FMUC **FACULTY OF MEDICINE**
UNIVERSITY OF COIMBRA, PORTUGAL

School of Dentistry

In vitro study on the performance of a new computerized occlusal analysis system: T-Scan®III HD

Integrated Master in Dental Medicine

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Supervisor: Professor Doutor Pedro Miguel Gomes Nicolau
Co-supervisor: Dr. Júlio André Ramalho da Fonseca

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1. ABSTRACT

Introduction: The performance of registration materials and methods has been researched by many investigators in an effort to thoroughly understand the patient's occlusion.[1-23] In the dental community, articulating paper has been widely accepted as the gold standard for occlusal analysis.[24] However, published studies about its physical properties (thickness, composition, ink substrate, plastic deformation) offer no evidence to suggest that variable articulating paper mark size can be descriptive of variable occlusal loads.[1, 3-5, 25-31] In 1987, Maness *et al*[32] first reported the development of the prototype of a new computerized occlusal analysis device *(T-Scan® Tekscan Incorporation, Boston, USA)*. From then to the present, the manufacturer states having improved the system's accuracy, sensitivity and reproducibility. Still, the latest generation (T-Scan®III HD) lacks of independent overall studies on its improved performance, which shall be tested in this paper. A better diagnostic interpretation of the results from the T-Scan®III HD system should be expected.

Materials & Methods: The present study aims to test, under different simulated anatomic circumstances, the performances of a computerized occlusal analysis device (T-Scan®III HD Tekscan Incorporation, Boston, USA). For this purpose, four different occlusal tables were created:

- two of 120° created with an artificial inferior first molar (Ivoclar® Vivadent, Vaduz, Liechtenstein) either embedded in a periodontal ligament simulator or not (representing the anatomy of posterior natural teeth vs an implant);
- one of 100° (simulating the distortion created to the sensor when anterior teeth occlude);
- and finally one plane surface of 180° (control) in static and variable positions.

Three levels of force (10N, 50N and 150N) were applied 40 times each by a universal testing machine *(Autograph®, AG-I; Shimadzu Co., Kyoto, Japan)*.

A polished spherical bur (diameter=2,2mm) assured the contact on the sensor film. All T-Scan®III HD recordings were compared through *a One-way ANOVA* statistical analysis with post-hoc tests using *Bonferroni* corrections for multiple comparisons.

Results: According to our study, the following results were obtained:

- The sensor film could produce repeatable data for a mean of 85.71 closures with a standard deviation of 35.99;
- 85% of the outliers are within the 5 first closures, representing the *conditioning time* required by the initially flat sensor
- Graphically and statistically sustained differences *($p < .05$)* could be found :
    - in the coefficients of variation between tables (180° Variable *vs.* all other)
    - in the coefficients of variation between the applied loads (10N *vs.* 50N vs. 150N);
    - in the mean RAW-sum between the different tables for the same applied load.

Conclusions: An undeniable improvement of this newest T-Scan® system as compared to former designs could be proved. However, when using the T-Scan®III HD system, some points of capital importance have to be considered:

- Its sensitivity seems to be improved as compared to former designs, however futher studies on its variability throughout its sensing surface are required;
- Its reproducibility could be proved, except for the 5 first values (outliers to the mean values), which shall be used as a *conditioning time* to both the sensor and the patient;
- Its accuracy proved to be dependent of the anatomic circumstances and requires a trained interpretation;
- Particular caution has to be taken when interpreting the force % of a rigid *vs.* non-rigid model, for instance when balancing a mixed occlusion (implant-tooth).

Our study shows that despite the technologic advances made in the area of occlusal analysis, a critical interpretation and a careful handling of the depicted values is indispensable, and can only be acquired through a long learning curve.

Key-words: T-Scan®III computerized occlusal analysis system, HD sensor design, dental occlusion, periodontal ligament simulator, dental implants.

2. INTRODUCTION

The importance of reliability in clinical measurements has been documented in health care literature,[33-36] a need which the World Health Organization (WHO) already in 1987 emphasized regarding oral health.[37] With this goal, many investigators have been researching the performance of registration materials and methods in an effort to thoroughly understand the patient's occlusion.[1-6, 8-23, 38]

In the dental community, articulating paper has been widely accepted as the gold standard for occlusal analysis and therefore should be used for baseline comparison with any other method.[24] However, published studies about its physical properties (thickness, composition, ink substrate, plastic deformation) and interactions with the field properties such as wetness, offer no evidence to suggest that variable articulating paper/film mark size can be descriptive of variable occlusal loads.[1, 3-5, 25-31, 39-40] For this reason and because of its subjective interpretation, paper/film should be carefully used as an occlusal registration material.[1, 5, 38]

Apart from articulating paper or films, other methods for occlusal analysis, such as impression materials, photoplastic/elastic wafers, wax bite or shimstock have been described in literature. None of them proved to be ideal.[4, 17, 38, 41-44] Those materials allow the clinician only to locate occlusal contacts. However, their strength must be extrapolated qualitatively or from the subject's evaluation.[20] The need to develop a device, which enabled the clinician to evaluate qualitatively and quantitatively the patient's occlusion, arose.

Technologic advances encouraged the development of the prototype of a computerized occlusal analysis device *(T-Scan®I Tekscan Inc., Boston, USA)*, first reported by Maness *et al*[32] in 1987. The T-Scan® system was designed to analyze and display occlusal contact information gathered by the pressure sensitive film. With this system, it became possible not only to detect the distribution of tooth contacts, but also to compare their relative intensity and even their timing. However, the first generations of the T-Scan system, T-Scan®I and T-Scan®II, generated some controversy in the dental community regarding their performance.[9, 20, 45-49] In fact, Moini and Neff[45] studied the reproducibility of detecting occlusal contacts using silk marking paper *versus* T-Scan system and reported the latter method to be less accurate.

Harvey *et al*[9] conducted a preliminary test on the reproducibility of the same computerized occlusal analysis system and obtained results with substantial variability including unpredictable variations scattered among the uses and levels of force.

Hsu *et al*[46] also reported on the sensitivity and reliability of the T-Scan system and concluded that the sensor did not have the same sensitivity throughout its surface. The T-Scan® always recorded fewer contacts than were actually present as checked by occlusal foils. Those non-sensitive areas described as “black spots” were often reported by other authors in relation to former designs of the T-Scan® sensor (T-Scan®I, T-Scan®II).[47-48]

However a study published in 1991, regarding the clinical use of the first T-Scan® systems, stated that the great advantage of the T-Scan instrument over silk marking ribbon was that it not only recorded the contact reliably, but also analyzed the timing and force of each contact for the 1st time in occlusal history.[45]

As a reaction to the low performance reported by some authors, Tekscan® Inc. developed a new sensor. In 2006, Kerstein *et al*[50] studied their newest generation, and reported the T-Scan®III HD to have increased its active recording area by 33%, and decreased inactive recording area by 50% as compared to the previous design. The HD sensor exhibited significantly less variable force reproduction for at least 20 in-laboratory loading cycles and no existence of “black spots” was described.[51] Koos *et al*[52-53] published two studies emphasizing the HD sensor’s reproducibility (95%) and clinical use, as well.

Important requirements for the clinical applicability of a measuring system are that exact values are depicted as precisely as possible and differ only slightly in repeated measurements.[33-37] However, due to its recent development, the new T-Scan®III HD sensor does not yet present a large amount of independent reports on its performance in comparison to former designs.

In the current paper, the T-Scan®III HD will be tested on its accuracy, sensitivity and reproducibility, and also on the interpretation of its values by the operator.

3. MATERIALS & METHODS

As the aim of the present study was to verify the HD sensors performance using single point loading of the sensor in the same location repeatedly and in multiple single locations, we tried to recreate in laboratory some anatomic circumstances on which the the sensor could be tested.

In order to perform the study, four different occlusal tables were created as follows:

i. 180° (plane surface) simulated by a cylinder filled up with a self-curing acrylic *(Orthocryl® Dentaurum, Ispringen, Germany)* under 2bar pressure and 100°C water to polymerize evenly. After polymerization the cylinder was cut and polished at exactly the given angle. It was used as a control. *(Fig.1-i.)*

ii. 100° table, representing the distortion inflicted to the sensor when anterior teeth occlude. We used the same materials as mentioned above, together with a diamond covered metallic disc to help cutting the acrylic cylinder at 100°. *(Fig.1-ii.)*

iii. 120° table without PDL-simulator, representing the typical intercuspal angle of posterior natural unworn teeth. It was simulated by an artificial inferior first molar *(Ivoclar® Vivadent, Liechtenstein)* included into a cylinder with Orthocryl® *(Dentaurum, Ispringen, Germany)*. *(Fig.1-iii.)*

iv. 120° table with PDL-simulator, representing the typical intercuspal angle of posterior natural unworn teeth, simulated by an artificial tooth *(Ivoclar® Vivadent, Liechtenstein)* included into a transparent acrylic *(Orthocryl® Dentaurum, Ispringen, Germany)* cylinder. *(Fig.1-iv.)* The model was prepared in two stages. First, the roots of the artificial tooth were covered with melted wax to obtain a homogeneous thickness of PDL-simulator and embedded into the acrylic block *(Orthocryl® Dentaurum, Ispringen, Germany)* and then left to set. Second, the tooth was removed from the block, the residual wax was cleaned and the impression material, addition-type silicone[54-55] *(Affinis® Putty soft, Coltène/Whaledent, Aldstätten, Switzerland)*, was poured into the alveolus-shaped crater. The tooth was then returned and pressed into the acrylic block. The excess material which was unrestrained to release from the crater was removed with a scalpel n°11. By this method, the uniformity of PDL-simulating material around the roots of the tooth was assured.

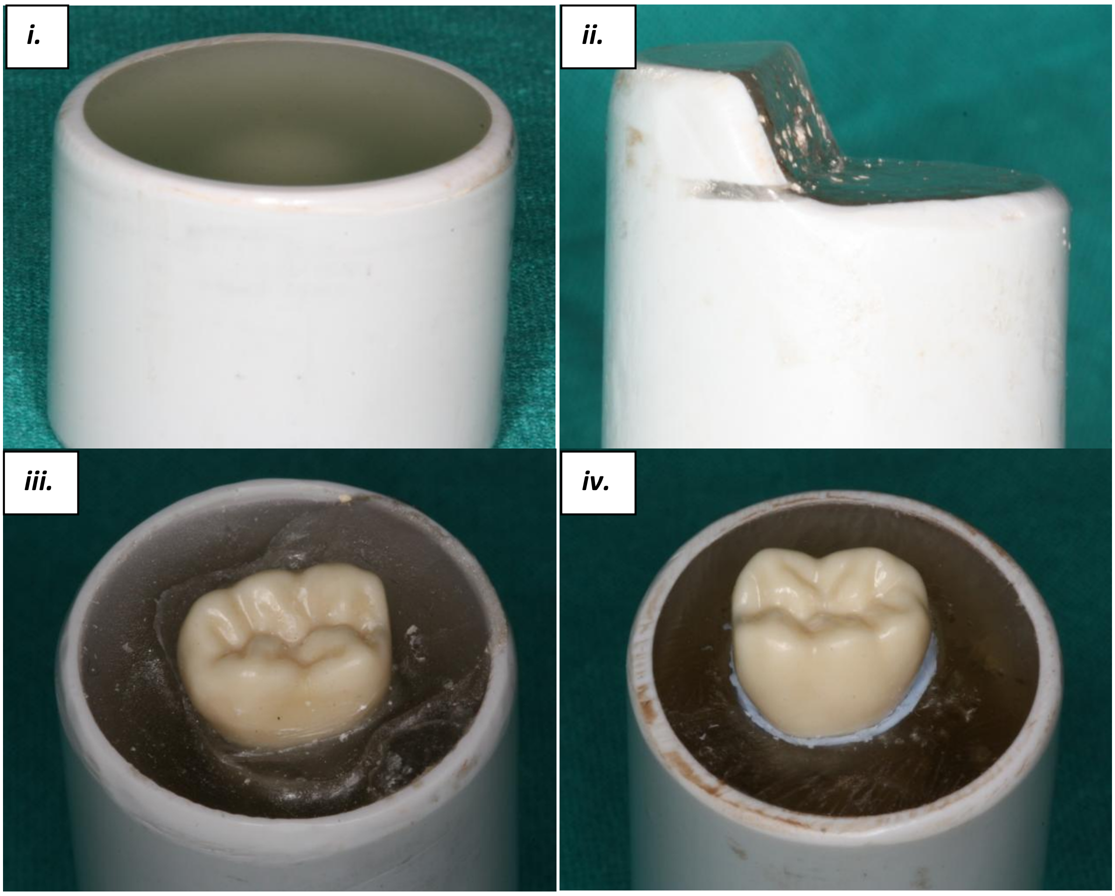


Fig. 1 – i.-iv. – Representing the four respective tables used in our study.

Increasing forces (10N, 50N and 150N) were applied to the above mentioned 4 simulated occlusal tables, 40 times each, with a polished spherical bur (Ø=2.2mm) through a universal test machine *(Autograph®, AG-I; Shimadzu Co., Kyoto, Japan)*. Those known forces were previously programmed into the machine's own software *(Trapezium® X, Shimadzu Co., Kyoto, Japan)*. The T-Scan® 7 software has several sensitivity levels that can be adjusted to match a range of occlusal strengths *(Low 1, 2 and 3; Default; Mid 1, 2 and 3; High 1, 2, 3 and 4).* Regarding the range of load magnitudes used, the recording sensitivity for this study was set on *Default* sensitivity.

Type of table	**180°**		**100°**	**120°**	
	Static positions	Variable positions		Without PDL-simulator	With PDL-simulator
Force level	10N	10N	10N	10N	10N
	50N	50N	50N	50N	50N
	150N	150N	150N	150N	150N

Fig. 2 – The different tables used in our study and the loads applied to each of them.

According to a study by Koos *et al*[15] (2010), external influences, such as changing the foil was not found to have any statistically significant influence on the results. And therefore, anytime our measurements depicted far too high data that appeared suddenly, the sensor was changed.

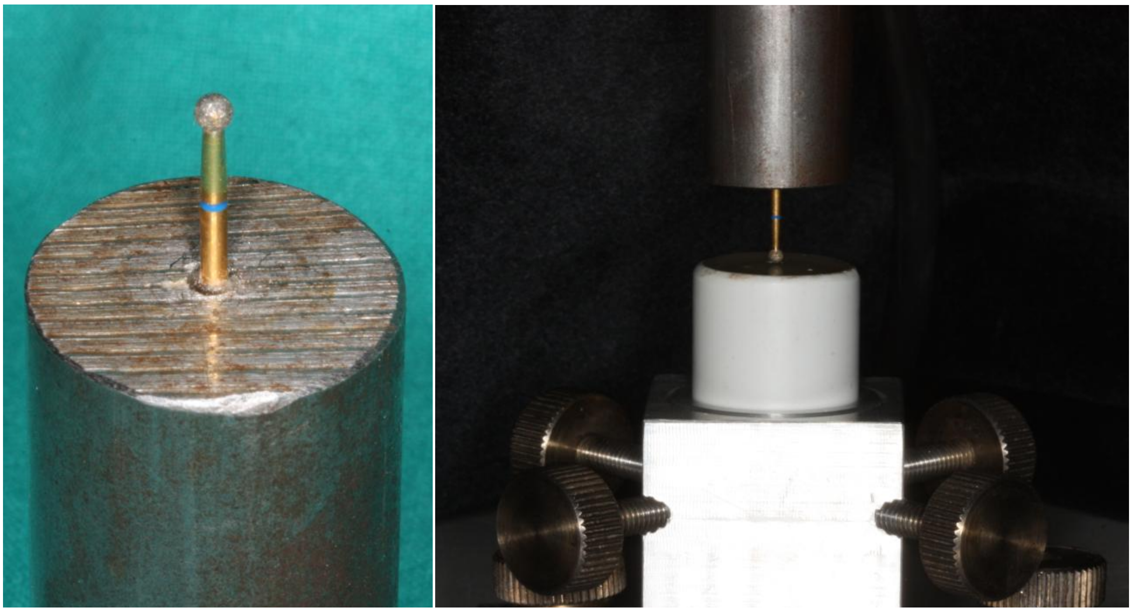


Fig. 3 – The spherical bur after being polished with a diamonded disc and included into a steel cylinder with cyanoacrylate glue (Henkel Co., Germany); The table of 180° mounted on the Autograph®, AG-I.

