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Accuracy evaluation on linear measurement through opto-electronic plethysmograph

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***Abstract*—Opto-electronic plethysmograph (OEP) is a motion analysis device able to measure chest wall motion and volume variation by surface measurement. The estimation is obtained through displacements measurements of markers placed on the thorax. Therefore OEP accuracy on markers' displacement measurements may play a role in the volume's measurement.**

The aim of present work is to evaluate OEP accuracy in the estimation of linear displacements, taking into account the contribution due of number of cameras, markers size and displacement magnitude.

A linear DC-motor was used to move the marker fixed on its shaft. Trials have been carried out varying 1) marker size (diameters of 6 mm and 12 mm), 2) cameras number (2, 4, and 6) and 3) the magnitude of displacements (from 10 µm up to 200 µm). Number of cameras and marker size do not seem to play a crucial role as far as it concerns accuracy on linear displacements. The relative percentage uncertainty decreases from 10% to 6% for marker A, increasing number of cameras from 2 to 6; for marker B, the percentage relative error decreases from 17% to 10%, increasing number of cameras from 2 to 4. Moreover, OEP shows a discrimination threshold of 30 µm.

I. INTRODUCTION

Optoelectronic systems for motion analysis (OS) are used in order to quantify the kinematic and temporal features describing the movement of various body segments. [1, 2]. Measurement of human posture and movement is an important area of research of bioengineering and rehabilitation fields: in orthopaedics and physical rehabilitation; in sport medicine, to study athletic performances; in pulmonology, to analyse respiratory pattern; in neurophysiology, to achieve more data about motion control and in neurology to control slight deviations which are not observable by simple overview [3].

OS consists of an interface, a video signal processor and a computer. Interface comprises a defined number of cameras, depending on application, and of a number of markers, placed on the body [4]. Markers could be active or passive; in both cases, for 3D analysis as a function of time, images must be recorded by at least two cameras. Markers can be detected by threshold detection or by image signal processing. The first one is the method implemented in Vicon System and Motion Analyser; the second method consists of real-pattern recognition and it is implemented in ELITE (ELaboratore Immagini TElevisive; Milan Polytechnic Milan®). This system works on real-time recognition of the shape and size of the markers rather than their brightness, showing higher reliability [4, 5].

Opto-electronic plethysmograph (OEP) is a particular OS, based on ELITE system, employed in clinical applications, for example in respiratory rehabilitation [6], to measure chest wall motion and rib-cage volume variations. OEP allows to measure volume of Chest Wall (CW) and of six different compartments (right and left): Rib Cage Pulmonary (RCp), Rib Cage Abdomen (RCa) and Abdomen (AB).

Some research [7,8,9,10] assessed the main metrological characteristics of OS for clinical applications. Experimental set-up and trials were different depending on the system and its application. In most of them, authors have tried to simulate human movements, trough either subjects and trough mechanical devices [8,11]. In [8] and in [9], OS have been analysed to evaluate the clinical performance changing four factors: (1) cameras number, (2) input device, (3) marker identification process and (4) type of marker. In [8], eleven commercially OS calculated relative distance between two markers, fixed on rigid bar, held by a subject walking, sequentially. The number of cameras used ranged from two to six, depending on the system. The mean absolute percentage error of relative distance measurement ranged from 0.2% to 2.0% in systems with 2 cameras, from 0.1% to 0.2% in systems with 4 cameras and from 0.6% to 0.8% in systems with 6 cameras. The maximum relative distance error measured has been 5.7% with 2 cameras. In [11], seven passive markers are fixed on rotating plate, driven by motor, and distance between them has been measured by seven different motion analysis systems (the distance between markers is constant during trials). The accuracy of these systems ranged from 0.1 mm to 15 mm. Maximum relative distance error measured is 16.1 mm.

The aim of present work is to evaluate OEP accuracy and resolution in measuring linear displacement, because they influence metrological characteristics of OEP in volume estimation. For example, accurate volume measurements are essential in the assessment of pulmonary rehabilitation.

Linear displacements were performed by a linear DC-motor varying systematically marker size, cameras number and the magnitude of displacements.

II. EXPERIMENTAL SETUP

A. OEP System

OEP records marker's trajectories placed on the thorax thanks to 6 cameras (800x600 pixels, C-mount compatible

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lens with focal length 8 mm, acquisition frequency 60 Hz), synchronized with coaxial infrared flashing light-emitting diodes (LEDs) [12-13]. A processor acquires the three dimensional markers' coordinates and an algorithm based on Gauss's theorem, computes chest wall volume of the closed surface starting from markers' coordinates [12].

