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RESEARCH AND EDUCATION

Repeatability and reproducibility of 2 digital occlusal analyzers for measuring the right- and left-side balance of occlusal contact forces: An in vitro study

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ABSTRACT

Statement of problem. Although different digital occlusal analyzers have been marketed, comparative studies are lacking.

Purpose. The purpose of this in vitro study was to compare the repeatability and reproducibility of 2 different digital occlusal analyzers (T-Scan and OccluSense) for measuring the right- and left-side balance of occlusal contact forces.

Material and methods. The repeatability and reproducibility of the 2 digital occlusal analyzers for measuring the balance of occlusal contact forces were determined and compared by using the Gauge Repeatability and Reproducibility tests based on the International Organization for Standardization (ISO), ISO 5725-2 and ISO 5725-3 standards. Ten different dental casts were mounted in the maximum intercuspation position on a semi-adjustable articulator. Then, the balance of occlusal contact forces in each of the 10 articulated dental casts was measured 24 times with each of the 2 digital occlusal analyzers. In addition, as the OccluSense, unlike the T-Scan, does not have a centering support for the piezoelectric film sensor, measurements with it were performed without and with a custom-designed and manufactured centering support. Finally, the repeatability and reproducibility of both digital occlusal analyzers were determined and compared using the Gauge Repeatability and Reproducibility tests.

Results. The repeatability and reproducibility tests revealed that only 0.8% of the variance of the measurements obtained with the T-Scan was due to repeatability and reproducibility (0.4% repeatability, 0.4% reproducibility). In contrast, 12% of the variance of the measurements obtained with the OccluSense was due to repeatability and reproducibility (2.2% repeatability, 9.8% reproducibility). However, when using OccluSense with the centering support, the variance decreased to 6.4% (2.8% repeatability, 3.6% reproducibility). According to the Automotive Industry Action Group classification, the repeatability and reproducibility of the T-Scan were good, those of the OccluSense poor, and those of the OccluSense with the centering support medium.

Conclusions. The repeatability and reproducibility of the T-Scan were significantly better than those of the OccluSense for measuring the balance of occlusal contact forces. Furthermore, the repeatability and reproducibility of the OccluSense were significantly improved when used with a device to center the piezoelectric film sensor between the incisors. Nevertheless, the repeatability and reproducibility of the T-Scan were better. (J Prosthet Dent xxxx;xxx:xxx-xxx)

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Clinical Implications

Digital occlusal analyzers can be used to measure the right- and left-side balance of occlusal contact forces. Dentists should be aware of the precision of commercially available devices, to inform their decision on their use in clinical practice.

Traditionally and most commonly, occlusal contacts have been detected using articulating paper or foil.[1] Although these diagnostic methods are able to determine the exact location of occlusal contacts, they are not able to measure their forces reliably.[2]

Digital occlusal analyzers were developed to detect occlusal contacts and also measure the relative intensity of force at each occlusal location.[3] The reliability of the first and most widely used digital occlusal analyzer (T-Scan; Tekscan, Inc) to determine the location of occlusal contacts has been widely studied.[4–9] However, studies of its reliability to measure the forces at these occlusal contacts are sparse.[10–14]

Since the introduction of the T-Scan, additional digital occlusal analyzers with similar functionalities have been developed and marketed at a lower cost, such as the Accura (Dmetec Co) and the OccluSense (Dr Jean Bausch GmbH & Co KG).[11,15] The OccluSense has the additional advantage that the sensor has built-in articulating paper to mark the occlusal contacts on the teeth. However, studies on its use are lacking,[15] and the authors are unaware of any studies on its reliability.

Digital occlusal analyzers provide valuable information for determining the quality of occlusion, which is important for different clinical purposes, including the detection and correction of temporomandibular disorders,[16,17] the evaluation of prostheses,[18,19] the evaluation of orthodontic treatment,[20] and the resolution of dental problems such as bruxism,[21] severe tooth wear,[22] and muscle pain.[23] The valuable information provided includes the balance of occlusal contact forces (BOCFs) with respect to the mid-sagittal plane, also known as right- and left-side balance. The software programs of digital occlusal analyzers such as the T-Scan provide this information directly (Fig. 1), while it can be easily calculated from the sum of the force percentages of the