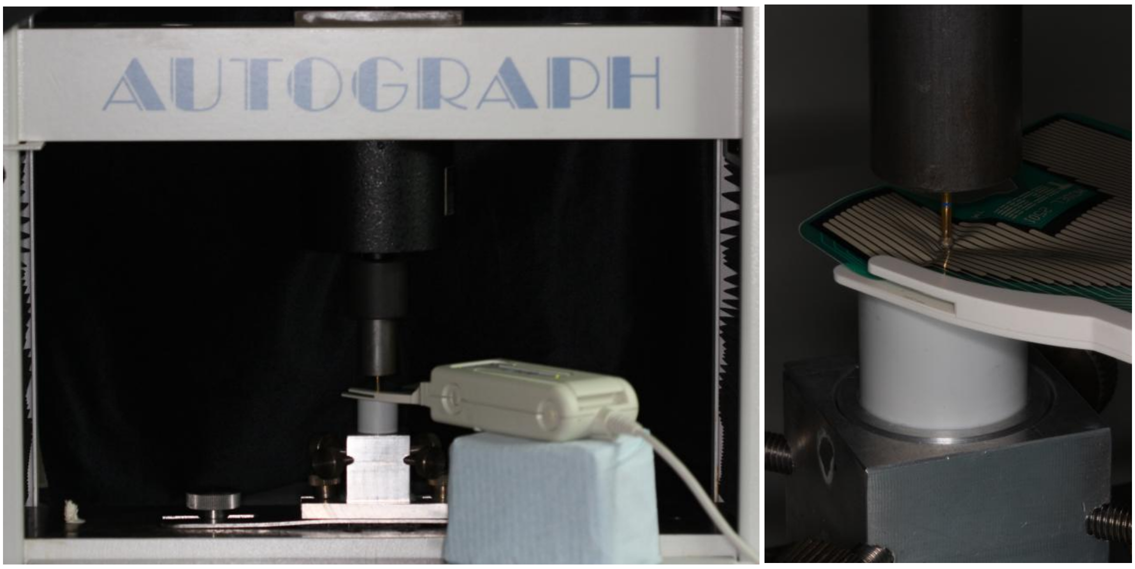


Fig. 4- The table of 180°mounted on the Autograph®, AG-I with the T-Scan®III HD interposed and being loaded.

Since we aimed to determine the sensor reproducibility of force values measured during repeated closures, the sensors were purposefully placed in the same position with respect to the bur/table, except for table 180°-Variable. Consistent sensor placement would ensure that the same points were loaded at each closure.[50]

Afterwards, we studied the correlation between the magnitudes of the forces measured with the T-Scan®III HD sensors and the forces actually applied through the machine for the 4 simulated anatomic circumstances. The following points were analyzed:

- The sensor's saturation (RAW-sum mean and standard deviation) visualized through a bar-chart;
- A graphical interpretation of the RAW-sum *vs.* closures for each table;
- An analysis of the values' distribution using boxplots (for the three levels of force) and their coefficients of variation (for the three levels of force and for each table);
- A graphical illustration of the RAW-sum Means *vs.* applied Load and their tendency lines;
- A comparison of RAW-sum Means between the tables & Confidence Intervals *(CI=95%).*

The statistical analysis was performed on Windows® 7 using Microsoft Excel *(Microsoft® Co., Redmond, WA, USA)* and SPSS® v17.0 *(SPSS® Co., Chicago, Illinois)* software assuming a level of significance of $\alpha = .05$. In order to compare the coefficients of variation and the RAW-sum means for each case, the variables were tested by an *ANOVA* statistical analysis. The assumption, that variances of the data from which different samples are drawn were equal, was verified using a *Levene's* test. Post-hoc tests were performed using *Bonferroni* corrections for multiple comparisons, which is statistically more reliable than the *LSD* (Least Significant Difference).

4. RESULTS

4.1. Graphs of the 40 load cycles registered on the Trapezium® X software

After performing the loading cycles, some of the graphs were saved in order to illustrate the load precision achieved by the testing machine *(Autograph®, AG-I; Shimadzu Co., Kyoto, Japan)*.

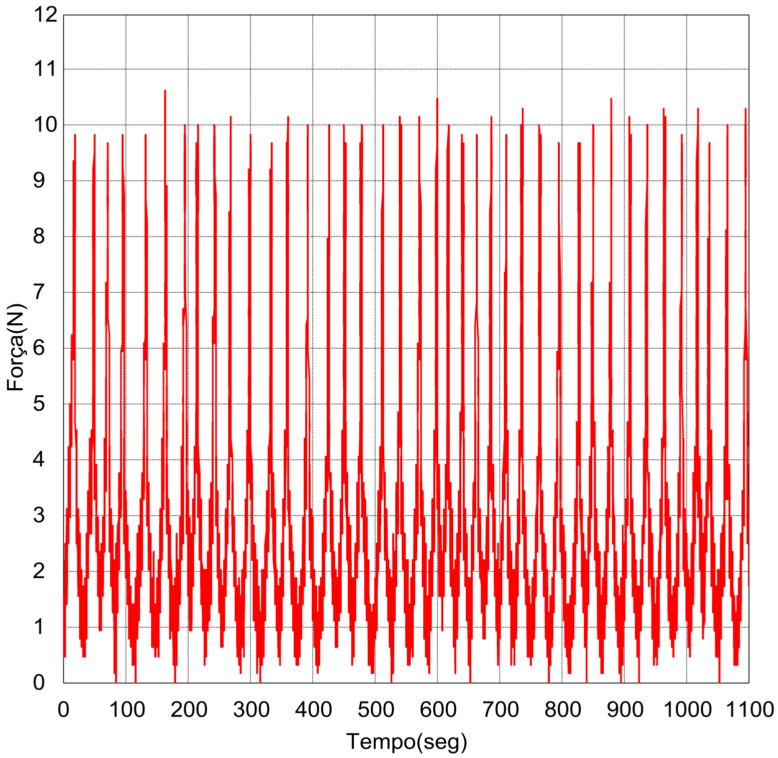


Fig. 5 – Graph showing 10N load performed on table 180°-Static. A variability of less than 1N in magnitude can be noticed in the load actually applied by the machine.

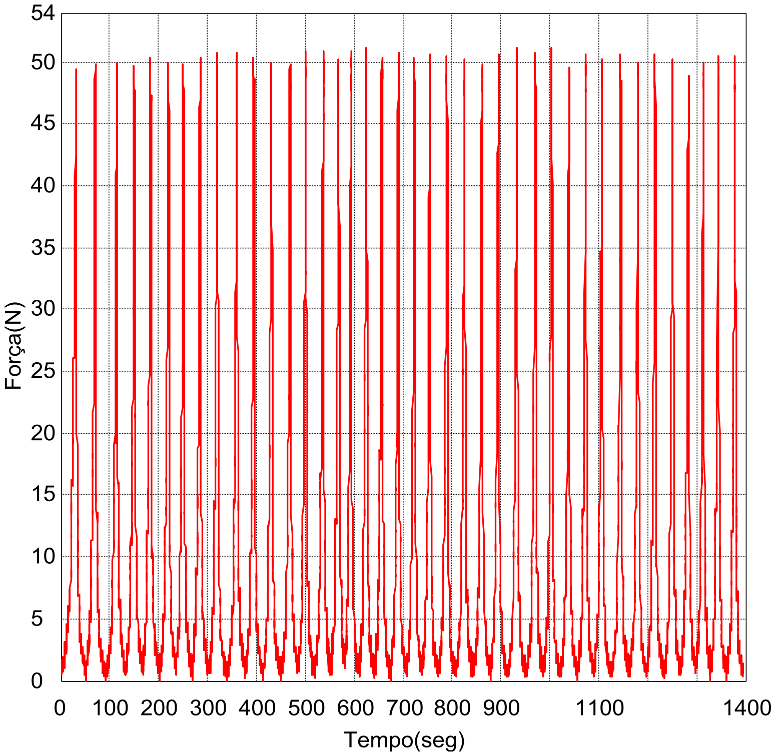


Fig. 6 – Graph showing 50N load performed on table 180°-Variable. Here again, in the load actual applied by the machine a variability of less than 1N in magnitude can be noticed.

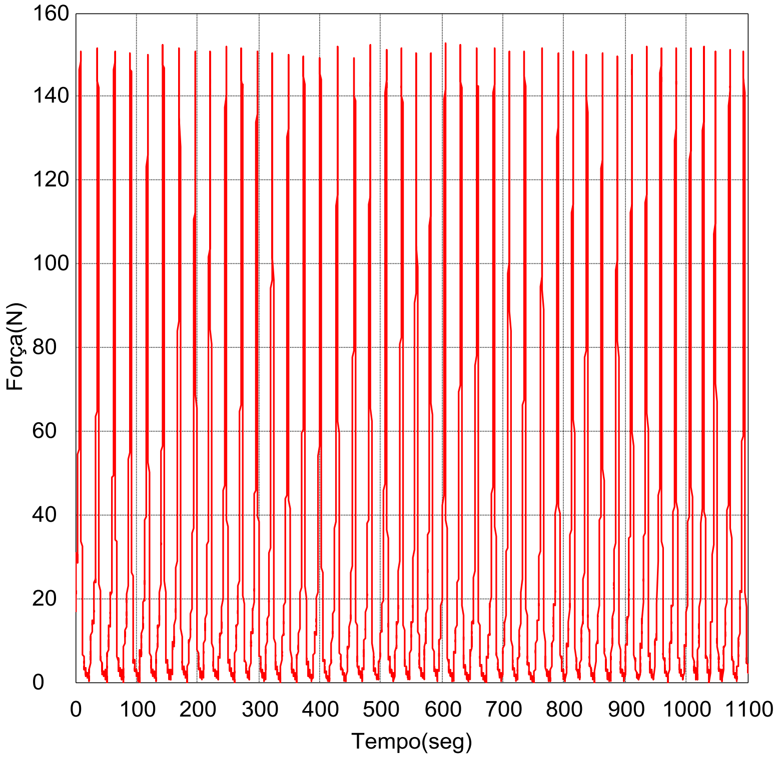
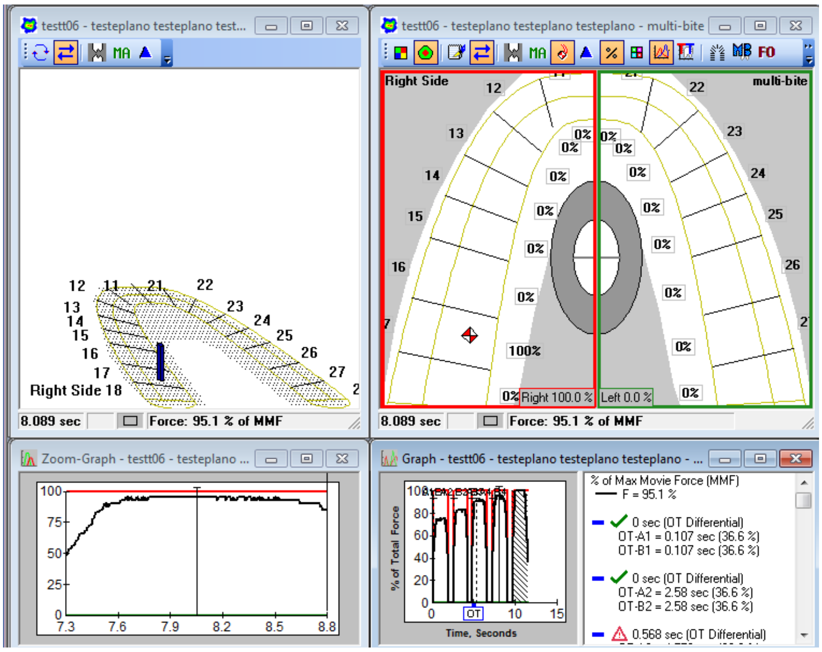


Fig. 7 - Graph showing 150N load performed on table 120° with PDL. Here again, in the load actual applied by the machine a variability of about 1N can be noticed.

4.2. T-Scan®III HD software and its output graphs

In order to visualize the presentation of the output data given by the sensor's software, some examples of our test are shown below.



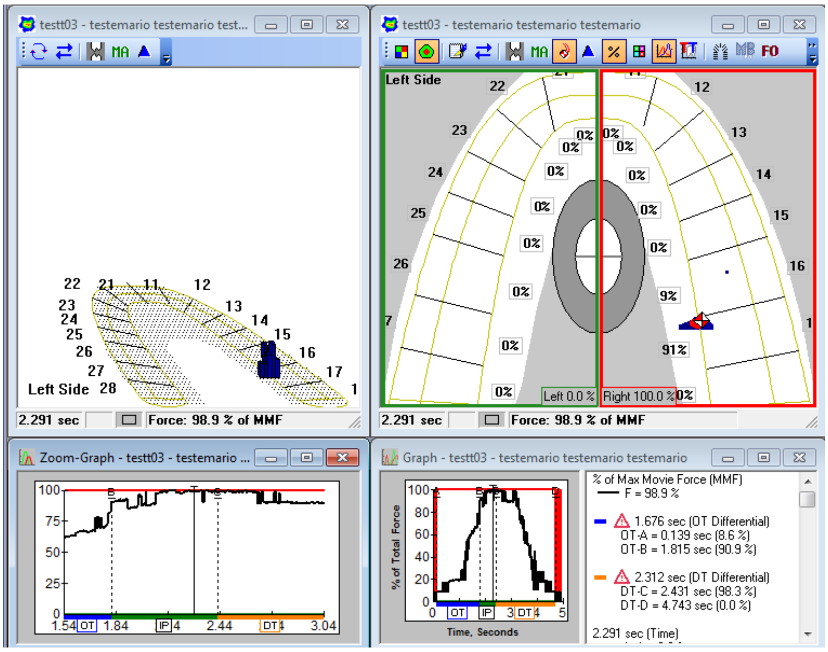
% of Max Movie Force (MMF)
F = 95.1 %

✓ 0 sec (OT Differential)
OT-A1 = 0.107 sec (36.6 %)
OT-B1 = 0.107 sec (36.6 %)

✓ 0 sec (OT Differential)
OT-A2 = 2.58 sec (36.6 %)
OT-B2 = 2.58 sec (36.6 %)

⚠ 0.568 sec (OT Differential)

Fig. 8 – T-Scan®III HD software showing 10N load on table 180°-Static. Notice the fast increase in the force detection and the small contact area.



