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Short communication

Appropriateness of plantar pressure measurement devices: A comparative technical assessment

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ABSTRACT

Accurate plantar pressure measurements are mandatory in both clinical and research contexts. Differences in accuracy, precision and reliability of the available devices have prevented so far the onset of standardization processes or the definition of reliable reference datasets. In order to comparatively assess the appropriateness of the most used pressure measurement devices (PMD) on-the-market, in 2006 the Institute the author is working for approved a two-year scientific project aimed to design, validate and implement dedicated testing methods for both in-factory and on-the field assessment. A first testing phase was also performed which finished in December 2008. Five commercial PMDs using different technologies—resistive, elastomer-based capacitive, air-based capacitive—were assessed and compared with respect to absolute pressure measurements, hysteresis, creep and COP estimation. The static and dynamic pressure tests showed very high accuracy of capacitive, elastomer-based technology (RMSE $< 0.5\%$), and quite a good performance of capacitive, air-based technology (RMSE $< 5\%$). High accuracy was also found for the resistive technology by TEKSCAN (RMSE $< 2.5\%$), even though a complex ad hoc calibration was necessary.

1. Introduction

Even today plantar pressure measurement is hardly considered a meaningful tool in clinics or in research contexts, although its potential is highly recognized [1]. Reasons for such poor success may be searched in different accuracy and reliability of existing pressure measurement devices (PMDs) due to different sensor technology, spatial resolution, pressure range, sampling rate, calibration and processing procedures. Very few technical studies have been published until now on this issue [2–5], and no peer-reviewed studies have been found about technical assessment and comparison of different PMDs.

To overcome this need, in 2006 the Institute the author is working for approved a two-year project to design, validate and implement dedicated testing methods and instruments for PMD technical assessment with respect to accuracy and reliability of measured pressure, hysteresis, accuracy and precision of centre of pressure (COP) estimation. Once instrumentation and procedures had been implemented and validated, Companies were officially invited to take part in the study to assess their best product on the market. The testing phase finished in December 2008. Five PMDs were tested in all: three had resistive sensors (TEKSCAN, RSSCAN, MEDILOGIC, all taken from the market), one had capacitive elastomer sensors (NOVEL, delivered by the Company), one had capacitive air sensors (AM CUBE, delivered by the Company). The study reports on the testing equipment and protocols, and on the main results of the technical assessment of the above products.

2. Materials and methods

Two testing devices were constructed and validated (Fig. 1): a custom pneumatic bladder pressure tester (PM) and a dedicated pneumatic-force testing device (PTD).

The PM, used to uniformly apply pressure over the entire PMD sensor matrix, is a very heavy structure with a membrane interfacing the inflated air and the PMD surface. It was used together with a digital pressure transducer (resolution 10 Pa) to deliver pressure ramps of loading from 0 to the maximum declared PMD pressure (1200 kPa at maximum) and back to 0, with 50 kPa steps, between-step transition time 5 s, step duration 5 s.

The PTD – widely described elsewhere [6] – consists of a pneumatic testing device with an on-off valve, a proportional valve, force and pressure controls (relative error <1%). Pressure is applied through a stainless steel head (7.03 cm^2, no membrane in between). Applied pressure ranges from 0 to 600 kPa. For each PMD, the following tests were performed over 5 randomly selected areas:

(1) 100 kPa steps of static pressure from 0 to 600 kPa and back to 0, each step lasting 5 s, the area being completely offloaded after each step;
(2) sinusoidal pressure cycles (0–500 kPa; 0.75 Hz; at least 10 cycles) applied through the proportional valve;
(3) constant pressure (350 kPa; 60 s) to investigate creep.

To assess COP estimation an additional tool was constructed to apply known forces through the PTD, whose core is a graduated aluminium table, 15 cm diameter, with three 3 cm-diameter pylons, and a central hole to vertically insert a pin and acquire the theoretical COP coordinates. For each area, COP measurements were performed at a fixed load under 6 different angular positions (angular step 20°).

Raw data, acquired at 20 Hz for the sinusoidal test and at 5 Hz for all the remaining tests, were processed as follows:

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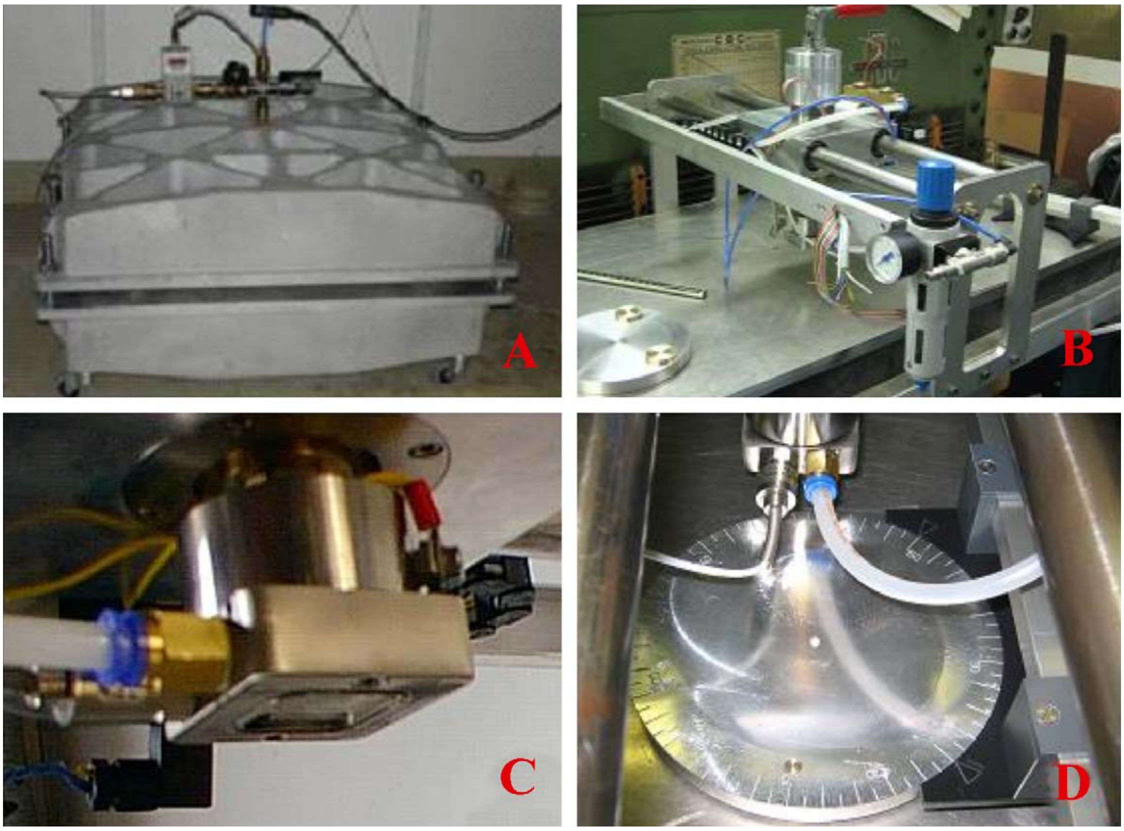

Fig. 1. test devices and tools: (A) custom pneumatic bladder pressure tester (PM); (B) dedicated pneumatic-force testing device (PTD); (C) PTD stainless steel pressure head; (D) graduated table of the tool to apply known forces through PTD. The tool is complete with a graduated positioning system and a pressure chamber protective case.

- *global static pressure test (whole surface)*: at midpoint of each loading period and for each step of the applied up-ramp minimum, maximum, mean pressure, RMSE and linear regression were calculated over the loaded area with the only exclusion of 1.5 cm of boundary;
- *local static pressure test (5 areas)*: in each area and for each pressure step RMSE was calculated at half of the loading period;
- *sinusoidal test (5 areas)*: in each area, %hysteresis of the central sensor was averaged over three cycles;
- *creep (5 areas)*: in each area pressure gradient was calculated over the central 40 s of the loading period;
- *COP estimation (5 areas)*: for each area, COP coordinates were averaged over a 10 s static loading period under each of the 6 angular positions; RMSE was calculated with respect to the theoretical coordinates (accuracy) and among the 6 positions (precision).

3. Results

AM CUBE and NOVEL positively answered to the call and delivered their products for the assessment. Among the remaining relevant PMDs, the MEDILOGIC, RSSCAN and TEKSCAN PMDs were obtained from the market, thus 5 devices were tested in all (Table 1). Each PMD, taken new and considered as a whole with all its hardware and software components, was tested under its best working conditions by the same operator.

RSSCAN data had not been reported in this Technical Note, since a deeper investigation has been agreed with the Company. The manufacturer (RSscan INTERNATIONAL) agreed to cooperate fully and offered the footscan® system and technical assistance to complete the study.

As for TEKSCAN, the PMD best performance was obtained by using a special on-site calibration procedure [7]; such calibration was only available through the Research Software option and called for a dedicated equilibration file built by means of a bladder pressure device [7].

Main results of the technical assessment of the PMDs are summarised in Table 2.

Table 1
Main characteristics of the five tested PMDs.

	AM CUBE	MEDILOGIC	NOVEL	RSSCAN	TEKSCAN
Tested device	AM3 platform (delivered by the Company)	Medilogic platform	EMED-x (delivered by the Company)	RSscan platform	Matscan
Technology	Capacitive, air-based	Resistive	Capacitive, elastomer-based	Resistive	Resistive
Calibration	In-factory (up to 900kPa)	In-factory	In-factory	In-factory plus user calibration	In-factory plus user calibration
Overall sensor matrix	64 × 64	32 × 64	64 × 95	64 × 64	44 × 52
Pressure range (kPa)	0–1200 kPa	0–640 kPa	0–1270 kPa	Not available	0–850 kPa
Resolution (sens/cm^2)	1.7	1.78	4	2.67	1.4
Active sensors per area[a]	9	9	16	9	9

[a] For each tested local area, number of active sensors under the pressure chamber of the testing device.

Table 2
Main results of the technical assessment performed on the PMDs.

