The use of pressure mapping to assess the comfort of agricultural machinery seats

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Abstract

Interface pressure measurement gives an objective value to human comfort. Prolonged sitting is known to contribute to musculoskeletal disorders. Driving a tractor involves several actions such as steering, operating levers, buttons, brake and clutch pedals, and looking behind to observe and maneuver the machine. These operations affect sitting posture and create a pattern of loading on the structures of the operator's body.

The aim of this study was to study barometric mapping at the operator's buttocks-seat interface for comfort evaluation of the agricultural and forestry machine seats. Three different tractor seats (A "low cost"; B "medium cost"; C "high cost") were tested during ploughing, harrowing and haying operations, by 8 different operators. Two standardized conditions were used, one on a track with ridges and one on an asphalted surface, with driving tests conducted on both. From each test, the following values were obtained: maximum pressure peak (P_{max}); average pressure value (P_{avg}); and the average percentage of cells activated by pressures ranging between 50-130 g/cm^2 (NC_{50-130}), 131-400 g/cm^2 ($NC_{131-400}$) and higher than 400 g/cm^2 ($NC_{401-1000}$). Mean values of P_{avg}, P_{max}, $NC_{131-400}$, recorded after the two lab tests (on the road and the ridged track) carried out with seat-A tractors were greater ($p<0.05$) than those obtained in tests with more comfortable seats (seats B and C). P_{avg} and

Abbreviations in the article: P_{max}: max pressure peak; P_{avg}: average pressure value;
NC_{50-130}, $NC_{131-400}$, $NC_{401-1000}$: percentage value of cells activated respectively by pressures ranging between 50-130 g/cm^2, 131-400 g/cm^2, and higher than 400 g/cm^2.

P_{max} mean values recorded after three field tests carried out with A-seat tractors were greater than those obtained in tests with more comfortable seats (B and C). Similarly, the cell activation in the pressure interval 131-400 g/cm^2 ($NC_{131-400}$) in A-seat tests was significantly greater than that of both B and C seats. Based on our findings, it is possible to conclude that the analyzed pressure indexes in this study are useful instruments to describe the characteristics of seat mapping and compare agricultural machine seats as a function of operator's buttocks-seat interface, thus highlighting the comfort rate obtainable in dynamic situations by the operator.

Summary

The sitting posture is one of the main factors that contribute to musculoskeletal disorders. The methodology is based on barometric mapping for comfort evaluation. Tractors seats were tested in three agriculture operations and on two standardized tracks. The study showed indicators to evaluate barometric maps in dynamics conditions.

1. Introduction

While driving a tractor, seated operators usually carry out several actions such as steering, operating levers, buttons, brakes and clutch pedals, and looking behind to check and maneuver the tractor. These operations determine the sitting posture and create a pattern of loads on the body joints of the operator (Metha and Tewari, 2000). Extended sitting time may determine a higher risk of back pathologies. In addition, a large surface pressure under the buttocks and thighs can, in the long run, cause damages to the nervous and vascular systems in these areas (Metha and Tewari, 2000; Smith et al., 2015; Sang et al., 2011). Literature suggests that agricultural machinery workers report back pain and discomfort due to prolonged sitting (Futatsuka et al., 1998; Morgan and Mansfield, 2014). The sources of such discomfort may be due to: transmission of vehicle vibration to the operator; body pressure distributed on the operator's buttocks, thighs and back; control of posture adopted during sitting; clothing and seat covering material; and perceptions and interior ergonomic characteristics (Mehta and Tewari, 2000). These operators are usually exposed to low-frequency vibrations transmitted to the whole body (Zeng et al., 2017; Solecki et al., 2007). The transmitted vibration depends on several factors, namely the characteristics of the ground and the tractor's speed (Zeng et al., 2017; Solecki et al., 2007). Exposure to whole-body vibration is a health risk factor due to a degeneration of the rachis structure, the dorsomedial position in the torso (Morgan and Mansfield, 2014; Zeng et al., 2017; Solecki et al., 2007). Several studies on strains for the operator have been developed, evaluating vibrations in different work conditions (Gomez-Gil et al., 2014; Zeng et al., 2017; Solecki et al., 2007).

One of the most important factors affecting seating posture is the distribution of pressure between body and seat (Jones et al. 2017; Ren et al. 2017). The comfort or discomfort of a seat depends on several factors (Hiemstra-van Mastrigt et al., 2017), although the most critical issues are its capability to adapt to the body’s contact area (Hostens et al., 2001; Porter et al., 2003). The underlying physical principle is the distribution of an occupant’s weight on a surface: the greater the surface, the lesser the pressure (De Looze et al., 2003; Kyung et al., 2008a; 2008b). Furthermore, a high-comfort seat provides a uniform pressure distribution and a lower average pressure than a low-comfort seat (de Looze et al., 2003; Taboga et al. 2012). Barometric maps have been used since the ‘90s in the automotive sector, in order to study the effects of the magnitude and frequency of the vibrations transmitted to the operator as well as the pressure distribution in the ischial areas (Gyi and Porter, 1999; Wu et al., 1999). In agriculture, few studies have dealt with this issue (Mehta et al., 2000; Hostens et al., 2001). The design and engineering of seats have procedures to measure only the basic mechanical aspects, such as the geometric parameters of the seats, as well as the choice of the suspension system and cushion material used (Kyung et al., 2008a; 2008b). However, when an occupant sits on a seat, the mechanical parameters interact with the body and trigger physiopathological processes leading to discomfort (Mehta and Tewari, 2000; Pirozzi et al., 2017). Tractor seat designers have focused on ride vibrations and seat geometric parameters with respect to anthropometric data of the users (Wu et al., 1998). However, pressure distribution at the seat-operator interface and body posture are the main factors leading to discomfort for a tractor operator (Kyung et al., 2008a; 2008b). Researchers suggest that subjective comfort assessments would not be representative of a real situation and would not add more information to the seat comparison (Hostens et al., 2001; Hiemstra-van Mastrigt et al., 2017). Hostens et al. (2001) also showed that back pain and sitting discomfort might be associated with prolonged pressure peaks in the human body-seat interface. The aim of the study was to assess the comfort of agricultural machine’s seats, testing several agricultural operations and using a methodology based on the barometric mapping. Furthermore, this study had the aim of identifying some comfort indicators by testing the main agricultural machine seats available on the market.