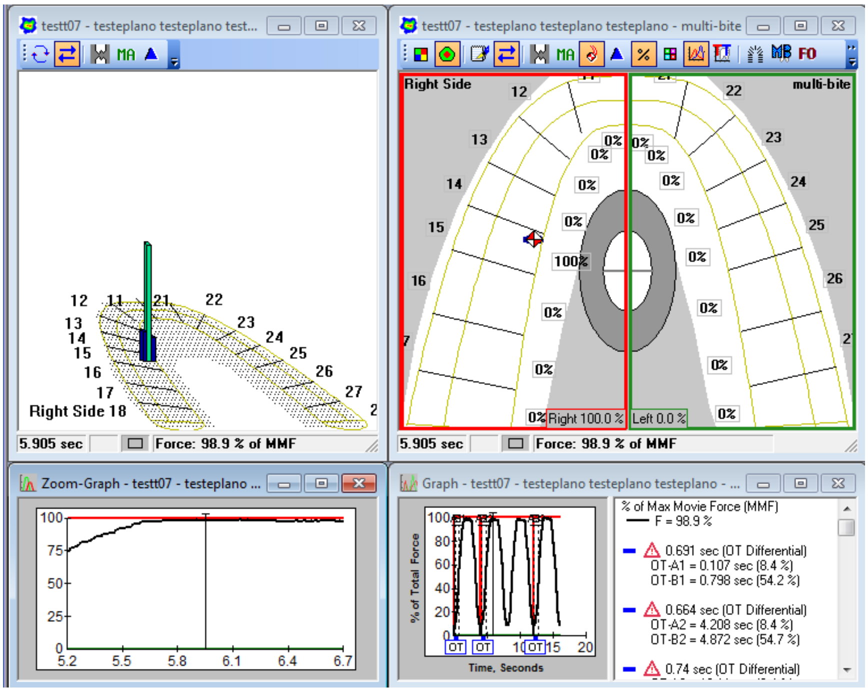
% of Max Movie Force (MMF)
F = 98.9 %

⚠ 1.676 sec (OT Differential)
OT-A = 0.139 sec (8.6 %)
OT-B = 1.815 sec (90.9 %)

⚠ 2.312 sec (DT Differential)
DT-C = 2.431 sec (98.3 %)
DT-D = 4.743 sec (0.0 %)

2.291 sec (Time)

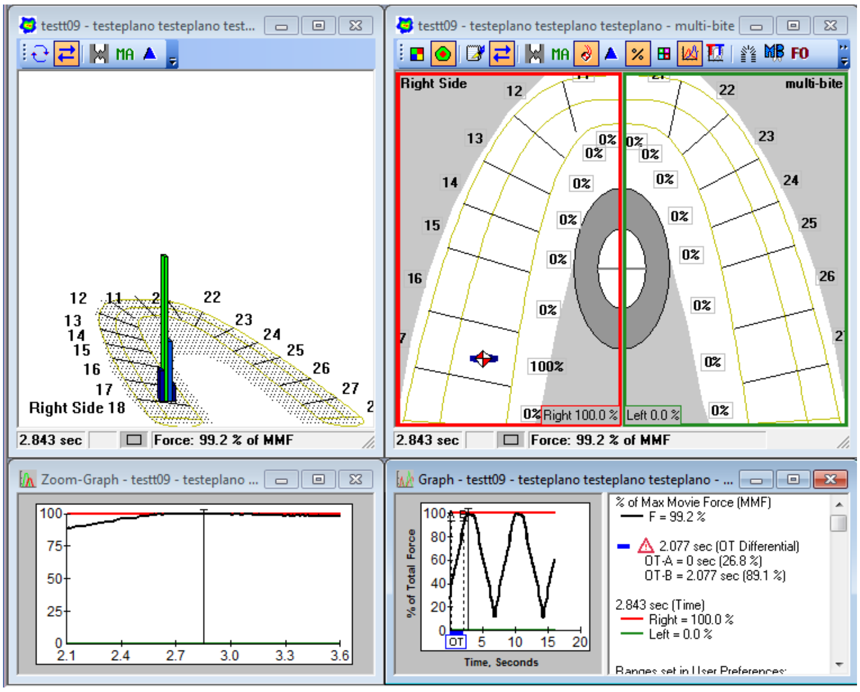
Fig. 9 - T-Scan®III HD software showing 10N load on table 100°. Notice the intermittent force increase due to the friction caused on the surface topography and the sensor film's bending to this angled table.



5.905 sec
Force: 98.9 % of MMF

% of Max Movie Force (MMF)
F = 98.9 %
0.691 sec (OT Differential)
OT-A1 = 0.107 sec (8.4 %)
OT-B1 = 0.798 sec (54.2 %)
0.664 sec (OT Differential)
OT-A2 = 4.208 sec (8.4 %)
OT-B2 = 4.872 sec (54.7 %)
0.74 sec (OT Differential)

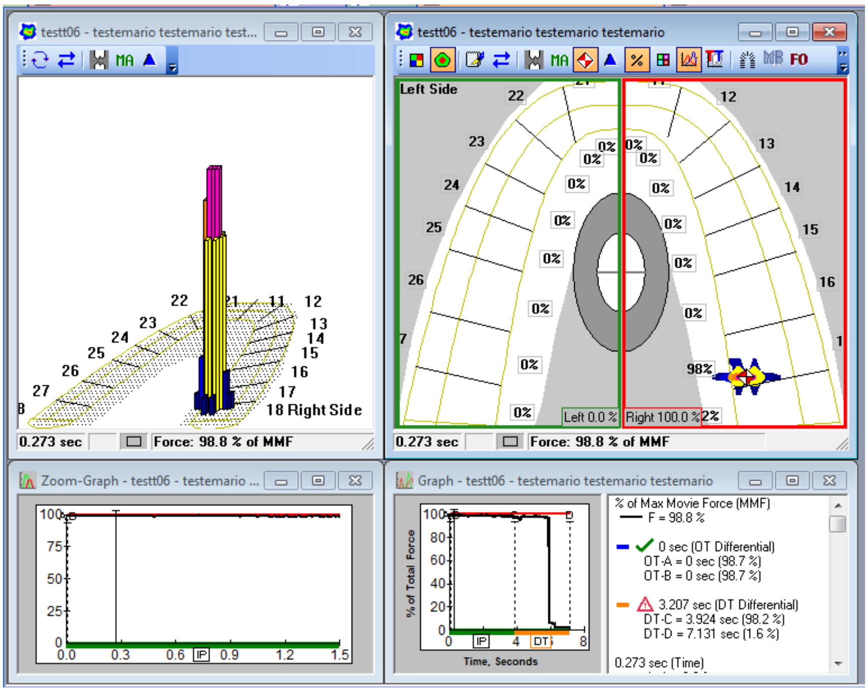
Fig. 10 - T-Scan®III HD software showing 50N load on table 180°-Static. Notice the fast increase in the total force and the small, but already bigger contact area than for 10N load.



2.843 sec
Force: 99.2 % of MMF

% of Max Movie Force (MMF)
F = 99.2 %
2.077 sec (OT Differential)
OT-A = 0 sec (26.8 %)
OT-B = 2.077 sec (89.1 %)
2.843 sec (Time)
Right = 100.0 %
Left = 0.0 %
Ranges set in User Preferences:

Fig. 11 - T-Scan®III HD software showing 50N load on table 180°-Static. Notice the fast increase in the total force and the larger contact area.



0.273 sec

Force: 98.8 % of MMF

% of Max Movie Force (MMF)
F = 98.8 %

0 sec (OT Differential)
OT-A = 0 sec (98.7 %)
OT-B = 0 sec (98.7 %)

3.207 sec (DT Differential)
DT-C = 3.924 sec (98.2 %)
DT-D = 7.131 sec (1.6 %)

0.273 sec (Time)

Fig. 12 – T-Scan®III HD software illustrating the force columns and contact area when applying 150N on table 120° without PDL (closure 42). Notice that the total force stays at 100% across the top of the graph. It shows no variability and a complete vertical force drop, showing sensor matrix damage.

4.3. The sensor saturation

The sensors' longevity could be exponentially increased beyond the manufacturer's indications (20 times[50]) when the tests were performed only on its extremities (anterior and posterior-left and -right areas). These data are analyzed and discussed in the Discussion chapter.

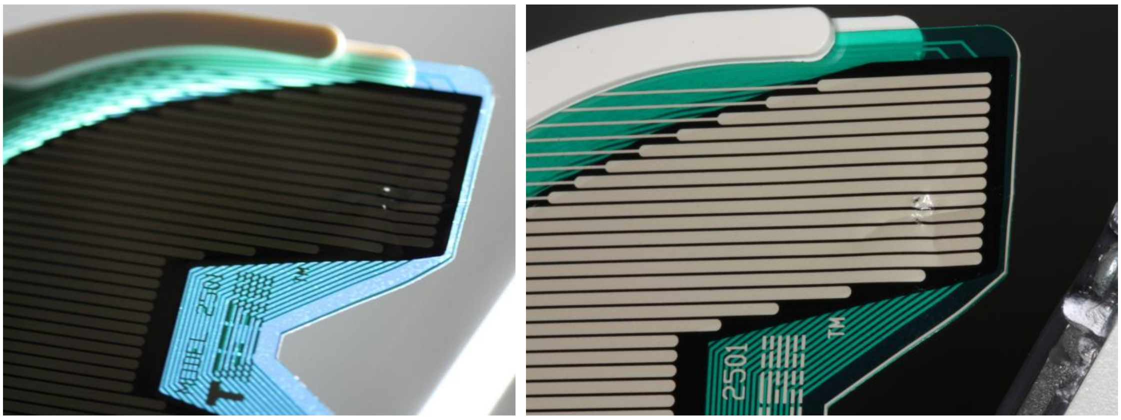


Fig. 13 – Perforation occurred after 40 closures at 150N load on an artificial tooth without PDL-simulator as seen on Fig.12.

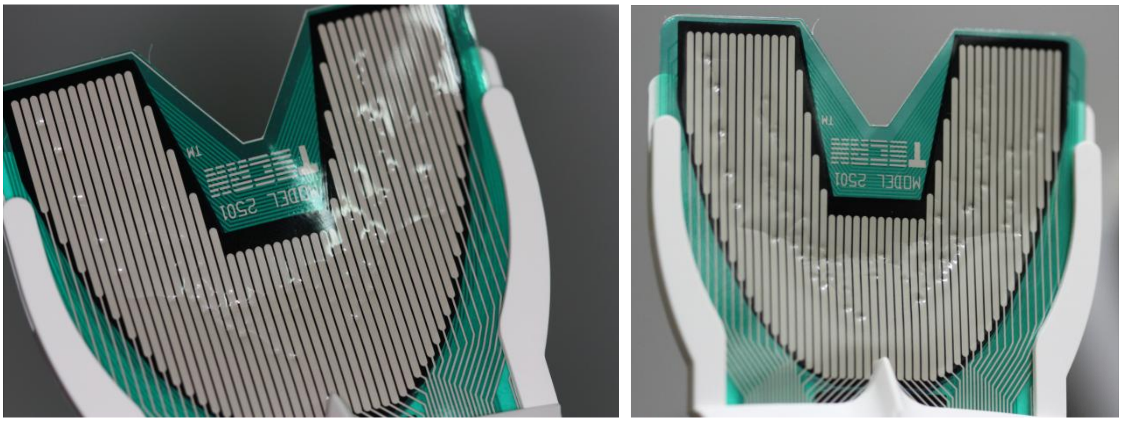


Fig. 14 – Showing sensor n° 4 after 120 closures on table 180°-Variable and table 120° without PDL-simulator.

Sensor n°	**1**	**2**	**3**	**4**	**5**	**6**	**7**
n° of uses	80	40	80	120	120	40	120
Mean	85.71						
Standart deviation	± 35.99						

Fig. 15 – Table showing the total and mean closures accomplished with each of the 7 sensors used in our tests.

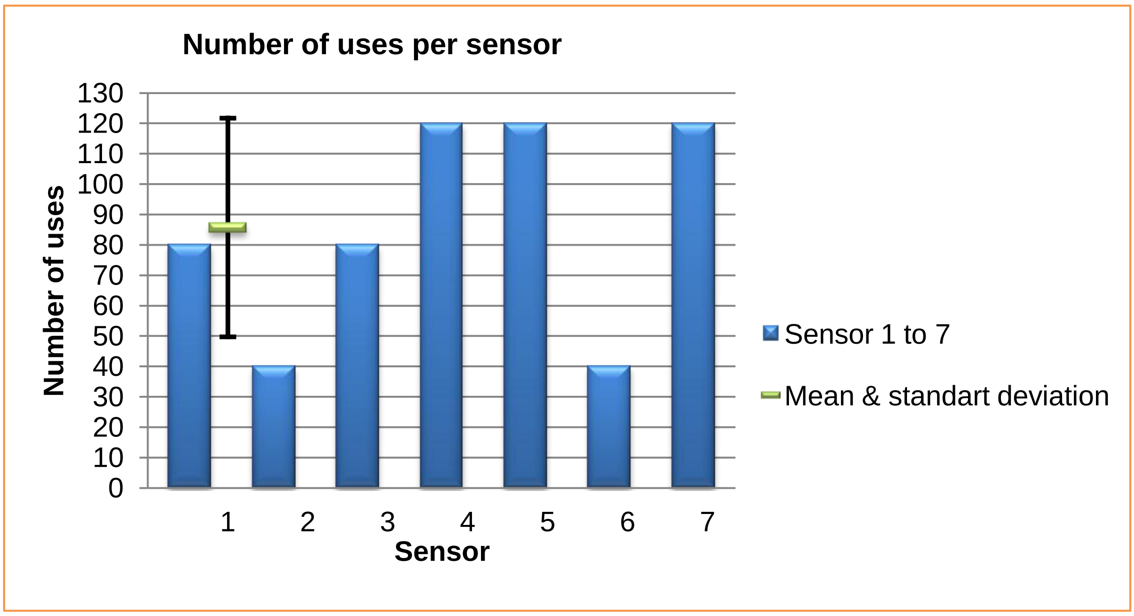
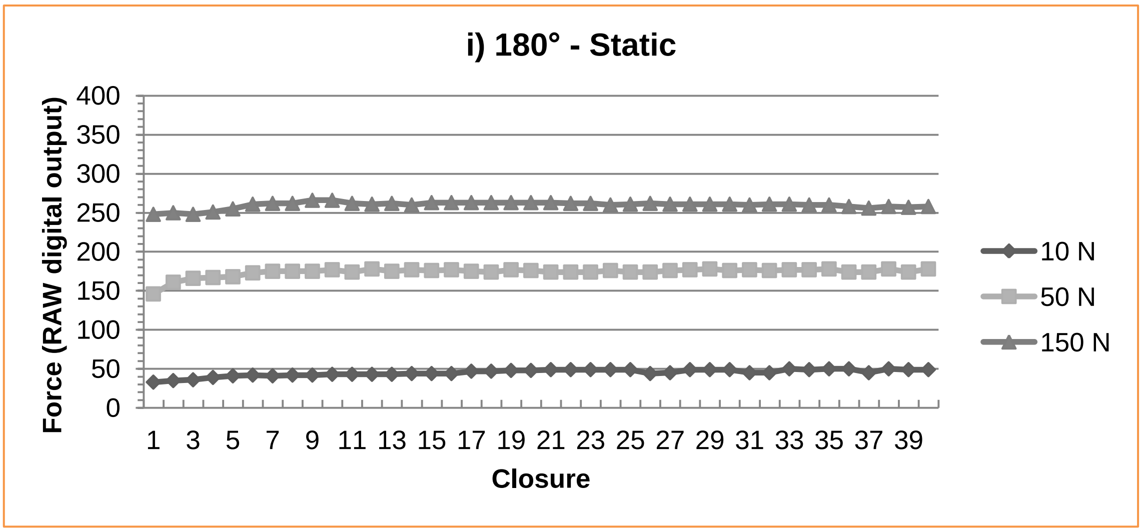
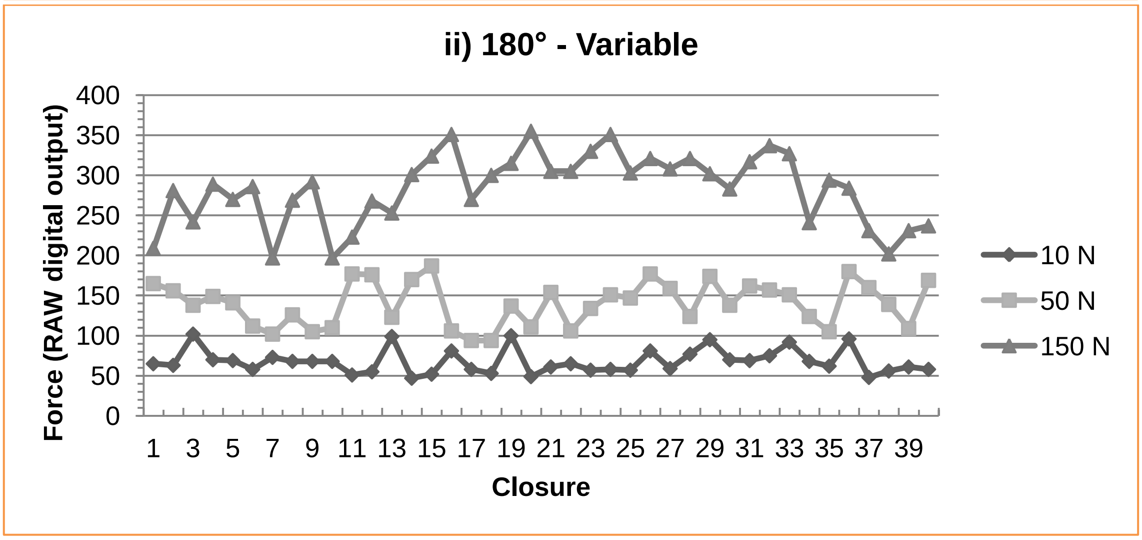


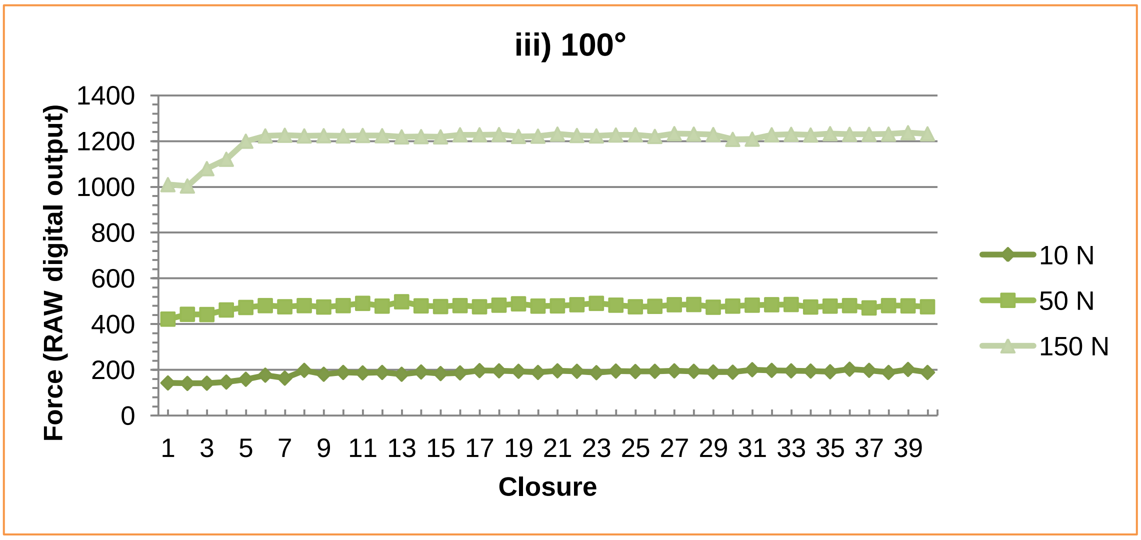
Fig. 16 – Bar-chart illustrating the total and mean closures accomplished with each of the 7 sensors used in our tests.