Company	AM CUBE		MEDILOGIC		NOVEL		TEKSCAN	
Static pressure test over the whole surface (applied to the PMD declared pressure range)								
Linearity (R^2)	0.974		0.708		0.999		0.995	
%RMSE	23.8 (±8.5)		65.0 (±46.7)		3.0 (±3.2)		14.3 (±10.1)	
Static pressure over 5 small areas (pressure range 0–600 kPa)								
	Best	Worst	Best	Worst	Best	Worst	Best	Worst
RMSE (kPa)	21.6	43.7	36.7	76.8	1.9	2.1	7.4	18.2
Mean RMSE (kPa)	28.8 (±8.6)		59.2 (±13.9)		2.0 (±0.1)		12.7 (±3.4)	
Sinusoidal pressure test (0–500 kPa, 0.75 Hz)								
	Best	Worst	Best	Worst	Best	Worst	Best	Worst
% hysteresis[a]	5.6	21.7	62.8	63.5	2.2	4.1	2.0	7.1
Correlation	0.979	0.957	0.788	0.738	0.998	0.997	0.998	0.995
RMSE (kPa)	140.6	67.2	258.0	281.7	10.5	11.0	23.5	25.3
Creep test (300 kPa constantly applied for 60 s; parameters calculated over the central 40 s)								
	Best	Worst	Best	Worst	Best	Worst	Best	Worst
Error (kPa)	61.0 ± 8.3	85.4 ± 8.5	300 ± 0.0[b]		9.6 ± 1.3	2.4 ± 2.1	26.7 ± 2.2	23.4 ± 3.7
$\Delta P/\Delta t$ (kPa/s)	0.07	0.28	0.00[b]		0.04	0.13	0.04	0.26
COP estimation (accuracy with respect to theoretical coordinates; precision over 6 measurements per area)								
		x ; y		x ; y		x ; y		x ; y
Accuracy [x;y]:	Best	0.22;0.25	Best	0.40;0.43	Best	0.07;0.04	Best	0.19;0.13
RMSE (cm)	Worst	0.44;0.67	Worst	0.51;0.69	Worst	0.17;0.19	Worst	0.16;0.50
Precision [x;y]:	Best	0.16;0.24	Best	0.09;0.13	Best	0.03;0.01	Best	0.07;0.04
RMSE (cm)	Worst	0.26;0.13	Worst	0.13;0.21	Worst	0.04;0.02	Worst	0.05;0.04

For local tests over the 5 random areas of each device, the table shows the results of their best and worst performing area. The best and worst performances were defined on the basis of: (i) the absolute RMSE for the static pressure test; (ii) the %hysteresis for the sinusoidal test; (iii) the slope for the creep test; the *x* and *y* overall accuracy for the COP estimation test.

[a] Calculated over three loading-unloading cycles

[b] Same result for all 5 areas.

4. Discussion

The technical assessment of 5 PMDs based on different sensor technology, electronic solutions and mechanical features proved the implemented testing set-up to be reliably applicable and effective to assess different commercial PMDs.

From the reported results some observations can be drawn:

- the global static pressure test (whole surface) showed a highly linear behaviour of NOVEL up to 1200 kPa and of TEKSCAN up to 800 kPa;
- as for local tests over the 5 random areas:
- the static pressure test showed high accuracy for NOVEL, TEKSCAN and AM CUBE, low variability for NOVEL and TEKSCAN, moderate variability for AM CUBE and MEDILOGIC.
- the %hysteresis (sinusoidal test) was <5% for NOVEL and TEKSCAN except for the worst result of the latter; AM CUBE showed a lower and more variable performance;
- the creep test showed a 0 slope for MEDILOGIC whose causes deserve further investigation. The pressure gradient was comparable for the remaining PMDs under their best performing area, less variable for NOVEL;
- COP estimation showed high precision for all PMDs; NOVEL accuracy error was always lower than its PMD spatial resolution (0.25 cm); TEKSCAN and AM CUBE error was greater than the spatial resolution (0.35 and 0.39 cm respectively) in the worst case only; MEDILOGIC error was always greater than the spatial resolution (0.37 cm).

5. Conclusions

The implemented testing equipment and procedures seem to be appropriate and effective for the technical assessment of commercial PMDs. The study, although restricted to 5 PMDs only, allowed to test and compare the performance of devices with different sensor technologies and assembly modes:

- the capacitive, elastomer-based PMD by NOVEL showed high linearity, low creep, low hysteresis and high correlation under slow sinusoidal loading, high accuracy and precision in COP estimation, low variability of all performances over the whole sensor matrix;
- after dedicated calibration, the resistive PMD by TEKSCAN showed high linearity and moderate spatial variability, low even if variable creep, low hysteresis and high correlation under sinusoidal loading, high accuracy and precision in COP estimation except for one tested area;
- the capacitive air-based PMD by AM CUBE showed good linear fitting and some spatial variability, low even if variable creep, variable hysteresis ranging 6–22%, high accuracy and precision in COP estimation except for one tested area.

Conflict of interest

There are no potential conflicts of interest or any financial or personal relationships with other people or organizations that could inappropriately bias conduct and findings of this study.

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