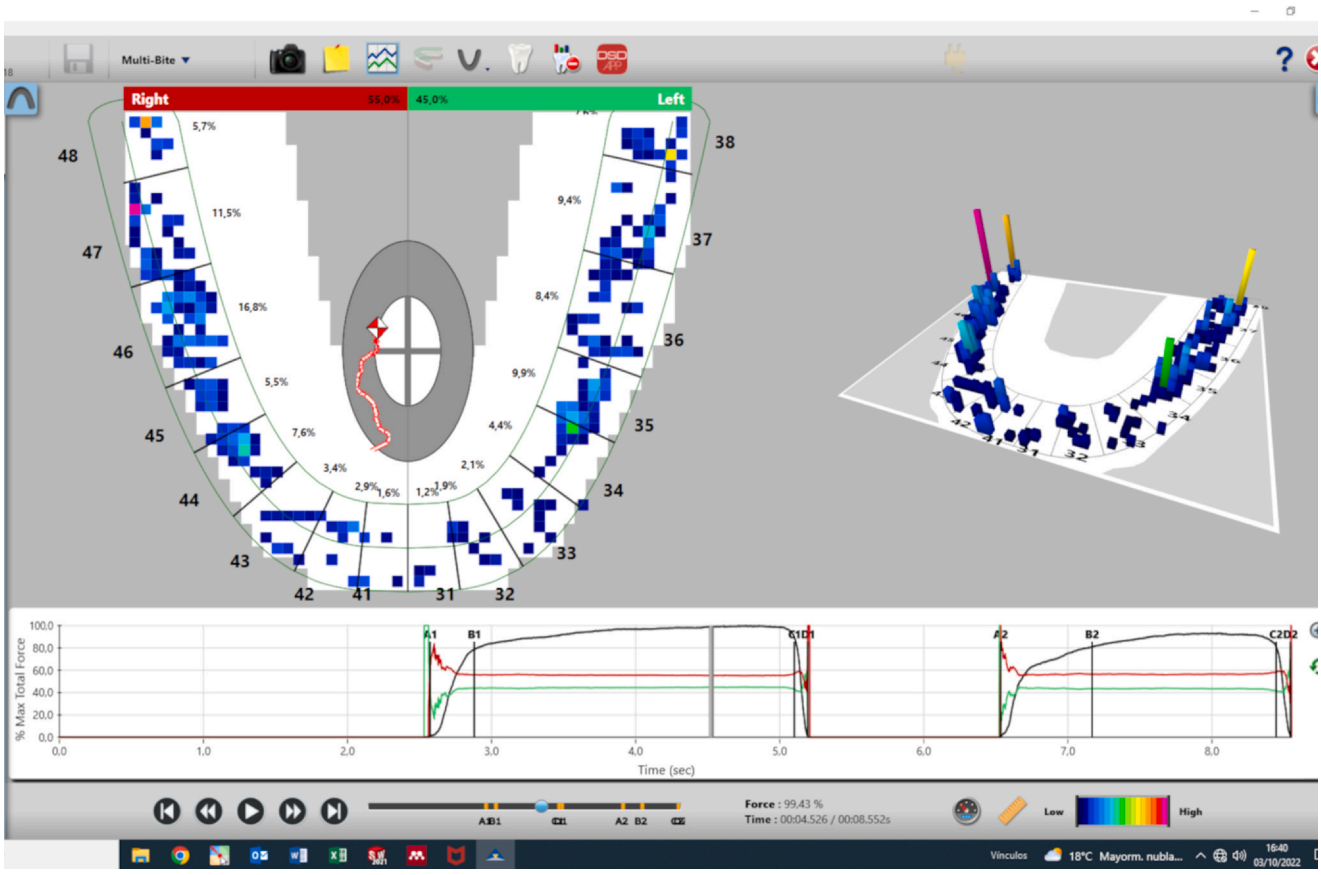

Figure 1. Digital occlusal analyzer (T-Scan) software screen with right- and left-side contact forces percentage results at MIP. MIP, Maximum intercuspal position.