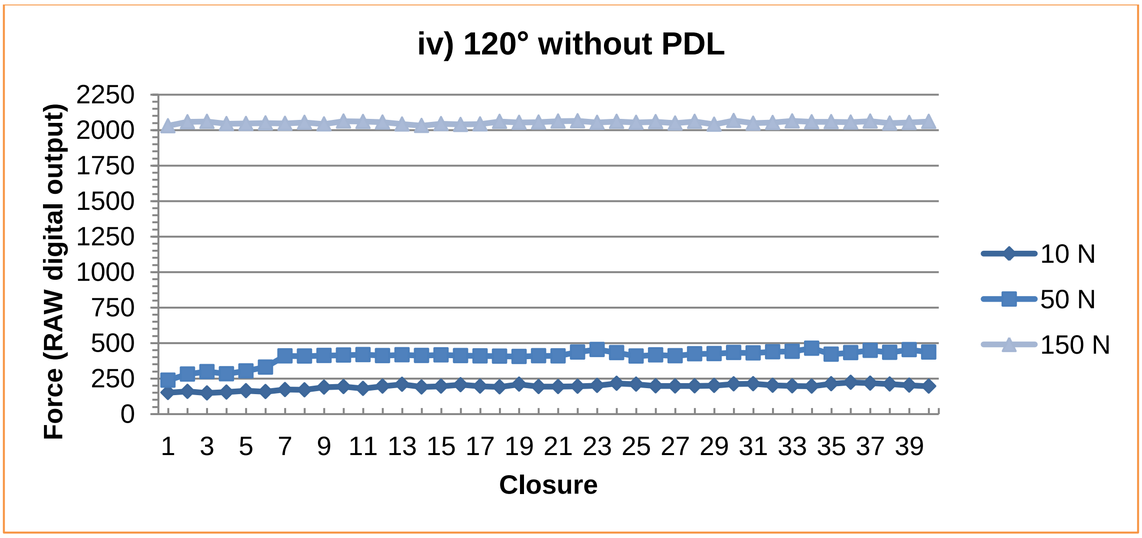
4.4. Graphical interpretation of the measurements

A graphical analysis is achieved through the representation of the values per table, drawing an X-axis with the number of closures and a Y-axis with the RAW-sum values.









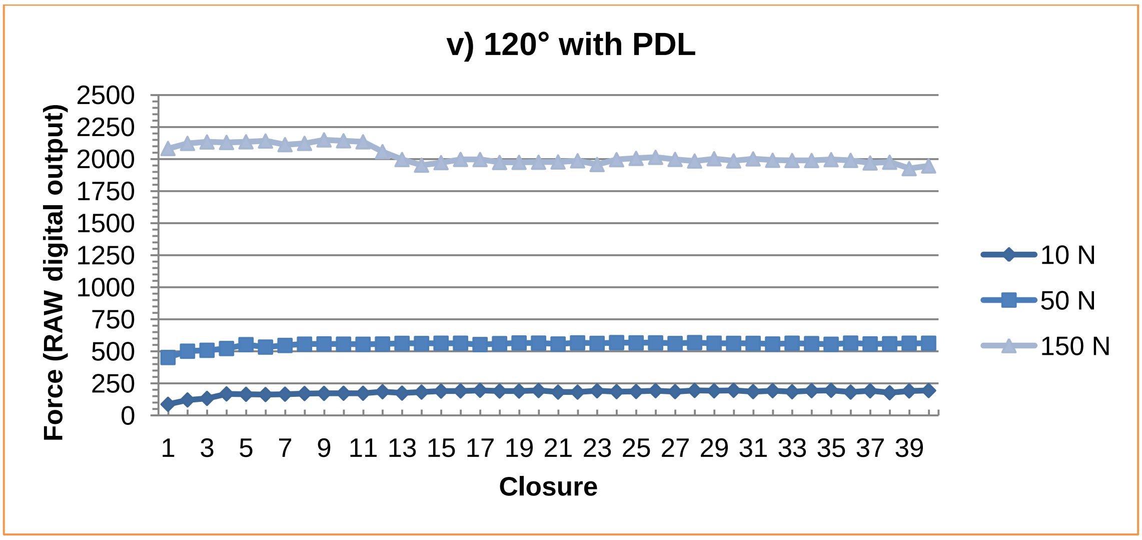


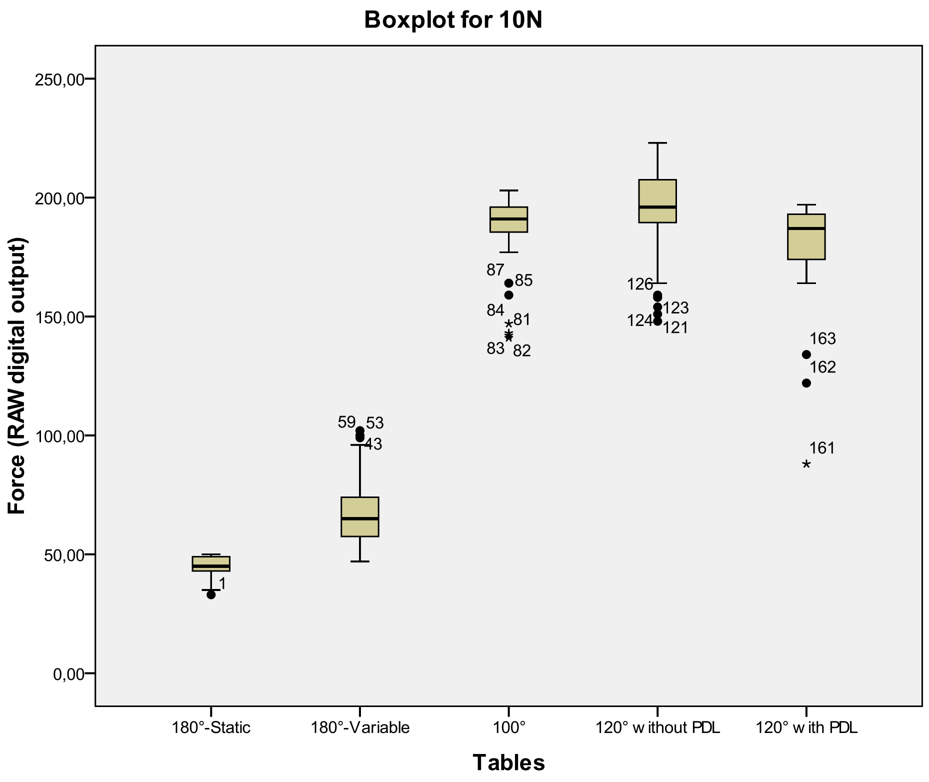
Fig. 17 – Graphs i) to v) representing all five tables, with the RAW-values (Y-axis) depicted at each of the 40 closures (X-axis).

Graphically, the RAW force varied more widely between closures for table 180°-Variable. However, the force data capture illustrates a consistent digital output, in general, with a trend towards a slight increase, as more closures are attempted for the remaining tables. Raw force output appears nearly constant after the early closures (about 5 times) are accomplished (except for the tables 180°-Variable and 120° with PDL at 150N).

4.5. Distribution of the values: Boxplot and Coefficient of Variation

4.5.1. Boxplots

In order to illustrate the distribution and make a visual comparison of the RAW-sum measurements obtained between the different simulated tables within a same occlusal load, boxplots at 10N, 50N and 150N respectively were performed. The distribution is depicted with the median, the lower (25%) and upper (75%) percentile representing a box. Depending on the interquartile distance, 1,5x or 3x, dots respectively asterisks are drawn for the outliers. The numbers associated with the outliners represent the test closure. Since each table was loaded 40 times, the first value per box is always a multiple of 40 plus 1 (example: for table 100° the first value is 2x40+1= 81).



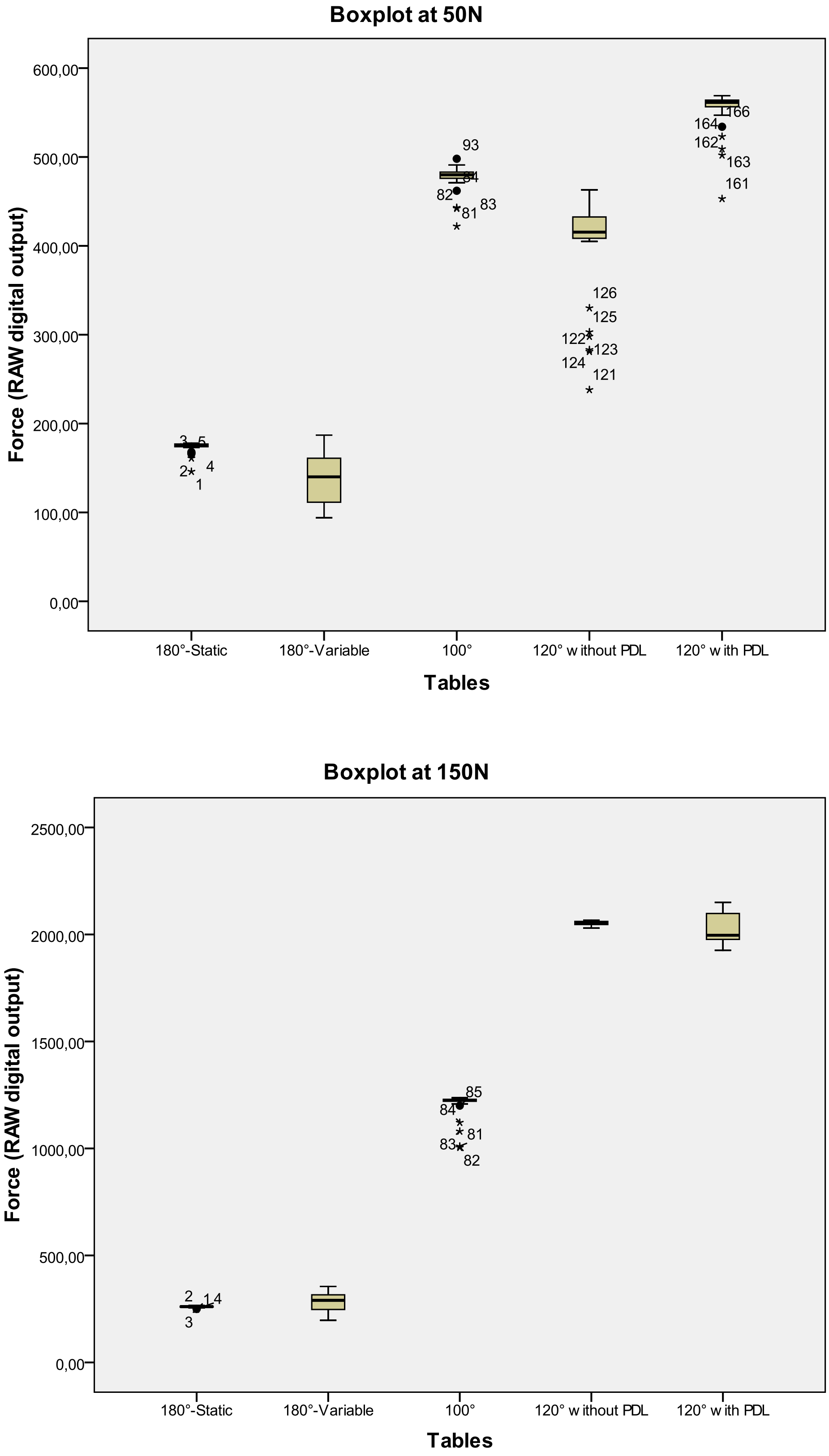


Fig. 18 – Boxplots at 10N, 50N and 150N respectively for the 5 simulated occlusal circumstances.

4.5.1. Boxplots – Outliers

Notice that 40 out of 47 outliers are within the 5 first closures, which represents 85% of all outliers registered. As already noticed graphically, these outliners are often values far below the mean (1.5x or 3x interquartile distance) rather than above.

4.5.2. Coefficients of Variation

The coefficient of variation (CV) is defined as the ratio of the standard deviation σ to the mean μ:

$$c_v = \frac{\sigma}{\mu}$$

It shows the extent of variability in relation to mean of the data collected and in contrast to the standard deviation and because it is a proportion, its value can be directly compared. The bigger the ratio, the higher is the variability of a set of measurements.

Table	**Force level**								
	10N			**50N**			**150N**		
	Mean	**Std dev**	**CV (%)**	**Mean**	**Std dev**	**CV (%)**	**Mean**	**Std dev**	**CV (%)**
180° - Static	45,20	4,36	9,64	173,95	5,74	3,30	259,88	4,24	1,63
180° - Variable	67,85	15,12	22,29	139,98	27,13	19,38	283,05	43,71	15,44
100° - Static	185,75	16,81	9,05	477,08	13,67	2,86	1207,80	54,77	4,53
120° without PDL	192,95	19,38	10,04	403,40	51,99	12,89	2053,08	9,05	0,44
120° with PDL	180,10	21,80	12,11	554,25	22,07	3,98	2024,95	68,06	3,36

Fig. 19 – Table showing the coefficient of variation in percentage for each table and under different loads.

At first sight, it seems quite clear that the CVs for (180°-Variable) are far above the values obtained for all the other tables, pointing out to less constant values when varying the sensor's position. This can be observed graphically as well as seen on the graphs before. But, in order to have a statistical confirmation of this hypothesis, the CV for each individual value must be calculated following mathematical formula $(x_i - \mu) / \mu$. They were compared using a *One-way ANOVA statistical analysis* with *Bonferroni*.

