can be considered as a group of h polyhedra [6]. Vertices of each polyhedron are 8 markers: 4 on the front and 4 on the back. A polyhedron can be splitted into 6 tetrahedra in different ways. The base area BA_i of *i-th* tetrahedron is calculated:

$$BA_i = \left(\left(\det \begin{vmatrix} y_{B_{3i}} - y_{B_{1i}} & z_{B_{31}} - z_{B_{1i}} \\ y_{B_{2i}} - y_{B_{1i}} & z_{B_{2i}} - z_{B_{1i}} \end{vmatrix}^2 + \right.\right.$$

det*zB31− zB1ixB3i− xB1izB2i− zB1ixB2i− xB1i2+* det*xB3i− xB1iyB3i− yB1ixB2i− xB1iyB2i− yB1i212* (3)

The plane equation of the tetrahedron's base is:

$$A_{ki}x + B_{ki}y + C_{ki}z + D_{ki} = 0 \tag{4}$$

where A_{ki}, B_{ki}, C_{ki} are the direction parameters, calcuted as follow:

$$A_{ki} = (y_{B_{2i}} - y_{B_{1i}})(z_{B_{31}} - z_{B_{1i}}) - (y_{B_{3i}} - y_{B_{1i}})(z_{B_{2i}} - z_{B_{1i}}) \tag{5}$$

$$B_{ki} = (x_{B_{3i}} - x_{B_{1i}})(z_{B_{2i}} - z_{B_{1i}}) - (x_{B_{2i}} - x_{B_{1i}})(z_{B_{31}} - z_{B_{1i}}) \tag{6}$$

$$C_{ki} = (x_{B_{2i}} - x_{B_{1i}})(y_{B_{3i}} - y_{B_{1i}}) - (x_{B_{3i}} - x_{B_{1i}})(y_{B_{2i}} - y_{B_{1i}}) \tag{7}$$

The co-ordinates of P_{ki} point of intersection between the plane (4) and the straight line perpendicular to the base and passing from the opposite vertex are the solution of the following system:

$$\begin{cases} A_{ki}x_{P_{ki}} + B_{ki}y_{P_{ki}} + C_{ki}z_{P_{ki}} + D_{ki} = 0 \\ x_{P_{ki}} = A_{ki}t_{ki} + x_{O_{ki}} \\ y_{P_{ki}} = B_{ki}t_{ki} + y_{O_{ki}} \\ z_{P_{ki}} = C_{ki}t_{ki} + z_{O_{ki}} \end{cases} \tag{8}$$

So, it is possible to obtain:

$$t_{ki} = -\frac{A_{ki}x_{O_{ki}} + B_{ki}y_{O_{ki}} + C_{ki}z_{O_{ki}} + D_{ki}}{A_{ki}^2 + B_{ki}^2 + C_{ki}^2} \tag{9}$$

The distance δ_{ki}between the vertex O_{ki} and the point $P_{ki}$is:

$$\delta_{ki} = \sqrt{A_{ki}^2 t_{ki}^2 + B_{ki}^2 t_{ki}^2 + C_{ki}^2 t_{ki}^2} = |t_{ki}|\sqrt{A_{ki}^2 + B_{ki}^2 + C_{ki}^2} \tag{10}$$

The volume of tetrahedron is computed as:

$$VU_{ki} = \frac{BA_i \cdot \delta_{ki}}{3} \tag{11}$$

Once the tetrahedra volumes have been calculated, polyhedron volume (V_P) can be obtained by summing as follows:

$$V_P = \sum_{k=1}^{2} \sum_{i=1}^{3} VU_{ki} \tag{12}$$

The sum of *h* polyhedra volumes is the chest wall volume (V_{CW}):

$$V_{CW} = \sum_{k=1}^{h} V_p \tag{13}$$

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