2. Materials and methods

The study was conducted at the research center of agricultural engineering of the CREA-IT (Centro di ricerca Ingegneria e Trasformazioni agroalimentari) in Treviglio (Bergamo, Italy) and various farms nearby. Tests were carried out according to the flow chart shown in figure 1.

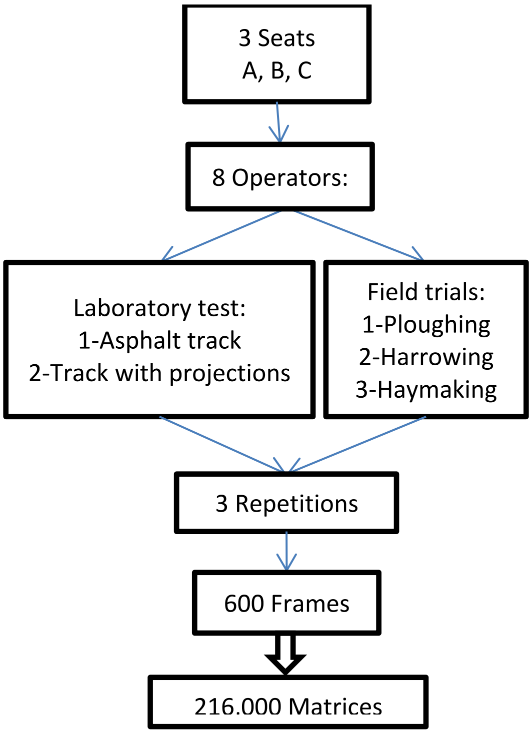


Figure 1. Flow chart of the experimental test

Tests were carried out by 8 operators on three tractors with three different seating conditions (A, B, C). These tests were repeated three times in random order by each operator in the lab (asphalt; corrugated track) and on the field (ploughing; harrowing; haymaking). The field tests were conducted after all the operators completed the laboratory tests. The conducted tests produced a total of 216,000 matrices (3 seats x 8 operators x 5 tests x 3 repetitions x 600 frames).

2. 1 Seats and tractors features

Three different seats regularly sold on the market, were tested. These seats differed in the characteristics listed below: seating surface; the presence of headrest; possibility to adjust the seating (mechanically, pneumatically); size and padding (see table 1). The three seats had the following characteristics: seat A) a “low cost“ seat with a smaller sitting surface, 4.5 cm thick padding, no headrest and/or poor adjusting modes; seat B) a “medium cost” seat with larger sitting surface, 5 cm thick padding, headrest, possibility of mechanical adjustment; and seat C) a “high cost” seat with armrests, headrest and automated adjusting, large and adjustable sitting surface and adjustable backrest, also in the lumbar area. In the case of seat C, the seat could even be adjusted according to the operator’s weight while making any further manual adjustment still possible.

	Seat A	Seat B	Seat C

Sitting area (cm^2)	2068	2288	2499
Backrest area (cm^2)	1634	1665	2021
Seat thickness (cm)	4.5	5.0	6.0
Backrest thickness (cm)	4.0	4.0	6.0
Headrest (Y/N)	N	Y	Y
Breathable fabric	N	N	Y
Height adjustment (Y/N)	N	Y	Y
Lumbar adjustment (Y/N)	Y	N	Y
Suspension type	Mechanic	Pneumatic	Pneumatic/Auto
Fitted to	Tractor A	Tractor B	Tractor C

Table 1. Characteristics of the seats (N=no; Y=yes)

The seat position has been kept fixed in order to avoid any pressure variation on the seat. Due to a mere technical requirement related to seat controls, it was necessary to perform the tests fitting all types of seats (A, B and C) on a corresponding compatible tractor. The tractors used in the tests (Table 2) were equivalent in terms of their technical features and had the same tires (front 480/65R28, back 540/65R38). All tests were conducted with full tanks of gas (140 liters in every machine).

	Tractor A	**Tractor B**	**Tractor C**
Weight (tons)	5.6	5.4	5.7
Power (CV)	150	130	158
Wheelbase (m)	2.856	2.750	2.643
Ground clearance (m)	0.53	0.56	0.56
Length (m)	4.5	4.62	4.63
Width (m)	2.23	2.28	2.30

Table 2. Characteristics of the tractors

2.2 Operators

Tests were carried out by 8 healthy male volunteers, who had the experience of driving agricultural machines for more than 6 months. All subjects had similar anthropometric features. Their demographics in mean ± standard deviation (SD) were: age 36.4 ± 5.3 years, height:174.3 ± 4.9 cm, weight: 72.5 ± 6.2 kg, and body mass index: 22.3 ± 1.4 $kg.m^{-2}$. All of them were right-handed.

2.3 Test types

Seats were tested in 5 different ways: 2 tests were carried out in the lab, and 3 in the field (see figure 1). Lab tests were performed on standard tracks: 1) asphalt; 2) corrugated track. The tests on the field were performed on agricultural fields while carrying out the following operations: 1) ploughing; 2) harrowing; 3) haymaking.

2.3.1 Lab tests

Lab tests consisted of two different phases: 1) motion tests on an asphalted track, conducted at a constant speed of 30 km/h; and 2) motion tests on a ridged track, where tractors moved at a constant speed of 10 km/h. Both the tracks and the tests carried out on them met the requirements provided by the standards OCSE 2/2009 and ISO 5008:2002. Figure 2 shows (a) the asphalted and the ridged tracks and (b) a top view of the circuit.

(a) **(b)**

Figure 2. Tracks used for performing standardized tests conducted in Treviglio's lab: a) standard asphalt, smooth and ridged; b) top view of the site, with part of the track and its inclination.