In detail, the Gauss's theorem is

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

where F is an arbitrary vector, S is the closed surface, V is the volume closed by S and n is the normal unit vector on S. Thanks to this geometrical model, the estimation of the whole chest wall and its compartment's volumes depends on S measurements (1). S is measured from marker's positions, therefore OEP accuracy on markers' displacement measurements assumes a crucial role in the volume's assessment.

B. *Camera Setup and Calibration*

Before performing OEP calibration, it is important to set cameras: to adjust the lens iris of cameras in order to obtain good contrast between the background and markers, to focus the lens at the center of the volume of interest and to modify the targeting of cameras by acting on the regulation of tripod. Workspace needs to be free of all objects that may block the view of the cameras or that reflect infrared light.

The calibration process consists on the acquisition of two sequences: in the first one, a set of carbon rods with 9 markers is placed in the middle of workspace; cameras record the static position of these markers for about 10 s. This procedure fixes the reference system. In the second, three movements (roll, pitch and yaw) of a wand with 3 markers, parallel to axes of reference system, are carried out sequentially for about 100 s. Environmental conditions and spatial arrangement of the cameras in the workspace must not be changed during the execution of trials.

C. *Experimental Protocol*

An experimental setup has been realized in order to perform an accuracy assessment of the OEP. Movements performed by means of an electrical linear DC-Motor (M-235, Physik Instruments®, travel range 20mm, resolution 0.5 μm). The marker is placed at the end of motor's shaft and controlled in position by MMCRun (Mercury Motor Controller), as shown in Fig. 1-a.

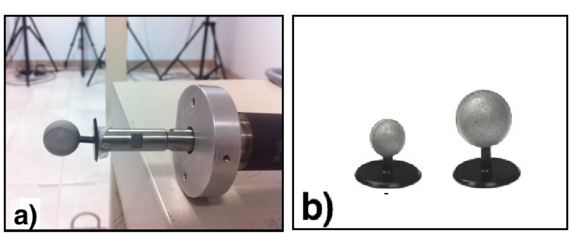

Figure 1. **a)** Marker placed on the end of linear DC-Motor's shaft; **b)** passive marker with two sizes: on the left, *Marker A* (diameter 6 mm); on the right, *Marker B* (diameter 12 mm).

In order to evaluate the influence of the number of camera on OEP performances, experimental trials have been carried out moving marker along *z-axis* and using three different cameras' configurations: 1) all six cameras (Fig. 2-a); 2) four cameras (Fig. 2-b); 3) two cameras (Fig. 2-c).

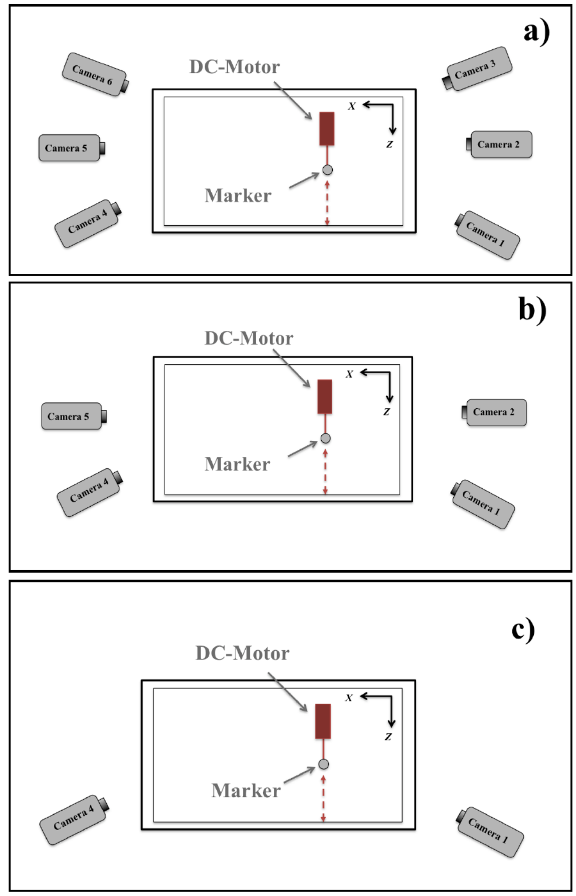

Figure 2. Three different configurations: **a)** 6 TV cameras; **b)** 4 TV cameras; **c)** 2 TV cameras.

OEP performances are tested in all three cameras configurations using two passive spherical markers with different diameters (Fig. 1-b): the marker A has a diameter of 6 mm and marker B of 12 mm. Five sets of measurements are performed with each marker and for every camera's configuration at displacements ranging from 10 μm up to 200 μm (10 μm, 30 μm, 50 μm, 100 μm, and 200μm). For each of them, five forward steps have been executed and the motor's shaft remained in required position for 5 seconds. The experimental protocol is shown in Fig. 3.