One – way ANOVA at a significance level of *p < .05* :

- Comparison of the CVs between the applied loads:

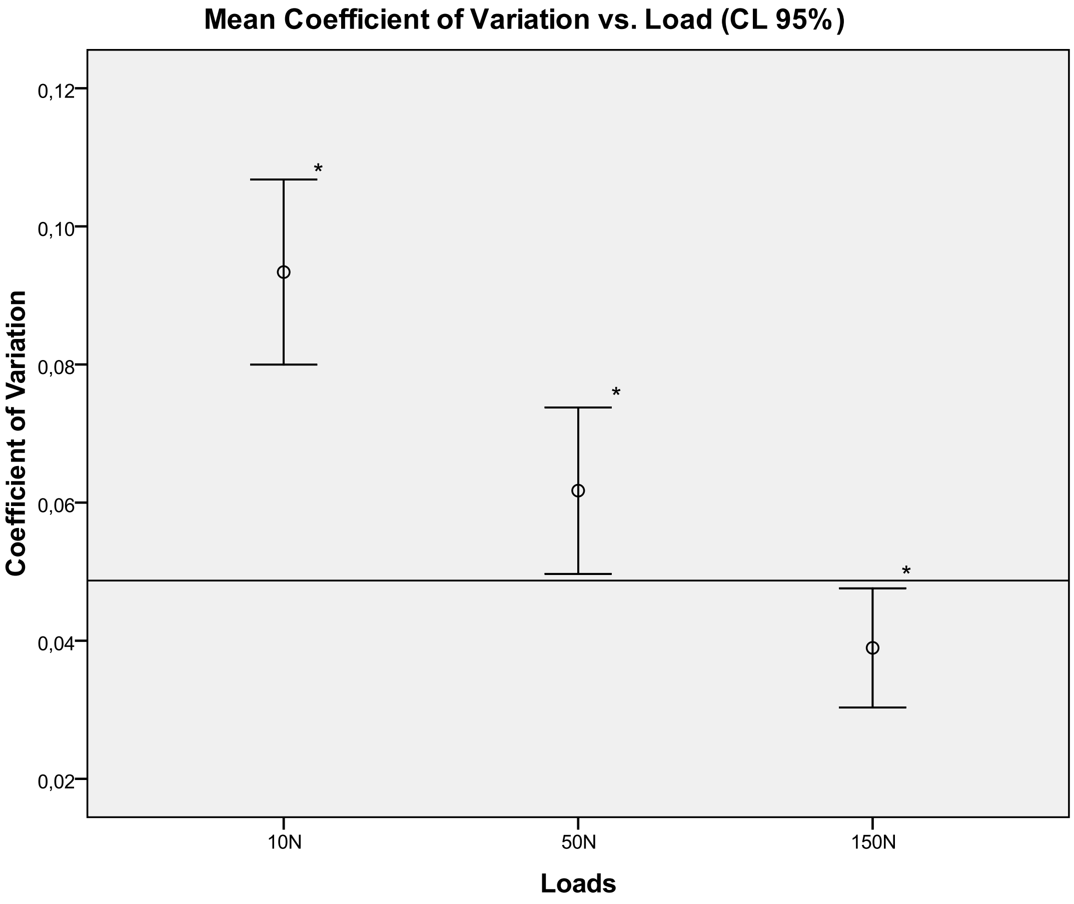


Fig. 20 – Graph illustrating the mean CV vs. the applied load and their Confidence Intervals (95%).

**.The mean difference between the groups is significant at the level p < .05.*

Statistical significant differences could be found between the loads 10N, 50N and 150N respectively. This is true for 10N compared to both 50N and 150N at a level of significance of *p < .001*. Between 50N and 150N the difference is significant at *p < .05,* only. According to the results, the dispersion of the values depicted by the T-Scan$^{®}$III HD is smaller at higher loads.

- Comparison of the CVs between the loaded tables*:*

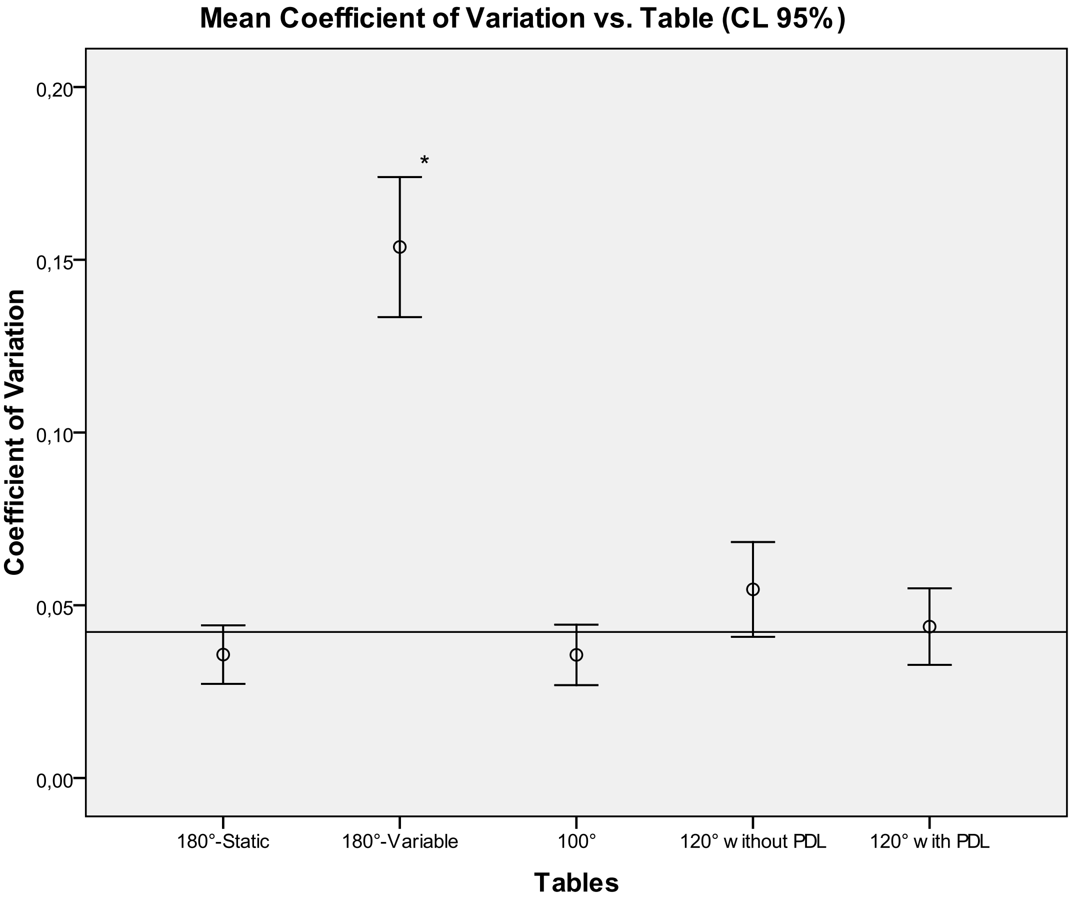


Fig. 21 - Graph illustrating the mean CV vs. the table used and their Confidence Intervals (95%).

**.The mean difference is significant at the level p < .001 vs. all other groups*

Statistical significant differences *(p < .001)* could be found between this table (180°-Variable) and all the other tables, but not between the remaining tables. The sensor's consistency within and between variable anatomic circumstances could be verified, with exception of table (180°-Variable) surface.

5.6. Graphical illustration of the Mean RAW-sum vs. applied Load

A graph was drawn representing the means of each table at the 3 levels of force (10N, 50N and 150N) in order to verify whether the values obtained with the T-Scan®III HD recordings are in accordance with the increase in force (example: when a five or three-fold load is applied, a five or three-fold RAW value should be expected).

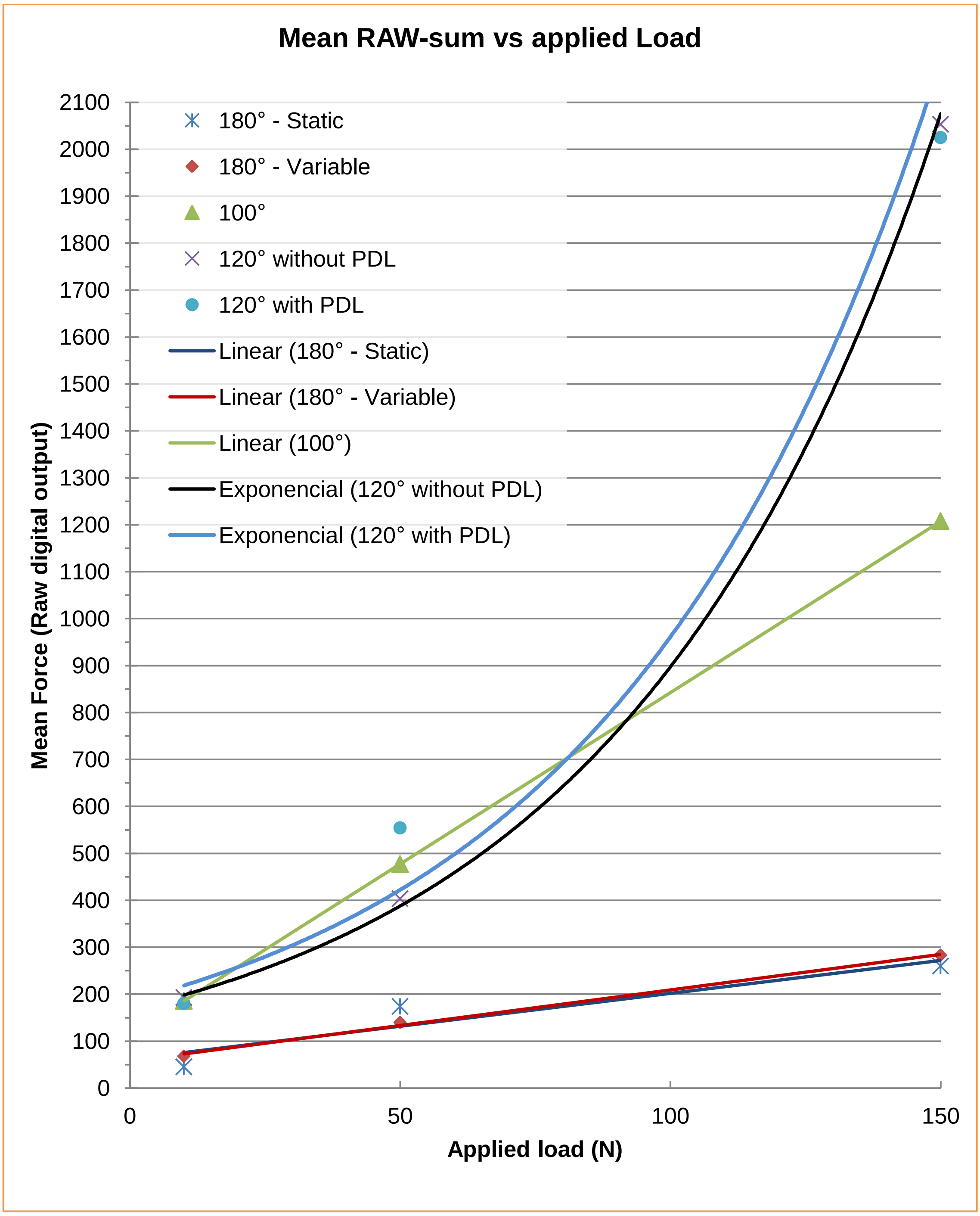


Fig. 22 - Graphical illustration of means vs. applied load.

In contrast to what would be desirable, no linear increase existed in the values, respecting the following formula $y = mx + b$, *with* $b=0$. None of the five simulated conditions presented a linear increase, so that the regression line passed through the 0 (zero) on the axis.

Only for the 180° and 100° tables a linear tendency line could be drawn, but with $b>0$, stating that the line does not pass through 0 on the axis.

However, for the tables representing a molar, the increase was non-linear, being closest to an exponential regression line. In other words, because the RAW-sum values for the 120° tables increased exponentially, when the load applied to them increased 5 times, the RAW-sum value detected by the sensor increased by a bigger factor than 5.

4.7. Comparison of Means between the tables & Confidence Intervals

Mean RAW-sum at 10N

			95% Confidence Interval	
Tables	Mean	Std. Error	Lower Bound	Upper Bound
180°-Static	45,20	,689	43,81	46,59
180°-Variable	67,85	2,390	63,01	72,69
100°	185,75	2,658	180,37	191,13
120° without PDL	192,95	3,064	186,75	199,15
120° with PDL	180,10	3,447	173,13	187,07

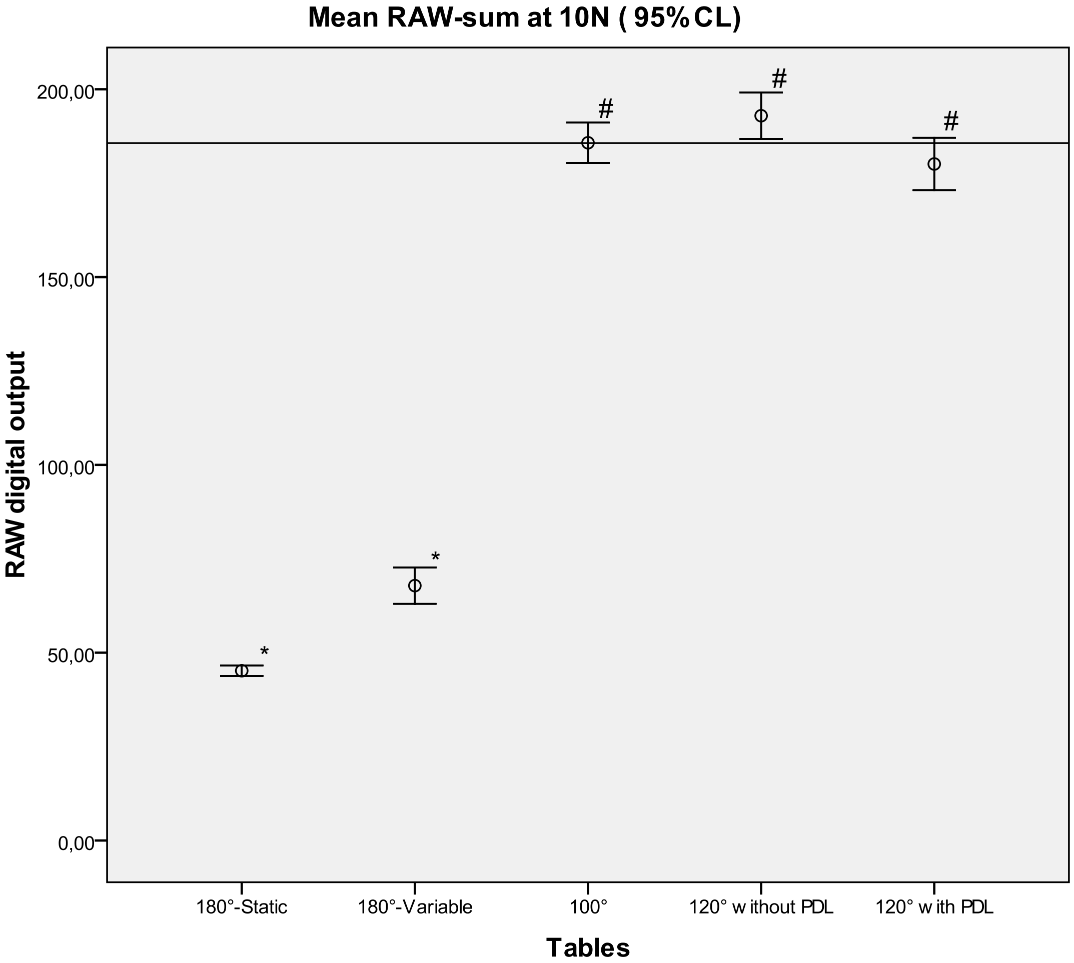


Fig. 23 – Graphical illustration of the mean RAW-sum and their confidence intervals (95% CL) per table at 10N load.

**.The mean difference between the groups is significant at the level p < .001.*

#.The mean difference between the groups is NOT significant at the level p < .05.