2.3.2 Tests on the field

Tests on the field consisted of three diverse phases: 1) Ploughing tests at 8 km/h, made with a three-bladed plow weighing 1600 kg, working in furrows 30 cm below ground; 2) Harrowing tests at 10 km/h, made with a 4 m wide, springed harrow, weighing 1400 kg; 3) Haymaking tests at 10 km/h, conducted on a stable lawn (the surface had not been worked for 20 years) carrying out the hay turning operation with a hay spin. The test carried out met the ENAMA no. 41 7/2002 procedure. For about 1/3 of the test field consisted of stone material. The field's main physical-mechanical characteristics were as follows: sand=68%; lime=24%; clay=8%. Median humidity was 18%, and the median resistance to penetration was 0,98 MPa.

2.4 Data acquisition system

The software, CONFORMat Research ver. 7.60-21C (Tekscan Pressure Measurement System, 1998-2012, Boston, MA, USA) was used for reading the data from the sensor arrays. This was a capacitance sensor system, which received the maximum effective pressure distribution relief while the subjects were seated (see figure 3). The sensors used for the tests consisted of a carpet of resistive sensors distributed in a regular matrix of 32 sensors x 32 sensors (Valentino et al., 2004). In particular, the instrumental chain consisted of 2 Evolution Handle data scanners (Tekscan Pressure Measurement System, 2015, Boston, MA, USA) that can collect data at a 100 Hz scan rate.

The system acquired data from eight pressure mapping pads. Each quadrant was the result of the equal division the seating and backrest: 4 on the seat (frames Q 1-4) and 4 on the backrest (frames Q 5-8) (see figure 3). The sensor was 0.64 mm thick and measured a pressure range between 0 and 1000 g/cm^2. Each pressure profile was called a frame. From each frame, the maximum and mean pressure values could be calculated.

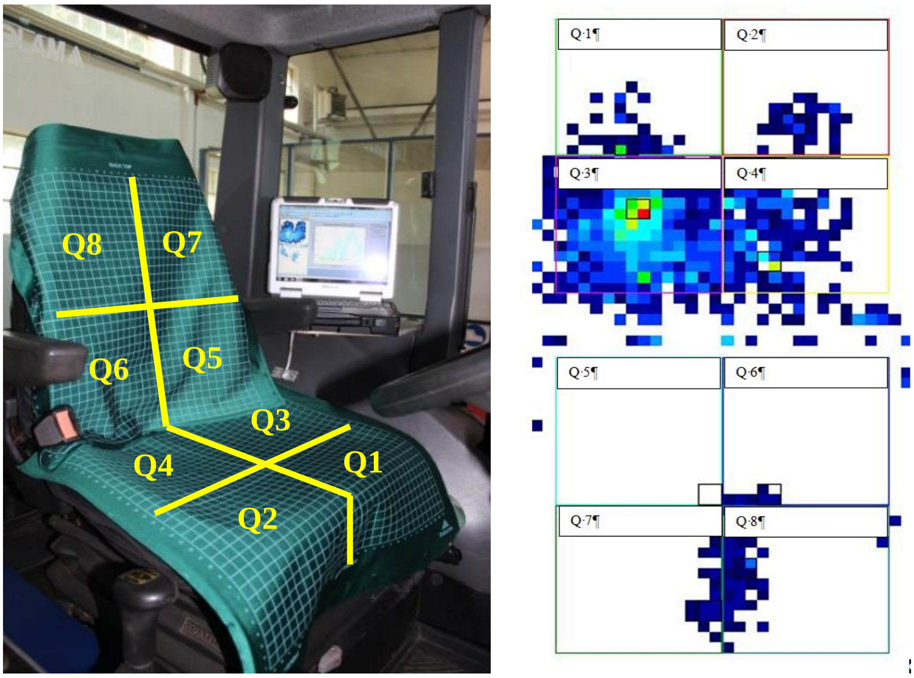
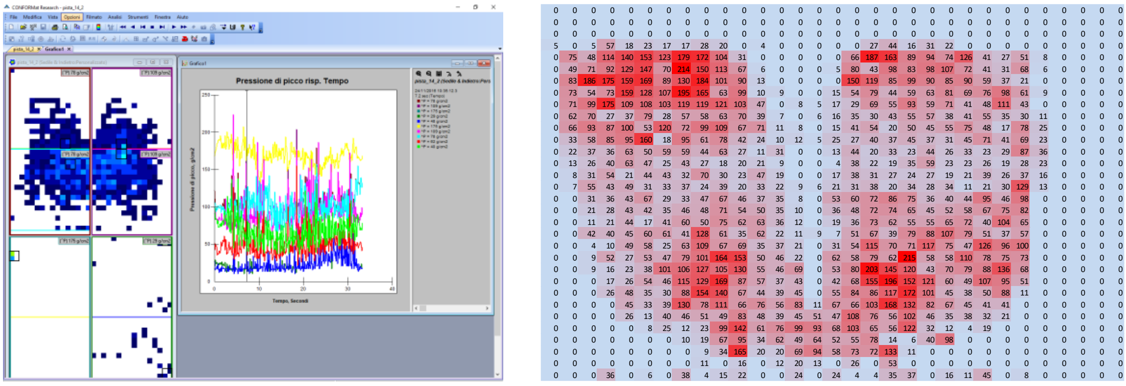


Figure 3. Sensor carpet for barometric measurements (CONFORMat Seat) (left); 8 frames (4 for the seat and 4 for the backrest) that make up the matrix (right).

The software was also able to provide graphs about the pressure, the contact area, and the distribution of force overtime. The software could execute the dynamic playback of 2 or more signals simultaneously; the system could export data in ASCII (see figure 4).