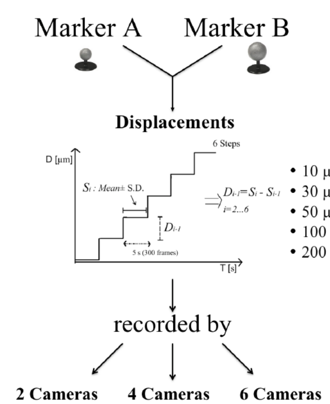

Figure 3. Schematic of experimental protocol.

D. Statistical analysis

A data set consists of 300 frames for each step, *S*, of a single displacement, *D*, being the cameras sampling frequency 60 Hz. Mean and standard deviation have been calculated on 300 frames for each *S* of a single trial, achieving 6 values (Fig. 3).

In order to obtain D_i, the difference between two following steps has been calculated:

$$D_{i-1} = S_i - S_{i-1} \qquad i=2...6 \qquad (2)$$

Therefore, mean and expanded uncertainty on five displacements are computed. The expanded uncertainty is estimated considering a Student reference distribution with four degrees of freedom and a level of confidence of 95 %.

The comparison between displacements measured with different kind of markers and different cameras configurations, is carried out with two approaches: the first one is the Bland-Altman plot [14], which allows to evaluate the agreement between measurements carried out through two different cameras configurations; the second one is the correlation to observe the trend between measurements.

III. Results and Discussion

The main results represented as mean± the expanded uncertainty are shown in Table I.

TABLE I. Mean±Uncertainty For Five Different Displacements, Two Different Markers (A and B) And Three Different Camera Configurations.

		Displacement [µm]				
N° Cameras		**10**	**30**	**50**	**100**	**200**
2	*Marker A*	8±6	33±3	52±3	100±10	212±15
	Marker B	16±12	35±5	54±6	104±18	198±5
4	*Marker A*	1±3	31±2	53±2	99±6	196±20
	Marker B	0±1	29±3	51±3	103±3	205±20
6	*Marker A*	0±1	32±2	53±2	99±1	190±12
	Marker B	5±6	27±4	52±9	9±1	194±11

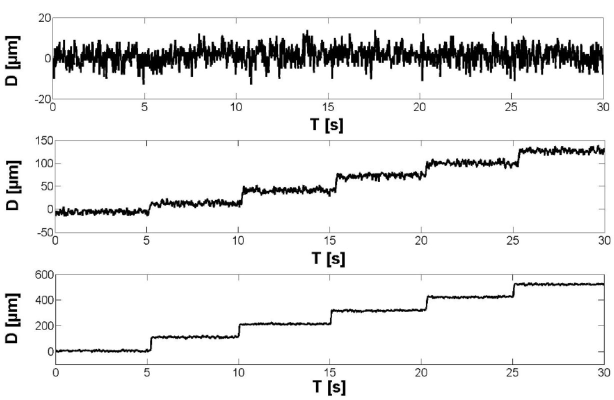

Figure 4. Example of displacements performed by motor with steps of 10 µm, 30 µm and 100 µm respectively.

OEP is not able to discriminate displacements of 10 µm, for any kind of marker and number of cameras used, because noise in almost all cases is higher than measured value. Fig. 4 shows experimental data recorded by OEP when displacements of 10 µm, 30 µm and 100 µm are applied: in 10 µm trail, the 5 steps performed by motor are not discernible.

The accuracy of linear displacement measured is ranged from 1 µm to 12 µm in the whole trials, and it is not influenced either by the size of marker or number of cameras. The accuracy is better than the accuracy obtained using other motion analysis systems: in this study, the accuracy is of linear displacement measured is ranged from 3% to 6%, on the other hand the accuracy of relative distance measured is ranged from to 1% to 17% [11].

The comparison between assigned displacements and measured ones (ranging from 30 µm up to 200 µm) have been reported using all camera configurations (Fig. 5). Generally speaking, we found no significant differences changing the size of marker. However, using 6 cameras, with D=50 µm, the percentage uncertainty of displacement, expressed as $\frac{\delta D}{D}*100$, is of 6% for marker A and 18% for marker B.

The maximum relative percentage uncertainty using 2 cameras is 17% (marker B, D=100 µm). Using 4 cameras, the maximum relative percentage uncertainty is 10 % (marker B, D=30 µm) and 18% using 6 cameras (marker B, D=50 µm). The maximum relative percentage uncertainty decreases from 10% to 6% for marker A, increasing cameras from 2 to 6; for marker B, the percentage relative uncertainty decreases from 17% to 10%, increasing cameras from 2 to 4.