Mean RAW-sum at 50N

Table	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
180°-Static	173,95	,907	172,12	175,79
180°-Variable	139,98	4,289	131,30	148,65
100°	477,08	2,161	472,71	481,45
120° without PDL	403,40	8,221	386,77	420,03
120° with PDL	554,25	3,489	547,19	561,31

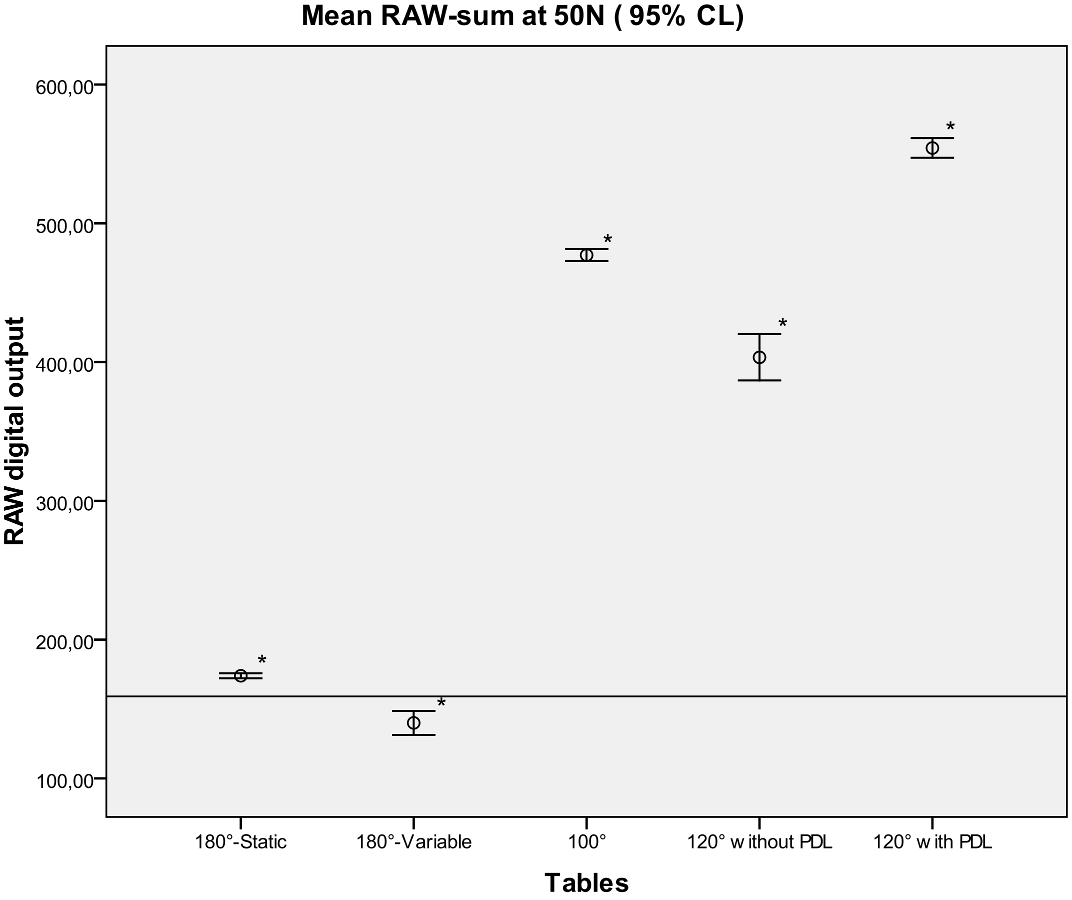


Fig.24 – Graphical illustration of the mean RAW-sum and their confidence intervals (95% CL) per table at 50N load.

**.The mean difference between the groups is significant at the level p < .001.*

Mean RAW-sum at 150N (95% CL)

Table	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
180°-Static	259,88	,671	258,52	261,23
180°-Variable	283,05	6,911	269,07	297,03
100°	1207,80	8,660	1190,28	1225,32
120° without PDL	2053,08	1,431	2050,18	2055,97
120° with PDL	2024,95	10,761	2003,18	2046,72

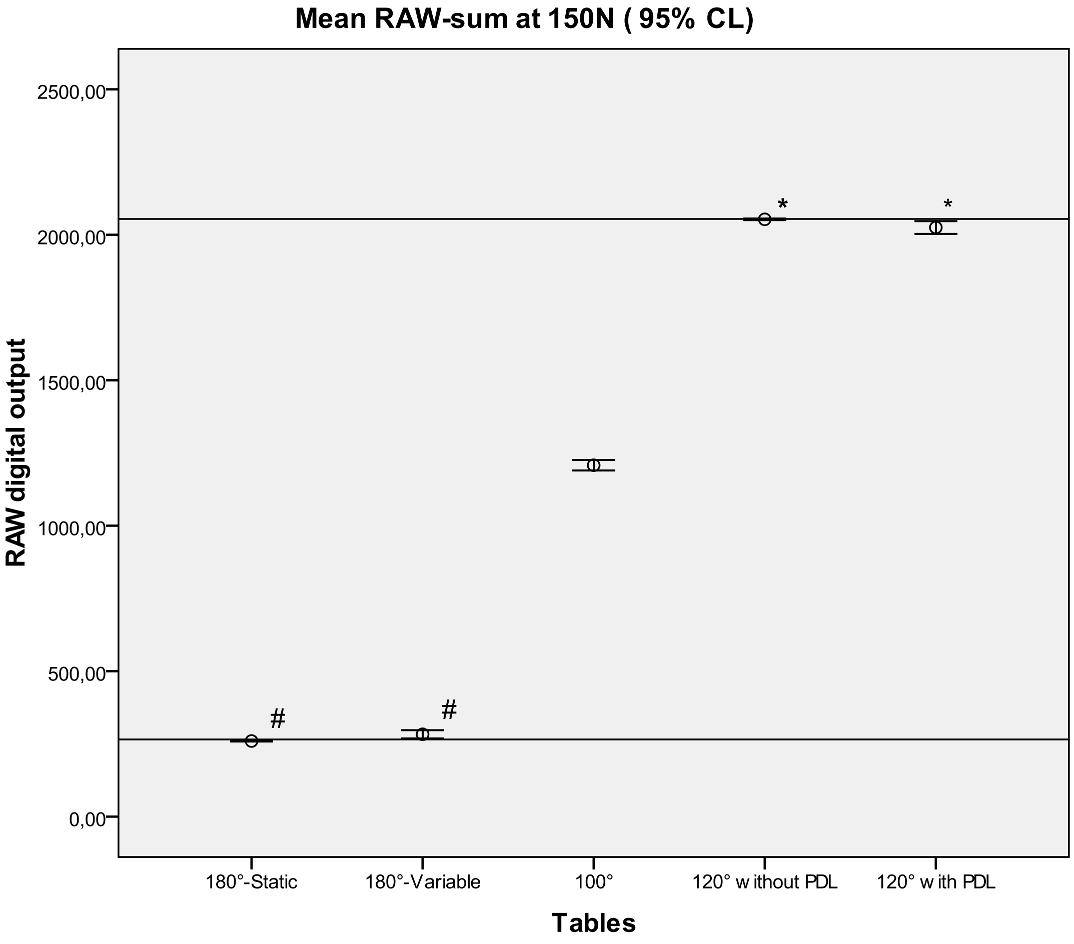


Fig.25 – Graphical illustration of the mean RAW-sum and their confidence intervals (95% CL) per table at 150N load.

**.The mean difference between the groups is significant at the level p < .05 (on the limit of significance p= .046)*

#.The mean difference between the groups is NOT significant at the level p < .05.

5. DISCUSSION

The distribution of occlusal contacts in an individual can vary with daytime.[56-57] Bite force and head posture influence the number and distribution of occlusal contacts in intercuspidation position.[58-59] These variations could be controlled only through careful scheduling and a consistent clinical technique. Another serious difficulty associated with conducting such a study is the lack of acceptable, proven, and widely accepted diagnostic criteria for the conditions being reviewed. To circumvent these problems and control such biases, we decided to design an *in vitro* study.

5.1. Occlusal forces

One of the questions we posed ourselves during the design of this experimental protocol was: what forces should we use? Biting forces have been studied for already more than half a century.

In 1975, Reynik *et al*[60] used micro-transducers and modified cephalometric roentgenogram techniques to measure maximum bite forces and moments in an adult male. In his study, the magnitude of the average bite force proved to vary by a factor of nine from the posterior to the anterior teeth. The average moment increased linearly between the anterior teeth and the first molar. The maximum force generated on a specific tooth increased nonlinearly as the perpendicular distance between the mid-sagittal plane and the tooth increased, and as the mesio-distal dimension of the teeth from the central line increased.[60] By simplification, the mandible was considered as a lever of Class III with the fulcrum located at the center of the condyle and the muscles of mastication applying forces. But, since the maximum moment was generated on the mandibular first molar, it was suggested that the mandible no longer functions as a Class III lever. Rather, the mandible may be characterized as a Class II lever.[60] This consideration might be of capital importance when trying to simulate *in vitro* the occlusion of two complete upper and lower jaws, but in our tests this was not taken into account because only the occlusion of a single tooth/cusp was simulated. Since in our study we only aimed to test the sensors' reliability, the force used should not be significant as long as its magnitude remained between clinical plausible values. In fact, when asking a patient to occlude on articulating paper or the T-Scan, the force exerted might be very variable and it depends on the operator, not only to guide the patients' occlusion but also to control the force used in order to obtain comparable data.

Nevertheless, we found it interesting to base ourselves on existing studies regarding human bite forces for complete dentate subjects in the first molar region.

Van der Bilt *et al*[61], for instance, observed in a group of 81 dentate subjects an average bilateral bite force of 569N. The average unilateral bite force was significantly lower, being 430N at right and 429N at left.

Hattori *et al*[62] found that a subjects' occlusal force during maximum voluntary clenching was 8 to 60N at premolars and 63 to 330N at molars. Proffit *et al*[63] verified the magnitude of bite forces during swallowing, chewing and the maximum bite force in normal and dolichofacial individuals, but failed to find any statistical significant difference between both. The forces found were very heterogenic and could reach from 0N to 100N at swallowing, from 40 to 350N at chewing and from 100 to 550N for maximum bite force in normal patients.

Due to the enormous heterogeneity in the magnitudes reported by this and many other authors, the choice of which forces to use had to be made quite randomly. Based on the values reported by Proffit *et al*[63], we used chewing and swallowing forces because, at best, patients use these forces when biting on the sensor but never their maximum bite force. So we calculated roughly the mean forces for each group to be programmed into the universal testing machine's own software *(Shimadzu, Trapezium® X)*. The third magnitude used was of 10N, a much slighter contact force, but over 10 times the sensor's reported lowest sensitivity threshold (0.89N for the T-Scan®II)[50].

5.2. Periodontal ligament simulator

In many areas of dentistry, there has been an increasing effort in understanding and accurately simulate the biomechanical behavior of teeth and their surrounding tissues, such as the periodontal ligament (PDL) or bone.[54, 64-78] It is well known that tooth movement is primarily a periodontal ligament phenomenon,[79] which is a visco-elastic soft tissue that, under normal circumstances, occupies a space of approximately 0.5mm in width surrounding the root and connecting the tooth to the alveolar bone.[78] Yoshida *et al*[75] and Ruse[80] reported on elastic modulus for human PDL *in vivo* of 0.12–0.96MPa and 0.07–0.7MPa respectively. The values of Young's moduli increased almost exponentially with the increment of load due to a non-linear elasticity of the PDL.[75]

The importance of including materials that can simulate, even partially, the mechanical behaviour of PDL is clear. Accurate simulation of PDL behaviour in both numerical[81] and laboratorial models[64, 82] necessitates either proper definitions or incorporation of materials with similar visco-elastic properties, respectively. Inappropriate definitions of the mechanical properties of PDL or avoiding incorporating it in the model will probably result in inaccurate conclusions.[80, 83] Using finite element models, it has been shown that the stresses and strains that develop in bone-simulating materials supporting the tooth are influenced by the presence or absence of PDL-simulating materials.[83-85] For example, PDL-simulators characterized by low elastic modulus distribute the stresses more apically as compared to models without PDL analogue, and considerably modify the fracture modes in endodontic models.[76, 84, 86] In fact, models simulating a tooth without PDL resemble more an implant than a natural tooth. However, because of its simplicity, it was most commonly used, raising doubts on the validity of the obtained results.

In this respect and because of the lack of standardization, various materials have been used for that purpose: condensation silicones,[87-88] addition silicones,[55] polyethers[76, 86, 89-90] and wax[91]. Recovery and tensile/relaxation test values showed that impression materials of high viscosity,[76, 81] especially addition-type silicone (President® Plus, Coltène/Whaledent, Aldstätten, Switzerland)[54], are the materials of choice for this purpose because they simulated better the *in vivo* tests.[54] Considering this, we used a very similar addition-type silicone from the same manufacturer, Affinis® Putty soft *(Coltène/Whaledent, Aldstätten Switzerland)*, to represent PDL-analogue based on the best scientific evidence.

5.3. Alveolar bone

During masticatory function, the teeth and periodontal structures are subjected to intermittent heavy forces. Tooth contact lasts for 1 or 2 seconds or less, forces are quite heavy, ranging from 1 to 2 kg while soft substances are chewed up to as much as 50 kg based on the type of food being masticated.[63] When a tooth is subjected to heavy forces of this type, quick displacement of the tooth within the PDL space is prevented by the incompressible tissue fluid. Instead the force is transmitted to the alveolar bone which bends in response.[78] For this reason and in order to mimic the physiologic behavior of the masticatory system, not only a PDL analogue but also an alveolar bone analogue could have been used. However, due to logistic and economical reasons onerous materials such as alveolar bone simulator could not be included in this study.

5.4. Occlusal registration materials/systems

In the past decades, there has been a notorious increase in the development and use of computerized occlusal analysis methods, especially of the T-Scan® system. The need for this evolution was essentially due to the many error-prone interpretations classical occlusal registration materials could lead the clinician to, such as described hereinafter.

5.4.1. Inked registration materials

In the dental community, articulating paper/foil mark size has been widely accepted to be descriptive of occlusal load. In 2001, Millstein *et al*[5] studied in vitro the articulating paper's reproducibility. During repeated trials on epoxy models, inordinate variations in the marks were registered. But already in 1982, Halperin *et al*[1] had studied inked registration materials and confirmed variation in colour, substrate material and thickness. This research was corroborated by Schelb *et al*[3], three years later.

More recently, in 2007, Carey *et al*[27] designed a study with the objective to determine if any direct relationship existed between articulating paper mark area and applied occlusal load. A universal test machine, similar to the one used in our study, repeatedly applied a compressive load, beginning at 25N and incrementally continuing up to 450N, to a pair of epoxy dental casts with articulating paper interposed. Graphical interpretation of the data indicated significant differences in the size of the mark area at the same applied load approximately 80% of the time. Although the trend showed a non-linear increasing mark area with elevating load, no direct relationship between paper mark area and applied load could be found.

Kerstein *et al*[28](2008) even reported the reliability between mark size and applied occlusal load to be as little as 21%. The lacking relationship can be explained because the applied pressure of the occlusal force is measured relative to its surface area such that: Pressure=applied force/surface area.[92] The smaller the surface area that receives a given force is, the bigger its resultant pressure. Broad contacts dissipate force over a large area resulting in low-pressure concentrations; whereas, small contacts dissipate occlusal forces over a small area resulting in large pressure concentrations.[92] Large contacts may represent low pressure, while small contacts may represent high pressure.[92]

Some researchers have stated that silk strips are the best material for indicating occlusal contacts.[3, 93] Because of their texture, soft indicator materials do not produce pseudocontact markings. However, silk strips can lose their marking abilities when their stain components are dried, and they can also be ruined by saliva. It is therefore advisable to store them in a cool, closed environment.[31] Comparing to the conventional articulating paper and silk, the thinner Mylar film *(DuPont Co., Wilmington, Del.)* consistently produced the most reliable marks.[5, 31, 38] Furthermore, foils are the thinnest indicator materials. to be suitable for occlusal analysis, they should be less than 21µm thick and possess plastic deformation.[1, 46] However, under reduced pressure and on glossy surfaces, their marking capacity is less evident. This means that greater pressure must be applied for the clinical use of foils.[31]

In resume, when selecting teeth to adjust, a clinician must not assume the size of inked registration materials markings, to accurately describe the occlusal contact force content.[1, 3-5, 25-30, 39] In fact, many different sized marks can represent the same load, and equal sized marks do not represent similar loads.[28] Some authors also stated that in some cases, when the occlusal load is too strong, it may destroy the occlusal paper not allowing the ink to stick to the tooth and not producing any occlusal mark at all.[92] For this reason inked registration materials alone should not be considered to be ideal for occlusal examination.[1, 5, 38] Articulating film is considered as the gold standard mainly due to its widespread and easy to use method rather than its accuracy and should therefore be questioned and carefully interpreted by the clinicians.[94 95 96]

5.4.2. Shimstock

Mannes *et al*[97] compared Shimstock and Accufilm materials for identifying induced interceptive contacts in a laboratory model system. The conclusions drawn were: none of both adequately ensured actual contact identification and so they were combined to exploit complementary properties. Anderson et al[98] tested the inter- and intra-operator reliability of Shimstock for occlusal examination an found this method to have little reproducibility. Harper *et al*[99] studied *in vitro* the force needed to pull Shimstock in simulated occlusal gaps. He found that the force removal increased with occlusal force and was highest for the smaller gaps. Using 8µ Shimstock, 0µ, 2µ and 4µ gaps could not be differentiated, a gap of up to 6µ could still be assessed as a holding contact because the Shimstock was gripped, and even an 8µ gap could be recorded as a light contact since there is still friction on removal. This suggests, that although Shimstock is one of the thinnest occlusal analysis materials available, its thickness can still cause false positives. In clinical practice, Shimstock should therefore be used as a contact locator rather than a quantitative method, just like articulating paper.