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   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   5   0   5  57  18  23  17  17  28  20   0   4   0   0   0   0   0  27  44  16  31  22   0   0   0   0   0   0   0   0   0
   0  75  48 114 140 153 123 179 172 104  31   0   0   0   0   0  66 187 163  89  94  74 126  41  27  51   8   0   0   0   0
   0  49  71  92 129 147  70 214 150 113  67   6   0   0   0   5  80  43  98  83  98 107  72  41  31  68   6   0   0   0   0
   0  83 186 175 159 169  89 130 184 101  90  13   0   0   0   0 150 119  85  99  90  85  90  59  37  21   0   0   0   0   0
   0  73  54  73 159 128 107 195 165  63  99  10   9   0   0  15  54  79  44  59  63  81  69  76  98  61   9   0   0   0   0
   0  71  99 175 109 108 103 119 119 121 103  47   0   8   5  17  29  69  55  93  59  71  41  48 111  43   0   0   0   0   0
   0  62  70  27  37  79  28  57  58  63  70  39   7   0   6  16  35  30  43  55  57  38  41  55  35  30  11   0   0   0   0
   0  66  93  87 100  53 120  72  99 109  67  71  11   8   0  15  41  54  20  50  45  55  75  48  17  78  25   0   0   0   0
   0  33  58  85  95 160  18  95  61  78  42  24  10  12   5  25  27  40  37  45  37  31  45  71  41  69  23   0   0   0   0
   0  22  37  36  63  50  59  59  44  63  27  11  31   0   0  13  44  20  33  23  44  26  33  23  29  87  36   0   0   0   0
   0  13  26  40  63  47  25  43  27  18  20  21   9   0   0   4  38  22  19  35  59  23  23  26  19  28  23   0   0   0   0
   0   8  31  54  21  44  43  32  70  30  23  47  19   0   0  17  38  31  27  24  27  19  21  39  26  37  16   0   0   0   0
   0   7  55  43  49  31  33  37  24  39  20  33  22   9   6  21  31  38  20  34  28  34  11  21  30 129  13   0   0   0   0
   0   0  31  36  43  67  29  33  47  67  46  37  35   8   0  53  60  72  86  75  36  40  44  95  46  98   0   0   0   0   0
   0   0  21  28  43  42  35  46  48  71  54  50  35  10   0  36  48  72  74  65  45  52  58  67  75  82   0   0   0   0   0
   0   0  11  21  44  17  41  60  50  75  62  63  36  12   0  19  36  73  62  55  55  65  72  40 104  65   0   0   0   0   0
   0   0  42  40  45  60  61  41 128  61  35  62  22  11   9   7  51  67  39  79  88 107  79  51  37  57   0   0   0   0   0
   0   0   4  10  49  58  25  63 109  67  69  35  37  21   0  31  54 115  70  71 117  75  47 126  96 100   0   0   0   0   0
   0   0   9  52  27  53  47  79 101 164 153  50  46  22   0  62  58  79  62 215  58  58 110  78  75  73   0   0   0   0   0
   0   0   9  16  23  38 101 106 127 105 130  55  46  69   0  53  80 203 145 120  43  70  79  88 136  68   0   0   0   0   0
   0   0   0  17  26  54  46 115 129 169  87  57  37  43   0  42  68 155 196 152 121  60  49 107  95  51   0   0   0   0   0
   0   0   0  26  48  35  30  88 154 140  67  44  39  45   0  55  84  86 117 172 101  45  38  50  88  11   0   0   0   0   0
   0   0   0   0  45  33  39 130  78 111  66  76  56  83  11  67  66 103 168 132  82  67  45  41  41   0   0   0   0   0   0
   0   0   0   0  26  13  40  46  51  49  83  48  39  45  51  47 108  76  56 102  46  35  38  32  21   0   0   0   0   0   0
   0   0   0   0   0   8  25  12  23  99 142  61  76  99  93  68 103  65  56 122  32  12   4  19   0   0   0   0   0   0   0
   0   0   0   0   0   0   0  10  19  67  95  34  62  49  64  52  55  78  14   6  40  98   0   0   0   0   0   0   0   0   0
   0   0   0   0   0   0   0   0   9  34 165  20  20  69  94  58  73  72 133  11   0   0   0   0   0   0   0   0   0   0   0
   0   0   0   0   0   0   0   0  11   0  16   0  12  20  13   0  26   0  53   0   0   0   0   0   0   0   0   0   0   0   0
   0   0   0  36   0   6   0  38   4  15  22   0   0  24   0  24   4   4  35  37   0  16  11  45   0   8   0   0   0   0   0
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Figure 4. Picture of the acquired signal after one test (left); data output in ASCII (right).

All tests lasted 6 minutes, even though data acquisition took place between minutes 3 and 4.

This was done to prevent any errors linked either to the starting or closing phases of the test. In this way, the acquisition yielded 600 frames each composed by 1024 pressure values, i.e., ten numerical matrices for 60 seconds, both for the seat and the backrest.

From each single test, the following values were obtained: maximum pressure peak (P_{max}); average pressure (P_{avg}); average percentage of cells activated by pressures ranging between 50-130 g/cm^2 ($NC_{50\text{-}130}$), 131-400 g/cm^2 ($NC_{131\text{-}400}$) and higher than 400 g/cm^2 ($NC_{401\text{-}1000}$).

P_{max} is the mean value of maximum pressure peaks recorded by each frame, in each single test.

P_{avg} is the average value of all pressure peaks recorded by each frame for each single test.

$NC_{50\text{-}130}$, $NC_{131\text{-}400}$, and $NC_{401\text{-}1000}$ values have been calculated with the equation:

$$\%NC^{(range)} = \frac{N_{S(range)}}{N_S} * 100$$

where:

$N_{S(range)}$: number of sensors measuring pressure between 50-130; 131-400 and 401-1000 g/cm²

N_S: number of active sensors by a pressure >0 g/cm²

2.5 Statistical analysis

Statistical analysis was carried out with the software Comprehensive R Archive Network (CRAN) software (Institute for Statistics and Mathematics, Wien-Umgebung, Austria). Data were reported in mean ± SD values. The multivariate analysis, which allows to study hypothesized factors (P_{avg}, P_{max}, $NC_{50\text{-}130}$, $NC_{131\text{-}400}$, $NC_{401\text{-}1000}$) as descriptors and verify their effect on the points cloud distribution (matrix pressure distribution dynamics), was carried out by analyzing the main components (Principal

Component Analysis -PCA). The normality of data distribution was assessed by the Shapiro-Wilk test. The Levene test was used to evaluate the homogeneity of variances amongst seat types: working conditions, operators, and test repetition. An analysis of variance (ANOVA) was performed to evaluate the influence of the factors under examination (type of seat X type of test) on the dependent variables (P_{avg}, P_{max}, NC_{50-130}, $NC_{131-400}$, and $NC_{401-1000}$). Post-hoc test conducted with the Least Significant Difference (LSD) made it possible to assess whether the difference between the averages of ANOVA-sensitive factors was significant.