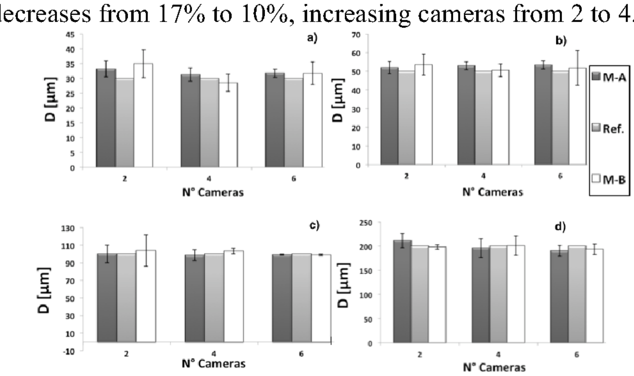

Figure 5. Measured displacements, for three cameras configuration (2,4, and 6) and for four assigned displacements: **a)** 30 µm; **b)** 50 µm; **c)** 100 µm; **d)** 200 µm.

The percentage relative uncertainty is slightly higher than percentage uncertainty of relative distance measured between two markers, shown in [8]. Moreover, percentage relative uncertainty between systems with 2 cameras and 6 cameras decreases of 88% in [8] versus only 4% in this study.

Bland-Altman plot is reported in Fig. 6 to observe if 2 and 6 cameras configuration have good correlation measuring the same displacement. These configurations have been chosen because 2 cameras are the minimum number to identify a marker and 6 cameras are the maximum number used in OEP. In Bland-Altman plot, the y-axis is the difference $\Delta D_{2,6}^{i,j}$ between the *i-th* displacement (from 1 to 5) with *j-th* size (ranged from 30 µm to 200 µm) measured through 2 and then through 6 cameras. In the *x-axis*, the average $A(D)^{i,j}_{2,6}$ between the same displacements, measured by 2 and 6 cameras. The results are shown in Fig. 6.

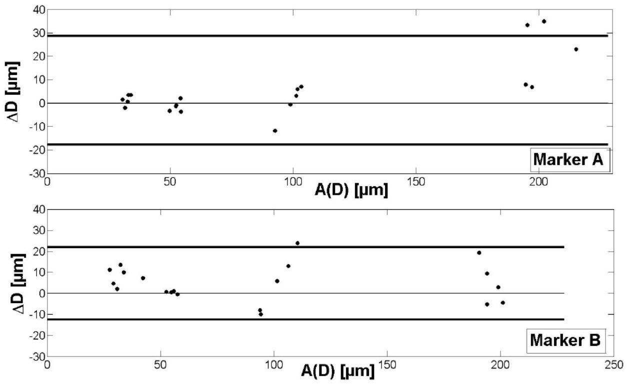

Figure 6. Bland Altaman plot comparing 2 cameras and 6 cameras configuration, for marker A and marker B.

Fig. 6 shows that measurements performed in both cases are consistent, only of 10% of data for marker A and 5% for marker B are out confidence interval.

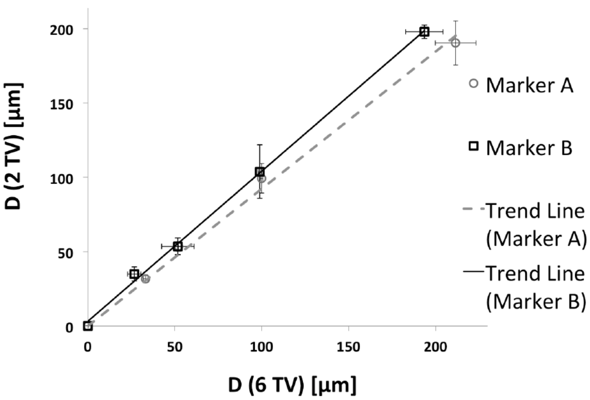

Figure 7. Correlation between mean displacements performed by 2 cameras and 6 cameras.

Fig. 7 shows a good linear correlation between mean displacements recorded by 2 camera and 6 cameras, both for marker A and for marker B. The coefficient of determination R^2 is 0.995 for marker A and 0.997 for marker B. The slope of trend line close to 1 (e.g., 0.992 for marker A and 0.97 for marker B) confirms the good agreement between the displacements measured using the two configurations.

IV. CONCLUSION

In this study, linear displacements ranged from 10 μm to 200 μm have been measured by OEP, with two different markers (diameter 6 and 12 mm) and varying the number of cameras (2, 4 and 6). Displacements of 10 μm are not discriminate by OEP, for any kind of marker and any number of cameras. Therefore, OEP shows a discrimination threshold of 30 μm.

The largest errors are measured for displacement less than 50 μm. Increasing number of cameras from 2 to 6, allows a better accuracy only if the smallest marker is utilized (marker A). Nevertheless, there is not a significant difference using 2 or 6 cameras.

This study is aimed to a preliminary evaluation of OEP performance, varying three factors. Other trials should be performed to evaluate the accuracy of volume measurements, increasing the number of markers.

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