5.4.3. Wax bite

The use of waxes to record and analyze a patient's occlusion has been described by several authors.[17, 20, 39, 100-103] In 1981, Ehrlich *et al*[100] used wax bite to record occlusal contacts in the intercuspal position in 29 young Class I adults. Three types of indentation were reported. Perforation of the wax represented supracontact; a translucent area represented contact; and slight thinning of the wax represented near contact. All three types of indentation were considered as contacts, but no quantitative measurement could be given. In literature, just like in this article, there is no evidence to support the use of wax bite instead of another occlusal registration material. Since wax bite has not been tested for either inter- or intra-operator reliability and no validation of the technique for occlusal record is offered, its clinical use can only be limited to contact location and registration but not quantitative measurement.

5.4.4. Silicones

In 1986, Durbin and Sadowsky[104] described a silicone impression material method for examining occlusal contact patterns before and after orthodontic treatment. Millstein *et al*[2] suggested this method to be more accurate in identifying tooth contacts when comparing to articulating paper. Korioth[94] reported on the number and location of occlusal contacts in intercuspal position using alginate impression material. Although this method showed good accuracy,[95] it proved to be impractical in daily practice. However, it might serve as gold standard against which other, easier to use clinical methods could be tested.

5.4.5. Occlusal contact sounds

In the late 1960s, the first studies to detect tooth contact by sounds generated during yaws closure began to appear in oral health literature.[105] A commercially available device was produced in the mid 1980s called "Dental Sound Checker" *(Yoshida Dental Trade Distributing Co. Ltd, Tokyo, Japan)* to evaluate occlusal contact sound patterns during closure in an attempt to detect occlusal disturbances.[105-106] However, it soon became clear that the nature of occlusal sound varies depending on the way subjects close their teeth. No good reproducibility studies have been reported on this occlusal examination method.[105-106]

5.4.6. Computerized techniques

Computerized techniques have been available for a couple of decades. It is an important requirement of such a method that the registering foil and the technique itself cause only minimal interference with the occlusion. Two methods that largely fulfill these requirements are the Dental Prescale system *(Fuji Film Co., Tokyo, Japan)* and the T-Scan® (*Tekscan, South Boston, USA)*. Photoplastic wafers were the first quantitative method introduced for occlusal analysis.[107]

The commercially available Dental Prescale System is a two-step technique which can determine absolute force by inspecting under a polariscope light the birefringence pattern produced by the photoplastic film after it is bitten by the patient for 10 to 20 seconds. In the first step, the force is registered intraorally with a pressuresensitive foil that changes color at the occlusal contacts depending on the masticatory force exerted.[15, 108] The second step involves scanning and analyzing this foil *(Occluzer FPD-703; Fuji Film Co., Tokyo, Japan; Occluzer Graph M, Scimolex Co., Tokyo, Japan)*. Hattori *et al*[62] evaluated the reliability of this device for occlusal force measurement, both on a subject and on casts. They reported the existence of a linear relationship between the applied and measured loads. One advantage of this system is the registration of absolute force, but crucial disadvantages are the lack of occlusal contact time sequences and the time taken to perform the technique. In a clinical comparison, Gazit *et al*[4] proved this method to be more reproducible in recording occlusal contacts than did inked marking foils, although none of the methods presented high reproducibility. Posterior contact intensity was enhanced while the anterior contacts were diminished.[4] Because photoelastic sensors depend on thick foils that inhibit dental proprioception, some reports of reliability have been disappointing.[4, 109] Furthermore, this technique is reported to be “difficult to apply.”[2, 110] In addition, analysis of premature contacts, laterotrusive or protrusive contacts is not possible.

By contrast, the T-Scan® allows simultaneous registration and imaging of the distribution of forces in relation to the maximum force exerted and the occlusal contact time sequences. Premature contacts and interferences in the dynamic occlusion can be identified. The system displays a recorded occlusal “force movie” in real-time 0.01-second increments, which illustrates the various occlusal pressures with a color legend during playback either on 2D or 3D.[25] The darker colors represent low occlusal pressures and the brighter colors indicate higher occlusal pressures. One of the most important applications is the system’s ability to describe the occlusal contact timing order as the different occlusal contacts sequentially load.

The device is licensed as a “medical attachment device – contact sensor system”. Historically, the first generations of the T-Scan system, the T-Scan®I and II, proved not to be quite reliable.[9, 20, 45-49]

The primary limitation of the sensor’s pressure sensitive film device was its far too thick recording medium. Although the foils’ layer thickness was 100µm and hence within the range of commercially available articulating foils, papers and silk (8–200µm),[15, 111] it resulted in heavier contacts on the posterior teeth than anterior teeth due to its little flexibility. Further, the sensor’s thickness disturbed the patient in attempting to close into the intercuspal position.[20] In fact, a study on interocclusal thickness discrimination has shown that already an aluminum foil as thin as 20µm can give bite-disturbing proprioceptive information to a subject.[107]

Another problem is directly linked to the sensor’s design itself. The sensor consists of two layers of Mylar films *(Dupont Tejjin Films, The Netherlands, B.V.)* with sagitally and horizontally running electrical conductive silver traces separated by small silver-free stripes (*Attachement 1*). The silver traces will be hereafter called conductive rows and the silver-free strips will be called nonconductive rows. The conductive rows, 0.82mm wide, are covered with a layer of force ink. The silver traces in the upper and lower Mylar films form a grid of conductive elements. Between these elements, which are 0.38mm apart, there are pressure-insensitive areas. Voltage drops in the conductive rows result from any force exerted on the foil. These voltage changes are measured and digitalized by the T-Scan® software. Thus, sensors consist of pressure-sensitive and pressure-insensitive areas. The sensitive parts have a total area of 1184.2mm^2, which corresponds only to approximately 53% of the sensor's total area.

In 1992, Ming-Lun Hsu B.[23] analyzed the sensor’s sensitivity threshold at 47 randomly selected points as well as along a "conductive" and a "nonconductive". Results indicated that the sensor did not have a uniform sensitivity throughout the surface. The sensitivity threshold along the conductive row differed significantly from that along the nonconductive one *($p< .001$).*

Furthermore, in some studies, the first T-Scan® generations always recorded fewer occlusal contacts than were actually present.[47, 112] Additionally, the sensitivity of the T-scan sensors has been reported to decrease when the sensors are used more than once.[39, 47, 113]

5.5. T-Scan®III HD: Our results on its
Sensitivity, Accuracy, Reproducibility and Clinical implications

Studies frequently show that it can be very difficult for a clinician to predictably identify which occlusal contact is more forceful when using articulating paper alone. With this system, it became possible not only to located the distribution of tooth contacts, but also to compare their relative intensity and even their timing. By enabling to identify previously unobtainable occlusal force characteristics, the T-Scan®III HD can help to obtain high quality and complete occlusal end-results, so that its use as an occlusal adjustment tool has been advocated and reported in several areas of Dentistry such as Prosthodontics, Orthodontics and Implantology.

5.5.1. The sensor saturation

As according to previous studies, changing the foil was not found to have any statistically significant influence, anytime inconsistent data appeared, the sensor foil was exchanged.[15] In this respect and while testing the sensor under 150N on table 120° without PDL, once the sensor was perforated, the perforation overrode all other data and reported consistent values *(Fig.12)*. The total force stayed at 100%, showing no variability, which indicated sensor damage. Furthermore, the complete vertical force drop moments, indicated sensor damage, which can be easily identified by the operator through these characteristics.

The bars, the mean and the wide standard deviation rank *(Fig.15-16)*, show that the number of uses that one sensor can provide is variable and depends on many factors such as the table used (the anatomy), the load magnitude applied and whether it is applied on the same spot or not. Still, all the bars show sensor use longevity well beyond the 20-24 times the manufacturer recommends.[50] The sensors longevity could be exponentially increased beyond the manufacturer's indications, when this kind of tests were performed only on its extremities (anterior and posterior-left and -right areas). A possible explanation for this phenomenon might be found when examining the sensor's pressure sensitive grid. Avoiding areas that contain conductive silver traces which have already been saturated could make the sensor provide accurate data for more trials. Another explanation is that the intra-oral conditions, multiple cusp and complexe anatomies are far more demanding for the sensors than the *in vitro* conditions tested. Still, all this was found only empirically and the explanation used is nothing but hypothetical.

5.5.2. Sensitivity

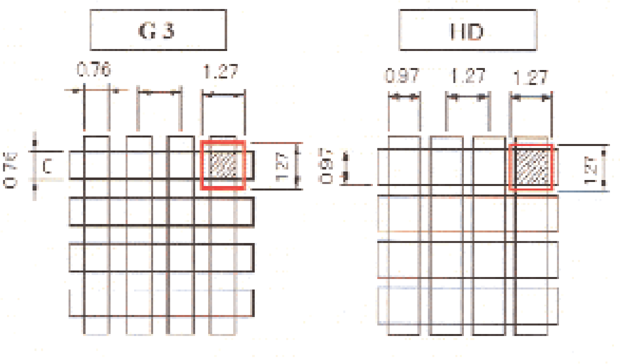


Fig. 26 - Size difference of the recording sensel and inactive area between G3 and HD sensor designs.

With the new T-Scan®III HD we did not encounter some of the problems quoted by various authors in the past as weaknesses of the T-Scan®I and T-Scan®II, such as the existence of pressure insensitive points know as ‘’black spots’’. But, according to the statistical analysis of the coefficients of variation *(4.5.2, Fig.21)*, there is a noteworthy increase in the variation of the Raw-sum measurements when the sensors’ position is altered. This may suggest that the sensor does not have the same sensitivity throughout its surface. However we recognize that it might have been an experimental procedure bias, since the tension applied to vary the sensor´s position may have induced vectors of force that could alter the results. Furthermore, no pre-conditioning of sensor (a pre-requisite to ensure good measurements as stated by the manufacturer and verified through our study) could not be executed with this method since all areas where newly pressured. Further studies should be conducted for better understanding of this phenomenon.

Nevertheless, we also recognize that a device design limitation may exist such that the spatial resolution of the sensor might not be dense enough to prevent this phenomenon *(Attachement 1)*. It is therefore probable that when using the sensor intraorally, a tooth contact point on one closure could be on the border of a sensel, and on another closure be located on the inactive recording area. It is also possible that some tooth contacts may be small enough to fit between sensels and land completely in the inactive area where they would not be detected. However, this did not occur at any time during our tests using the spherical bur, and has not been reported by any clinical study, suggesting that it may represent anirrelevant or inexisting clinical problem.

In 2006, Kerstein et al[50] stated that this new high definition (HD) sensor design has increased active recording area by 33%, and decreased inactive recording area by 50% as compared to the previous design (G3). This was accomplished by increasing the active sensing element (sensel), placing them much closer together within the recording grid *(Fig.26)*. Therefore, it is likely that tooth contacts present on the varying cuspal topography could more frequently land on a sensel instead of the inactive space between the sensels. Based on these facts, Kerstein et al[50] suggests that the closer sensel proximity of the HD sensor is better suited than former designs to compensate for the existence of "black spots", and therefore produces less variable results for at least 20 in-laboratory loading cycles.[50]

Though some variability exists throughout the sensor surface *(Fig.17, ii) and (4.5.2).* This is a typical characteristic of electronic sensors and due to the fact that even the active recording area of this new fourth generation of T-Scan® system could not cover up the whole sensor at 100%, leaving some very small insensitive points scattered all over the recording grid. However, the clinical relevance of this minor insensitive spots could possibly be neglected.

5.5.3. Accuracy

The possibility that by deflection, the sensor's sensitivity might alter had to be analysed. Unlike what happens to the Tekcan® sensors in industrial applications, in the oral cavity, because of the compensation curves (curves of Spee and Wilson) and cuspal morphology, the sensors suffer significant distortions. The sensor is fabricated flat, and when being repeatedly loaded, significant folding and crimping occurs in and around the teeth anatomy. The sensels are then positioned along the incline planes of the occlusal surfaces or incisal contours, such that they are receiving non-perpendicular forces. This angular force application can yield variable total applied force, as the sensor is crimped from closure to closure. A device design limitation exists such that the spatial resolution of the sensor may not be dense enough to compensate for this effect.

According to Throckmorton *et al*[16], it is possible to convert the RAW values into an absolute force when the sensor is first calibrated before performing the test, and then obtain a read out of RAW-sum from the known load. But as interpreted through *Fig.22*, depending on the anatomic circumstances there is not always a linear correlation between the actual force applied and the lectures done by the sensor. That means, when a force X is applied it will be interpreted as Y by the sensor, but when triplicating this force, for instance 3X, the sensor will not identify this force as 3Y, but as bigger than just the threefold of Y. This is true, when considerable deflection under simulated anatomic morphology is inflicted to the sensor (example: on the tables of 120°). Clinically, we must therefore be aware that a force identified to be much bigger on one tooth than on another, not necessarily is that much forceful.

The regression lines do not cross the origin of the axis (zero), which shows us that for low values (lower than 10N and close to zero) the data depicted by the sensor cannot be accurate. Even though the lowest threshold reported by the manufacturer is 0.89N this only means that 0.89N[50] can be detected by the sensor but not that the value depicted will be accurate.

Another phenomenon occurs when just altering the occlusal table. The use of a table creating a larger contact area *per se* makes more sensels being loaded, which again leads to a bigger digital output and therefore to an over interpretation of the load applied even when the force is maintained constant as seen on *Fig.22*.

The statistical analysis *(Fig.23, 24 and 25)* supports the above mentioned thesis, showing variations in means between the different tables for the same applied load. In clinical practice, we must take in account that the tooth morphology alone can bias the interpretation of the sensor's results.

5.5.4. Reproducibility

In order to verify whether the system provides reliable data, boxplots and an analysis of variance was employed to determine the variability of force reproduction over multiple closures across the recording area.

First of all, we studied the boxplots and calculated 85% of the outliners (40 out of 47) to be within the 5 first sensor compressions. This phenomenon has already been described by other authors before.[50] As the sensor is fabricated flat, according to the manufacturer, each sensor requires a *conditioning period* of test closures to allow for sensor deformation in and around the tooth anatomy, for assessing the patients' occlusal strength for proper recording Sensitivity adjustment, and for acclimating the patient to intercuspate well upon the sensor for future recording. When consistently placed under close to ideal laboratory conditions, the variability of the HD sensor data is not affected by repeated closures for at least 36 out of 40 trials and more, when a single contact exists.

Secondly, when comparing the coefficients of variation using a *One-way ANOVA,* we noticed that forceful contacts (150N) imply fewer variations than light contacts (10N). This effect is most probably linked to the testing machine's precision itself. The fact that independently of the load applied, a constant variation of 1N exists *(Fig.5, 6 and 7)*, it is easy to understand that this 1N represents a bigger percentage of 10N (10%), than of 50N (2%) or 150N (0,67%). And since the coefficient of variation is directly proportional to the variation (1N) and inversely proportional to the load detected, this inevitably results in a bigger coefficient of variation for lighter loads (10N).