3. Results

3.1 Lab test

Table 3 shows the pressure values measured for each test carried out with the three seats. Mean values of P_{avg}, P_{max}, $NC_{131-400}$, recorded after the two tests (on the road and on the ridged track) carried out with seat-A tractors were remarkably greater ($p<0.05$) than those obtained in tests with more comfortable seats (seats B and C); In the pressure interval ranging between 50-130 g/cm^2, cell activation was smaller during tests with the A seat than with the B seat ($p <0.05$). As compared to B and C seats, the cell activation in the $NC_{401-1000}$ interval showed remarkably high values in the ridged track test with the A seat ($p <0.05$). The road test recorded higher P_{avg} and $NC_{131-400}$ values for the A seat compared to the C seat ($p<0.05$), although not significant for the A seat compared to the B seat. P_{max} values in road tests were higher ($p <0.05$) for the A seat compared to B and C seats. However, regarding NC_{50-130}, the road tests showed greater ($p<0.05$) values for the B seat than for A and C.In the ridged track tests P_{avg}, P_{max} and $NC_{131-400}$ values turned out to be higher ($p <0.05$) for the A seat compared to the other two, whereas NC_{50-130} appeared remarkably greater ($p <0.05$) for the C seat than for A and B.

	P_{avg}	P_{max}	NC_{50-130}	$NC_{131-400}$	$NC_{401-1000}$
SEAT A	**193.14±52.04*°**	**521.20±228.16*°**	**6.67±3.33**	**0.31±0.29***	**1.31±0.57*°**
Road	130.78±35.21°	317.94±149.88*°	8.15±3.44	0.27±0.32°	0.00±0.00
Track/ridges	260.19±67.71*°	723.50±122.66*°	5.81±2.38	0.41±0.16*°	2.71±0.36*°
SEAT B	**143.71±32.54**	**337.41±141.66**	**9.70±6.41*^**	**0.28±0.24**	**0.15±0.24**
Street	125.98±26.80	267.81±82.00	12.48±6.75*^	0.30±0.26	0.00±0.00
Track/ridges	160.75±38.81	410.00±242.04	6.92±1.59	0.21±0.16	0.31±0.12
SEAT C	**123.78±29.68**	**223.78±108.30**	**7.98±2.13**	**0.08±0.18**	**0.03±0.18**
Road	107.13±26.17	187.62±93.74	7.35±2.30	0.08±0.19	0.00±0.10
Track/ridges	137.08±31.67	260.33±144.59	8.65±0.97*°	0.08±0.12	0.05±0.42

Table 3. Pressure values (in g/cm^2) expressed in mean and standard deviations recorded on different terrains for the three seats A, B and C. Significant differences at Duncan test ($p < 0.05$) represented by: *seat A vs. B; °seat A vs. C;^seat B vs. C. In bold the mean values recorded on the road and on the ridged track.

Data recorded in lab tests showed P_{avg} and P_{max} higher values on the ridged track than on the road. During ridged track tests, frames Q1, Q3, Q4, and Q8 presented greater P_{avg} and P_{max} values ($p<0.05$), compared to others (data not shown). However, during the road test, only frames Q4 and Q8 recorded higher P_{avg} and P_{max} values ($p<0.05$), as compared to others (data not shown). The row-column coordinate system of the obtained numerical matrices allowed us to observe that the majority (> 98%) of the maximum peak values in Q3 and Q4 concerned with the sensors under the area of the ischial tuberosity.

3.2 Field test

Table 4 shows pressure values measured for each test on the field with the three seats. The mean values of P_{avg} and P_{max} recorded after the three tests carried out with A-seat tractors were greater than those obtained in tests with more comfortable seats (B and C). In the pressure interval 131-400 g/cm2 ($NC_{131-400}$), cell activation in A-seat tests was greater than that of both B and C seat tests ($p<0.05$). Ploughing tests showed no differences in P_{avg} values for the three seats. However, the Pmax recorded for the A-seat was higher than that of the B-seat. The cell activation in the interval $NC_{131-400}$, in A-seat tests, was significantly greater than tests with B and C seats ($p<0.05$). The cell activation in A-seat for the interval $NC_{131-400}$ was greater than tests with B and C seats ($p<0.05$). Cell activation frequency in NC_{50-130} interval was greater for seat B as compared to that of in seats A and C ($p<0.05$). However, no cell activation was detected in the $NC_{401-1000}$ interval for the three seats. In harrowing tests, P_{avg} and P_{max} for seat A were higher compared to those recorded in tests with seats B and C tractors ($p<0.05$). The cell activation in seat A, in the pressure interval $NC_{131-400}$, showed no differences compared to those recorded in seats B and C. Cell activation frequency in NC_{50-130} interval was greater in seat B compared to seat C, and in seat A as compared to seat C ($p<0.05$). However, no activation was detected in any of the three seats for the $NC_{401-1000}$ interval. In haying tests, P_{avg} and P_{max} in the A-seat were greater for the ranges $NC_{131-400}$ and $NC_{401-1000}$ than those obtained in tests with B and C seat tractors ($p<0.05$). Furthermore, in the haying tests, P_{avg} in seat B were higher than those observed in the seat C ($p<0.05$). Cell activation frequency in NC_{50-130} interval was significantly greater in seat B compared to seat C, and in seat A compared to seat C ($p<0.05$). Whereas, in seats B and C, no activation was detected in the $NC_{401-1000}$ interval.

	P_{avg}	**P_{max}**	**NC_{50-130}**	**$NC_{131-400}$**	**$NC_{401-1000}$**

SEAT A	**162.18±56.70*°**	**443.22±205.02*°**	**8.33±3.00°**	**0.42±0.34*°**	**0.02±0.15*°**
Ploughing	137.35±37.91	389.76±129.37*	7.66±2.69	0.43±0.25*°	0.00±0.00
Harrowing	143.43±47.92*°	366.29±170.31*°	7.32±2.70°	0.31±0.30	0.00±0.00
Haying	205.77±59.80*°	572.00±252.67*°	10.30±2.88°	0.54±0.43*°	0.04±0.18
SEAT B	**139.67±40.00**	**310.33±153.24**	**8.97±2.65^**	**0.22±0.19**	**0.00±0.00**
Ploughing	147.36±38.11	348.21±136.92	8.48±2.17*^	0.27±0.19	0.00±0.00
Harrowing	119.01±24.45	249.95±79.63	8.02±2.69^	0.17±0.20	0.00±0.00
Haying	152.64±47.15^	332.81±204.55	10.39±2.54^	0.22±0.18	0.00±0.00
SEAT C	**134.14±48.10**	**322.36±184.90**	**7.62±2.24**	**0.24±0.28**	**0.00±0.00**
Ploughing	150.26±53.87	375.79±205.17^	7.82±1.56	0.29±0.29	0.00±0.00
Harrowing	133.09±26.38	363.81±186.98	6.42±1.68	0.25±0.31	0.00±0.00
Haying	119.08±35.30	227.48±121.13	8.62±2.76	0.19±0.24	0.00±0.00

Table 4.
Pressure values (in g/cm^2) expressed in mean and standard deviations recorded for different field tasks for the three seats A, B, and C. Duncan test sensitivity is represented by *seat A vs. B; °seat A vs. C; ^seat B vs. C., in bold the mean of values recorded on the three field trials.

Analysing the frames of seat A, P_{max} and P_{avg} values detected on each of the four frames measured at the seat region were higher in frame Q4 ($p<0.05$), which corresponds to the right buttock. Namely, frame Q4 showed the highest P_{avg} and P_{max} values (data not shown) in all field tests (ploughing, harrowing, and haying). However, no difference was observed in these values on the three different field tests with the three seats. P_{avg} and P_{max} recorded for each of the 4 frames at the backrest showed highest values on frame Q8 ($p<0.05$), where the right shoulder lies on the backrest. No statistically significant difference was observed in the values for the three seats on three different fields (data not shown). The principal component analysis for both lab and field tests enabled us to spot P_{max}, P_{avg}, NC_{50-130}, and $NC_{131-400}$ values recorded on frames Q4 and Q8 as seat pressure main markers. $NC_{401-1000}$ values were not taken as markers since they came up only for seat A during ridged track and haying tests. The biplot of the results, representing the two components, PC1 and PC2, accounting for 69.6% (PC1=39.0%, PC2=30.7%) of variance visible in the dot cloud (see figure 5). The graph shows a convergence area of three convex hulls, representing the most comfortable area of all seats in the various operating conditions. Seat A is left out of this comfort area, especially regards to field conditions as compared to lab tests.