Statistical significant differences *($p < .001$)* could be found in the coefficients of variation between the table (180°-Variable) and all the other tables, but not between the remaining tables, confirming that varying the sensor's position increases significantly the measurements' dispersion. So, when expecting to obtain reliable data during occlusal examination, we must assure the sensor's stability between the jaws. This guarantees us that always the same area, which has been conditioned before through repeated closures, is loaded. The clinician can assure the sensor's stability by fixing it firmly between the patient's central incisors.

Note: The above mentioned variability of the force machine did not have any interference in the conclusions drawn concerning the variability between the tables, since this was a bias present in all of the tables and all loads (10N, 50N and 150N) were calculated in.

5.5.5. Clinical implications

In clinical practice, some operators noticed empirically that when an anterior deep-bite exists, the forces in this region are perceived by the T-Scan® to be more forceful. We tried to verify this thesis by using a 100° table in static position and managed to recreate this scenario. This can be easily explained by the fact that the digital output given is not only dependent on the force magnitude, but also on the contact area created. Since in a deep-bite, more folding is inflicted to the sensor foil and a bigger contact area is created between the teeth surfaces, greater digital output is given. However, the use of lower levels of Sensitivity can reduce the effect the sensor folding adds, when reporting data in a deep bite patient. This is a skill a clinician learns through proper T-Scan use training.

The size of a tooth's contact area depends from many factors such as its cuspal morphology, and not the least from the physiological tooth movement guaranteed by the periodontal ligament. This physiologic mobility enables a tooth to increase its contact area when submitted to an increasing load. In former studies[27, 50] only rigid models were used to analyze the reproducibility of occlusal registration materials so that the contact area, independently of the force applied remained quite unaltered, which is not the case in natural teeth that are surrounded by a soft, dynamic tissue.

It is well known that natural teeth and dental implants have significant biomechanical differences with respect to movement under occlusal loading. The occlusal forces applied to an implant-supported prosthesis can be potentially destructive, shortening the longevity of any implant prosthesis. Poorly directed and non-uniform occlusal loading will torque the prosthesis and apply stresses that may ultimately result in prosthetic insuccess. Material failures, screw loosening, loss of cementation and implant deosseointegration have been related to excessive occlusal loading on dental implants.[96, 114] The objectives to occlusal adjustments on implant-supported prostheses are to achieve simultaneous loading of forces upon occlusion, a uniform distribution of forces and forces directed throughout the long axis of the implant.[114]

A primary reason for employing computerized occlusal analysis when restoring lost function with implant prosthodontics is that the patient's occlusal contact confirmation is subjective and significantly reduced, as compared to natural teeth.[96] This is because implants lack of a PDL with proprio- and mechanoreceptors. A study by Hammerle *et al*[96] in 1994 revealed that, without periodontal ligament feedback, the patient's perception of occlusal contacts, is 8 times less reliable when compared to natural teeth. In the abscence of periodontal ligament, each implant is loaded through a dental prothesis with less neurological feedback to the Central Nervous System.[115] So, utilizing a patient's subjective perception about existing occlusal contacts as a guide to occlusal force balance, is very inaccurate and highly error-prone. Combined also with a subjective interpretation of the occlusal paper markings as seen in previous chapters, the errors could be clinically very important.

The T-Scan® Center of Force analysis with its centering target, can additionally guide the operator in the orientation of the occlusal forces during the prosthetic insertion occlusal adjustment procedure.[116]

However, there are some points of clinical value in our study that should be focused on:

- At an applied force of only 10N, there is no statistical difference between both artificial molars, whether it is included in PDL-simulator or not. This suggests that the force might have been too light to sufficiently compress the PDL-simulator and create a significant larger contact area than for the tooth without PDL-analogue.
- At a load magnitude of 150N, there is a statistical significant difference on the very limit of significance *(p= .046).* Here we probably might have exceeded the limit of compressibility of the PDL-simulator, making the tooth act like a rigid

model. *Fig.17,v)* might help understand this phenomenon, because after 12 closures, there is an abrupt decrease in the detected RAW values.

- However, at 50N load, representing the most probable force used when a patient occludes on an occlusal analysis device, the statistical analysis (*ANOVA)* shows a large statistically significant increase *($p < .001$)* in the digital output for the model with PDL-simulator, pointing out to an adaptation of the contact area and therefore an excessive interpretation by the software of the load applied.

The RAW-sum given seems to be directly proportional to the contact area obtained rather than only depend on the force applied. This paradoxically has been criticized for being one of the major problems regarding articulating paper, representing an area but not actually a force. For the T-Scan®, this situation apparently, causes no problem when only the graphic's peak values and their timing are considered for occlusal adjustments, but when we want to use the percentages displayed per area this phenomenon might lead the clinician into error. Using a concrete and simplified example, when the same force X is exerted on two different teeth, the sensor will display a bigger % of force to be on the tooth providing the larger contact area even though the peaks may be equal.

Therefore, we have to take into account, that the T-Scan® can only be of any clinical utility when the values it depicts are correctly interpreted, especially in balancing a mixed occlusion with natural teeth and implant rehabilitation. Due to their significantly less physiologic mobility and therefore diminished ability to adapt (increase) their contact area with the opponent tooth, the force on an implant might be underestimated when compared to a natural tooth, if we only use the percentage distribution instead of the peaks to adjust the occlusion.

Considering the fact, that the calculation of the percentages per area (left, right, anterior and posterior) and the Centre of Force (COF) are dependent on the RAW-sum as well and therefore linked to the contact area, the clinician should always be careful in interpreting this data. However, the force % per tooth is not the most important factor to consider in adjusting someone's occlusion. It is tertiary issue, last after uneven individual contact forces, the timing order they rise in, and the timing of the disclusion. It shall be focused on one of the T-Scan®'s real advantages, its ability to display the time sequences in .01s increments. According to the scientific advisers from Tekscan®, it is therefore recommended, that rather than treating just the patient's force % per tooth, the clinician shall treat the timing order of the uneven force rises that occur around the arch. These are non-simultaneous column rises that occur between first contact and static intercuspation. The time required to disclude all posterior teeth (molars and premolars bilaterally) so that they separate in <.5 seconds per excursion appears to a more important clinical treatment issue than is the force % per tooth. According to the clinical advisers of this system, treating the timing order of the uneven force rises during closure, and removing prolonged friction from the excursions, can improve the overall force balance, the time simultaneity of all contacts, and the muscle activity levels from pre- to post-treatment dramatically.

6. CONCLUSIONS

As interpreted through our study results, the RAW-sum, which the T-Scan® software uses to compute de force % and COF, is a digital unit which cannot be directly linked to any physical unit such as a force or a pressure. We know it represents the total electronic digital output of the sensor when it is loaded. If a larger contact area exists, more sensels are loaded and more digital output is created. Regarding this situation and due to the fact that little information is given regarding the software processing of the T-Scan, namely what exactly the RAW value represents, a force, a pressure or something in between, a careful and trained handling of the RAW-sum linked values is required.

There are some points the clinician must be aware of when using T-Scan®III HD for occlusal analysis:

- Its sensitivity seems to be improved as compared to former designs, however futher studies about variability throughout its sensing surface are needed;
- It is of capital importance to assure the sensor's stability during repeated closures in order to obtain comparable data. Variable sensor placement intraorally can be minimized by orienting the sensor support repeatedly between the patient's central incisors prior to recording any occlusal data.
- Its reproducibility could be proved, except for the 5 first values (outliers to the mean values). Therefore, anytime occlusal data is recorded, those closures are used as a *conditioning time* for the sensor to adapt to the tooth morphology. It also assesses the patients' occlusal strength for proper recording sensitivity level adjustment, and acclimates the patient to intercuspate well upon the sensor for future recording;
- Its accuracy proved to be dependent of the anatomic circumstances and the contact area created;
- Apparently, less relative variation occurs at bigger loads (150N as compared to 50N or 10N). This effect is most probably linked to the testing machine's variability (1N) itself.
- Particular caution has to be taken when interpreting the force % of a rigid *vs.* a non-rigid model, for instance when adjusting a mixed occlusion (implant-tooth).
- Since, not only the applied force, but also the contact area given are quantified into a single value (RAW-sum), balancing a mixed occlusion can be a challenge to the clinician.

Conclusions

In general, this newest version of the T-Scan® system (T-Scan®III HD) seems to have undergone many improvements as compared to former designs. Its sensitivity and reproducibility unquestionably present very satisfactory results. However, despite the technologic advances made in the area of occlusal analysis, a critical interpretation and careful handling of the depicted values is indispensable, and can only be acquired through a long learning curve.

These investigations are a good beginning in the improved understanding of the weaknesses and strengths of the entire clinical occlusal examination process. Nevertheless, the practicing clinician's "gold standard" for diagnosing occlusal interferences is a combination of patient self-report opinion and the occlusal examination.

7. FURTHER PERSPECTIVES

7.1. We recognize that the occurrence of such a wide variation in the results when applying loads on different points of table 180°-Variable may have been due to some experimental procedure bias, since the tension applied to vary the sensor´s position (when applying 150N) may have induced vectors of force that could alter the results. Furthermore, no pre-conditioning of the sensor (a pre-requisite to ensure good measurements as stated by the manufacturer and verified through our study) could be executed with this method since all areas where newly pressured. Further studies should be conducted to better understand this phenomenon.

7.2. The Raw-sum *per se* is not used to treat patients, and one point sensor loading Raw Sum variances, cannot be directly extrapolated to indicate how the sensor will perform clinically when a complete denture is loading many differing sensing points on the sensor surface. The relative force and timing data output is the data used to treat patients clinically. Therefore, a clinical study should be designed in order to access the real reproducibility of the sensor under intraoral conditions.

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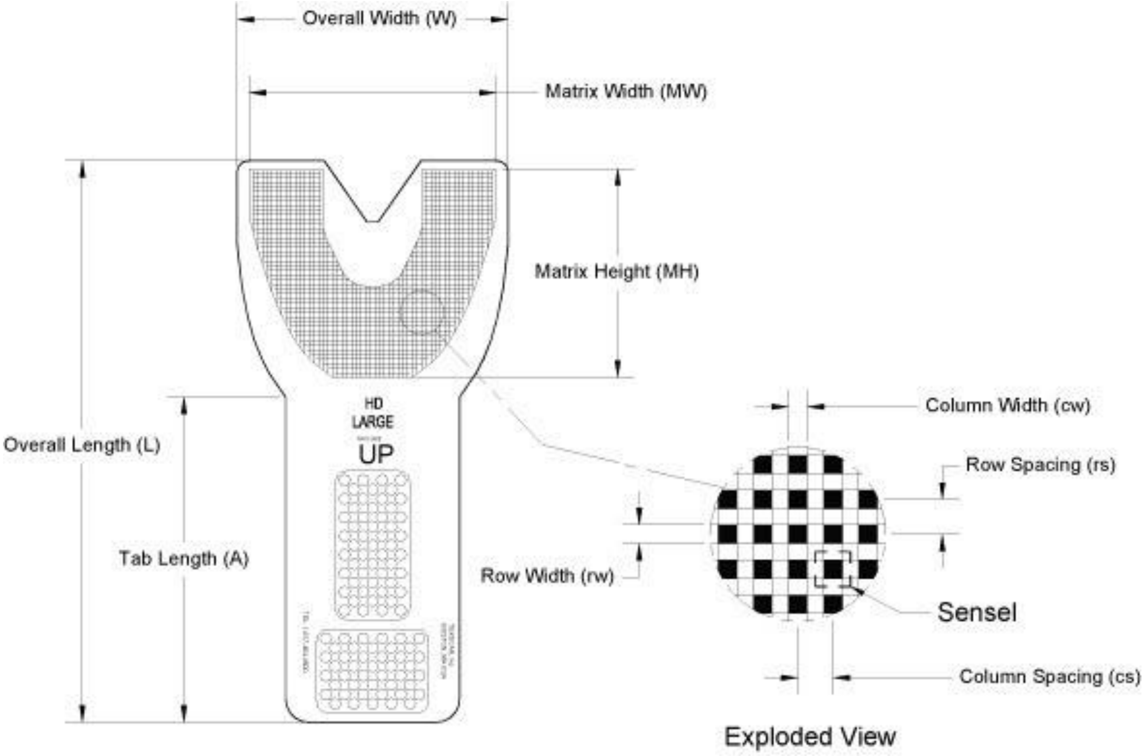
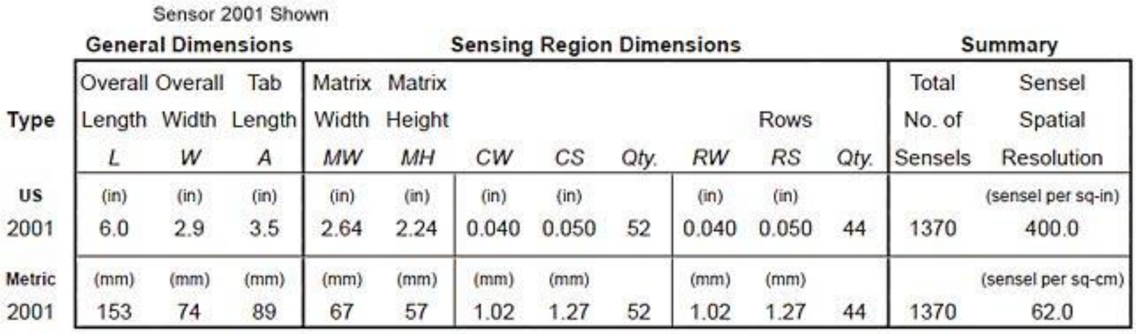
9. ATTACHEMENTS





Sensor 2001 Shown

	General Dimensions			Sensing Region Dimensions								Summary	
Type	Overall Length *L*	Overall Width *W*	Tab Length *A*	Matrix Width *MW*	Matrix Height *MH*	*CW*	*CS*	*Qty.*	*RW*	Rows *RS*	*Qty.*	Total No. of Sensels	Sensel Spatial Resolution
US	(in)	(in)	(in)	(in)	(in)	(in)	(in)		(in)	(in)			(sensel per sq-in)
2001	6.0	2.9	3.5	2.64	2.24	0.040	0.050	52	0.040	0.050	44	1370	400.0
Metric	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)		(mm)	(mm)			(sensel per sq-cm)
2001	153	74	89	67	57	1.02	1.27	52	1.02	1.27	44	1370	62.0

Attachement 1- T-Scan®III HD technical data.

Multiple Comparisons

Bonferroni

(I) load	(J) load	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
10N	50N	,03165*	,00828	,000	,0118	,0515
	150N	,05442*	,00828	,000	,0346	,0743
50N	10N	-,03165*	,00828	,000	-,0515	-,0118
	150N	,02277*	,00828	,018	,0029	,0426
150N	10N	-,05442*	,00828	,000	-,0743	-,0346
	50N	-,02277*	,00828	,018	-,0426	-,0029

*. The mean difference is significant at the 0.05 level.

Attachement 2 - One-way ANOVA statistical analysis of the coefficients of variation for the loads 10N, 50N and 150N.

Multiple Comparisons

Bonferroni

(I) table	(J) table	Mean Difference (I-J)	Std. Error	Sig.
180° - Static	180°-Variable	-,11798*	,00942	,000
	100°	,00009	,00942	1,000
	120° without PDL	-,01887	,00942	,457
	120° with PDL	-,00808	,00942	1,000
180° - Variable	180°-Static	,11798*	,00942	,000
	100°	,11806*	,00942	,000
	120° without PDL	,09911*	,00942	,000
	120° with PDL	,10989*	,00942	,000
100°	180°-Static	-,00009	,00942	1,000
	180°-Variable	-,11806*	,00942	,000
	120° without PDL	-,01896	,00942	,447
	120° with PDL	-,00817	,00942	1,000
120° without PDL	180°-Static	,01887	,00942	,457
	180°-Variable	-,09911*	,00942	,000
	100°	,01896	,00942	,447
	120° with PDL	,01079	,00942	1,000
120° with PDL	180°-Static	,00808	,00942	1,000
	180°-Variable	-,10989*	,00942	,000
	100°	,00817	,00942	1,000
	120° without PDL	-,01079	,00942	1,000

*. The mean difference is significant at the 0.05 level.

Attachement 3 - One-way ANOVA statistical analysis on the coefficients of variation for the 5 simulated occlusal circumstances.