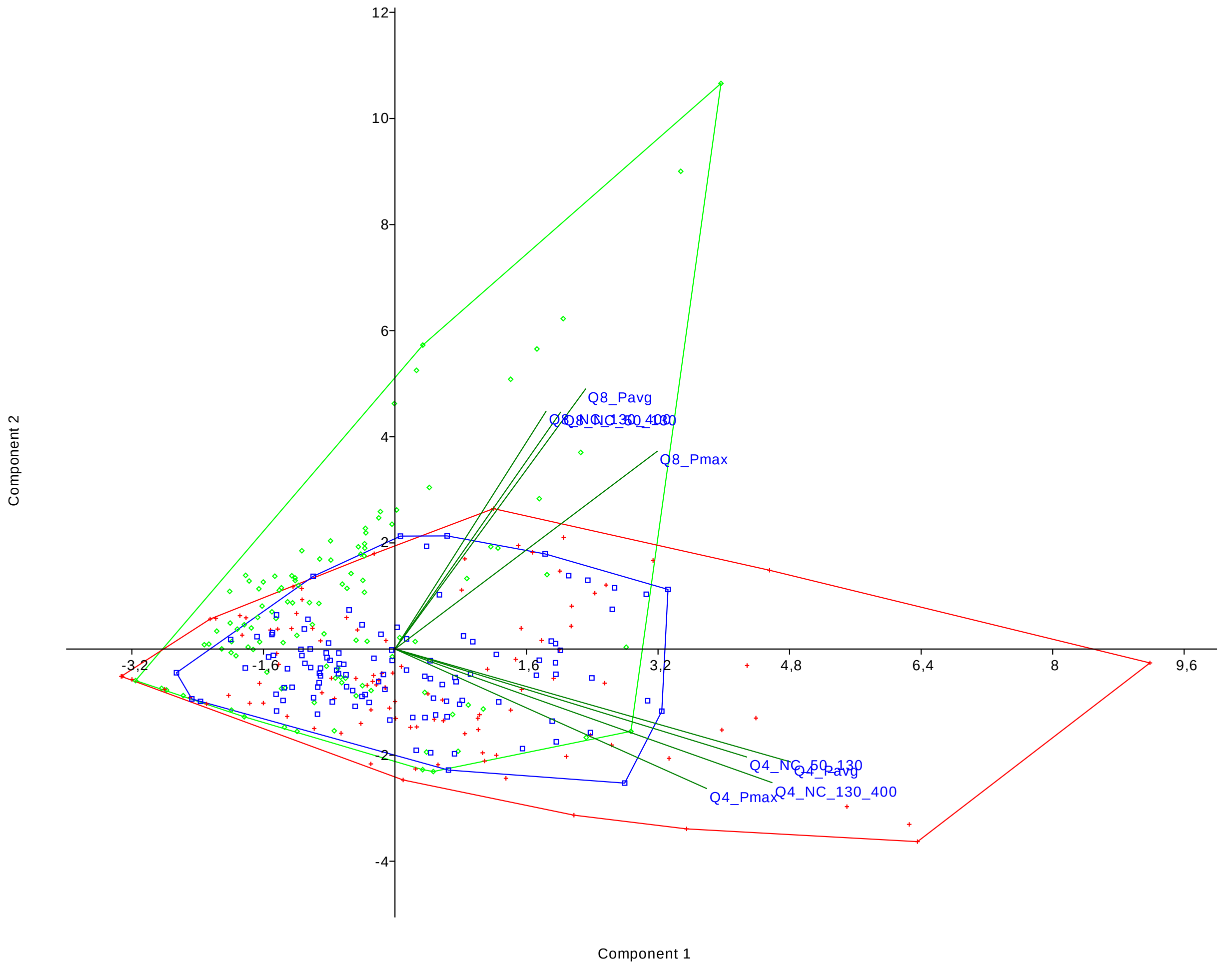

Figure 5. Biplot representing the distribution of cases observed in relation to vectors of frames Q_4 and Q_8 in the two main components (PC_1 and PC_2). Polygons represent the *convex hulls* (red=seat A, blue=seat B, green=seat C).

Based on ANOVA, seat type (A, B, C) and working conditions (the two laboratory tests and the three field trials) demonstrated significant interactions ($P<0.01$). However, the same was not observed for the operator and working conditions. Based on the LSD test, values of P_{avg}, P_{max}, NC_{50-130}, $NC_{131-400}$, and $NC_{401-1000}$ for seat A were higher than those for seats B and C. Table 5 shows the LSD analysis. The ridged track test showed greatest P_{avg}, P_{max} and, $NC_{401-1000}$ values, whereas the asphalted track test revealed the lowest values. The low-pressure cell activation in the NC_{50-130} interval was higher during haying procedures and on asphalted track. However, higher pressure cell activation in the $NC_{131-400}$ interval was recorded in all field operations (ploughing, haying, and harrowing), although only the ploughing procedure reached significance.

Seat	P_{avg}	**LSD**	**Test**	P_{avg}	**LSD**
A	155.98	a	ridged track	186.01	a
B	136.19	b	haying	156.83	b
C	131.46	b	ploughing	144.99	bc
			harrowing	137.96	c
			asphalted track	120.82	d
	P_{max}			P_{max}	
A	420.00	a	ridged track	464.61	a
B	306.59	b	ploughing	371.25	b
C	288.26	c	haying	367.70	b
			harrowing	326.68	b
			asphalted track	254.78	c
	NC_{50-130}			NC_{50-130}	
A	9.48	a	haying	9.75	a
B	8.31	b	asphalted track	9.38	a
C	7.46	c	ploughing	7.99	b
			harrowing	7.25	b
			ridged track	7.13	c
	$NC_{131-400}$			$NC_{131-400}$	
A	0.44	a	ploughing	0.33	a
B	0.24	b	haying	0.30	ab
C	0.19	b	harrowing	0.24	ab
			ridged track	0.23	b
			asphalted track	0.21	b
	$NC_{401-1000}$			$NC_{401-1000}$	
A	0.67	a	ridged track	1.02	a
B	0.08	b	haying	0.01	b
C	0.02	b	harrowing	0.00	c
			ploughing	0.00	c
			asphalted track	0.00	c

Table 5. *Post-hoc Least Significant Difference (LSD)* test results relative to the three seats and field and lab tests (equal letters to the right of the value indicate homogeneous categories for the same factor*)*.

NC_{50-130}, $NC_{131-400}$ pressure interval activation low levels recorded on ridged track tests were due to stresses superior to 400 g/cm^2.

4. Discussion

This paper examined the aspects of discomfort in the seat-operator interface, and presents a critical examination of three seats of different cost (A-low, B-medium, C-high) in two different lab test conditions (an asphalted track and a ridged track) and under three different field conditions (ploughing, harrowing, and haymaking). The study measured three comfort indicators: the average pressure (P_{avg}), the pressure peak (P_{max}), and the count of sensors measuring three pressure ranges of at the seat-buttock surface. Based on the lab tests, we observed that the operator exerted medium pressures, maximum peaks and sensor activations in the range 401-1000 g/cm^2 while sitting on seat A. However, when the operator was sitting on seats B and C, the cells in the range, 50-130 and 131-400 g/cm^2 were activated more as compared to that of while sitting on seat A. These findings imply that the use of seat A generated higher and more concentrated pressures compared to seats B and C at the highest pressure range. During the ridged track tests, the highest values of P_{avg} and P_{max} were recorded in seat frames, Q1, Q3, and Q4 and one of the backrest frames (Q8). This data can be accounted for by the weight-strength action the operator exerts through the buttocks region while experiencing mechanical stress due to the ridges of the track. In all tests, the majority (> 98%) of the maximum peak values in Q3 and Q4 were attributed to the sensors under the area of the ischial tuberosity.

Based on the results observed from various frames during the asphalt test, it is possible to observe that the highest P_{avg} and P_{max} values were recorded only in frame Q4 of the seat and frame Q8 of the backrest. This shows a pressure strain of the buttocks in line with the ischial tuberosity rear area, where the right coxo-femural joint (and then the femur) acts as a lever to lift and lower the limb in order to operate the tractor’s pedals. As a further confirmation, high-pressure levels were not found in frame Q2, corresponding to the ischial tuberosity front area, in the right coxo-femural joint, where the continuous movement produced by the tractor’s pedals takes place. These findings imply that on both asphalted and ridged track tests, as observed by Xiaoming et al. (2013), the position of the right femur, tibia, and fibula is asymmetric compared to the left side, which totally lies on the seat, and is due to activity the operator carries out with his right lower limb on the tractor’s pedals to brake and accelerate. In the same way, stronger pressure on backrest frame Q8 is produced by the right shoulder that, to enable the right arm and hand to operate the driving commands, needs constant foothold.

Depending on specific tasks, the tractor operator needs to look behind to monitor the operation, steer the vehicle, operate different levers, clutch, brake, gear, and throttle; this requires force, skill, alertness and often assuming awkward body postures (Kyung et al., 2008a; 2008b; Cafiso et al., 2014; 2015). These operations that involve the torsion of the torso can influence a greater movement of the right side of the body compared to the left. Moreover, lab tests showed that while driving without mechanical stress (on the asphalted track), the operator generated the highest pressures when needing an area to be used as a lever for supporting the uninterrupted right coxofemoral (Q4) and scapulohumeral (Q8) joint movements, respectively. In case of high mechanical stress (ridged track test), apart from the need to lay on Q4 and Q8, the operator’s strength exerted on the seat came into play as well (Q1 and Q3), which was needed to stabilize the driving, despite the seat shock-absorbing gear. Based on the field tests, higher P_{avg} and P_{max} pressure were recorded during tests with seat A, compared to those with seats B and C. In hay and harrowing tests, seats B and C showed pressures in the lower acquisition intervals (NC_{50-130}, $NC_{131-400}$), while seat A showed the highest frequency of pressures in the highest range ($NC_{401-1000}$), reducing comfort. The PCA analysis showed that P_{max}, NC_{50-130} and $NC_{131-400}$, recorded in frames Q4 and Q8, were the main markers of the pressure exerted by the operator on the seat.

Moreover, it has been pointed out that A seats generate the highest pressure between seat and operator, and thus influencing the comfort. Discomfort from a sitting posture is experienced when pressure on soft tissues under the thighs results in oxygen shortage, carbon-dioxide build-up and waste products such as lactic acid (Kyung et al., 2008a; 2008b; Metha and Tewari, 2000). These conditions occur when the pressure exerted on tissues increases, e.g., between buttocks and seat. Ng et al. (1995) showed disturbances (e.g., tingling and paraesthesia) in drivers when the pressure distribution was uneven across the thighs and buttocks, with most of the load concentrated in the buttock region.

The data we observed showed that P_{avg} and P_{max} pressures that were generated in the operator's buttocks-seat interface of "low cost" seat A were significantly greater compared to the "medium" and "high cost" seats B and C. In the same way, NCs showed higher values with seat A than with seats B and C and with B compared to C. These findings demonstrate how important it is to work with equipment that provides a balanced distribution of the operator's weight, avoiding pressure peaks like those observed during the ridged track tests and with ploughing with seat A, which may bring about pathologies in those operators with long driving shifts (>6 hrs/day). Mehta and Tewari (2000), in a critical review, suggested that the seat pan cushion (such as used for seat B) for tractor seats should neither be too soft nor too hard on the outlying portions of the buttocks so as to maintain blood circulation and prevent muscular fatigue and discomfort in the operator during long sitting periods. Most of the body weight while sitting must be supported at the ischial tuberosities and must diminish towards the surrounding areas, and can be accomplished by a proper selection of seat cushion material and a proper seat height above the footrest. Our study endorses this hypothesis since driving on seat A ("low cost") seems to generate significantly greater pressure than when sitting on "medium" (B) and "high cost" (C) cushions. Such pressure peaks, especially if prolonged, as in the case of professional operators, may provoke painful symptoms and, later, pathologies. The current findings enable us to hypothesize that "low cost" seats produce the greatest pressure at the seat-operator interface. Such a hypothesis will have to be corroborated by further studies which take into due account the machine-related vibrations and associate them with pressure distribution on the operator's body areas. Our results, similar to that of Wu et al., (1998), clearly show the concentration of considerably high pressure in the vicinity of right ischium tuberosity. Unlike our study, Wu et al. (1998) evaluated the pressure exerted by the operator on the seat, taking into account the frequencies and accelerations of the vibrations transmitted on the seat itself. In another study, Wu et al. (1999)

highlighted that vertical vibrations considerably influence the maximum pressure at the driver's seat interface, and this is also confirmed by the results of our study. However, it must be emphasized that Wu et al. (1999) used vibratory stimuli in the 1-10 Hz range with accelerations of 1 and 2 m/s^2, observing significant pressure increases especially in vibration exposures with accelerations of 2 m/s^2. Under normal operating conditions, a tractor develops vibrations within the frequencies considered by Wu et al. (1999), but in compliance with current European legislation, the accelerations transmitted to the operator are contained within the daily exposure limit value of 1 m/s^2/8 h (Vallone et al., 2016). This value, being weighted for the working hours, does not exclude the presence of acceleration peaks above 1 m/s^2, but the operator's exposure must always be contained within the value of 1.5 m/s^2 (although only for short periods), therefore below the value of 2 m/s^2. Nevertheless, Vallone et al. (2016) suggest that measuring dynamic pressure distribution in this region (similar to that of the current study) should provide considerable insight into the design requirements of seat cushions. Moreover, the outcome of our study is in line with those of Wu et al. (1998), revealing that the maximum interface pressure occurs in the vicinity of the ischial tuberosities in both lab and field environments. Consequently, in our study, seat C, whose cushion is thicker and wider, reduces the pressure between cushion and operator.

5. Conclusions

It is concluded that the analyzed pressure indexes in this study are useful to describe and compare agricultural machine seats, with the overall aim of highlighting the comfort rate obtainable in static and dynamic situations by the operator. We intend to leverage this paper as a useful comparing tool in designing, implementing and assessing materials, and technologies in this sector to improve the quality of the operator's working environment in the agricultural and forestry industries. Our study findings also provided important information about critical seat areas to be analyzed in simulations using a finite element or other computational models in order to intervene with shapes suitable for body-seat interaction, including auxiliary paddings. These findings from our study, therefore, suggest that both “field” and “lab” data acquisitions are valuable, thus enabling researchers to obtain more reliable data, as well as helping the manufacturers in potential ergonomic design consideration. In the future, the next steps for this cushion-seat development would be the implementation of an intelligent automatic controller with pre-programmed changes in the pressure of the different subsections as a function of task or track during driving.

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