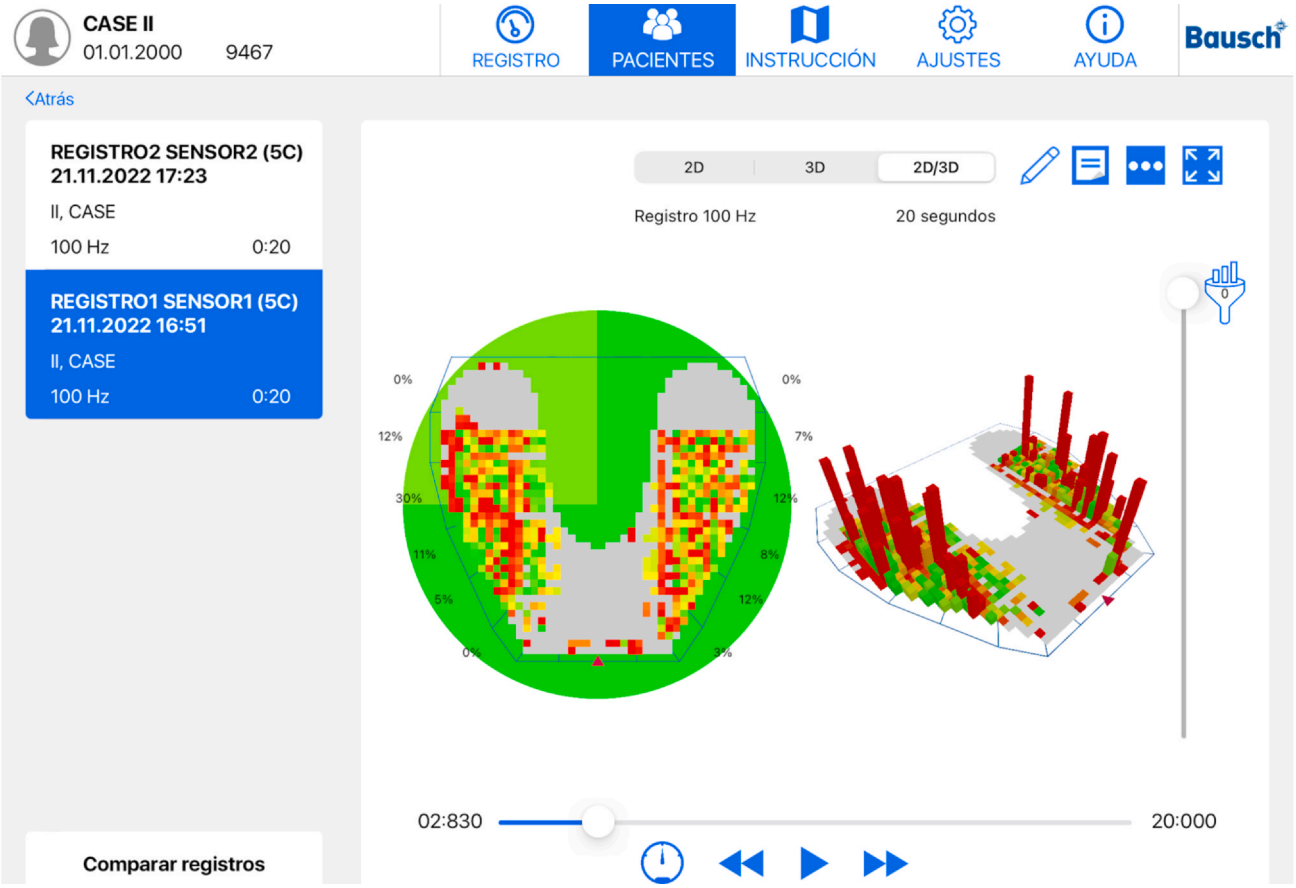

Figure 2. Digital occlusal analyzer (OccluSense) software screen with contact force percentage results of each dental piece at MIP. MIP, Maximum intercuspal position.

tooth on each side of the mid-sagittal plane offered by the software programs of other digital occlusal analyzers, including the OccluSense (Fig. 2).

Studies on the accuracy of digital occlusal analyzers are sparse,[10–14] with even fewer on their accuracy for measuring the BOCFs (almost all of them focused only on the T-Scan).[12] According to the International Organization for Standardization (ISO) 5725-1 standard, accuracy is a combination of trueness and precision, with trueness referring to the ability of the digital occlusal analyzer to provide measurements of the BOCFs that are as close to their real value as possible and precision referring to the closeness of agreement between independent measurements of the BOCFs provided by the digital occlusal analyzer under stipulated conditions.[24,25] According to the ISO 5725-1 standard, the 2 conditions of precision are repeatability and reproducibility, are useful for describing the variability of the measurements of the BOCFs provided by a digital occlusal analyzer. Under repeatability conditions, factors such as the operator, the device used, the environment, and the time elapsed between measurements are considered constants and do not contribute to the variability of the measurements, while under reproducibility conditions they vary and do contribute to the variability of the measurements. Therefore, to determine the precision of a digital occlusal analyzer for measuring the BOCFs, a standard repeatability and reproducibility test should be used, as described in the ISO 5725-2 and ISO 5725-3 standards.[24,26,27] In this study, the Gage Repeatability and Reproducibility (GRR) test was used, which classifies the precision of a device as good, medium, or poor according to the criteria accepted by the Automotive Industry Action Group (AIAG).[28]

The positioning of the digital occlusal analyzer's piezoelectric film sensor in the patient's mouth could influence the measurements of the BOCFs and thus also its repeatability and reproducibility. A recent study[29] concluded that the occlusal force measured at maximum intercuspal position (MIP) with a digital occlusal analyzer varied throughout the day, so it would be convenient to know whether this is because of the lack of precision of the digital occlusal analyzer or because of other circumstances.[30] Some digital occlusal analyzers, including the T-Scan, have a centering support with a central incisor pointer to help position the piezoelectric

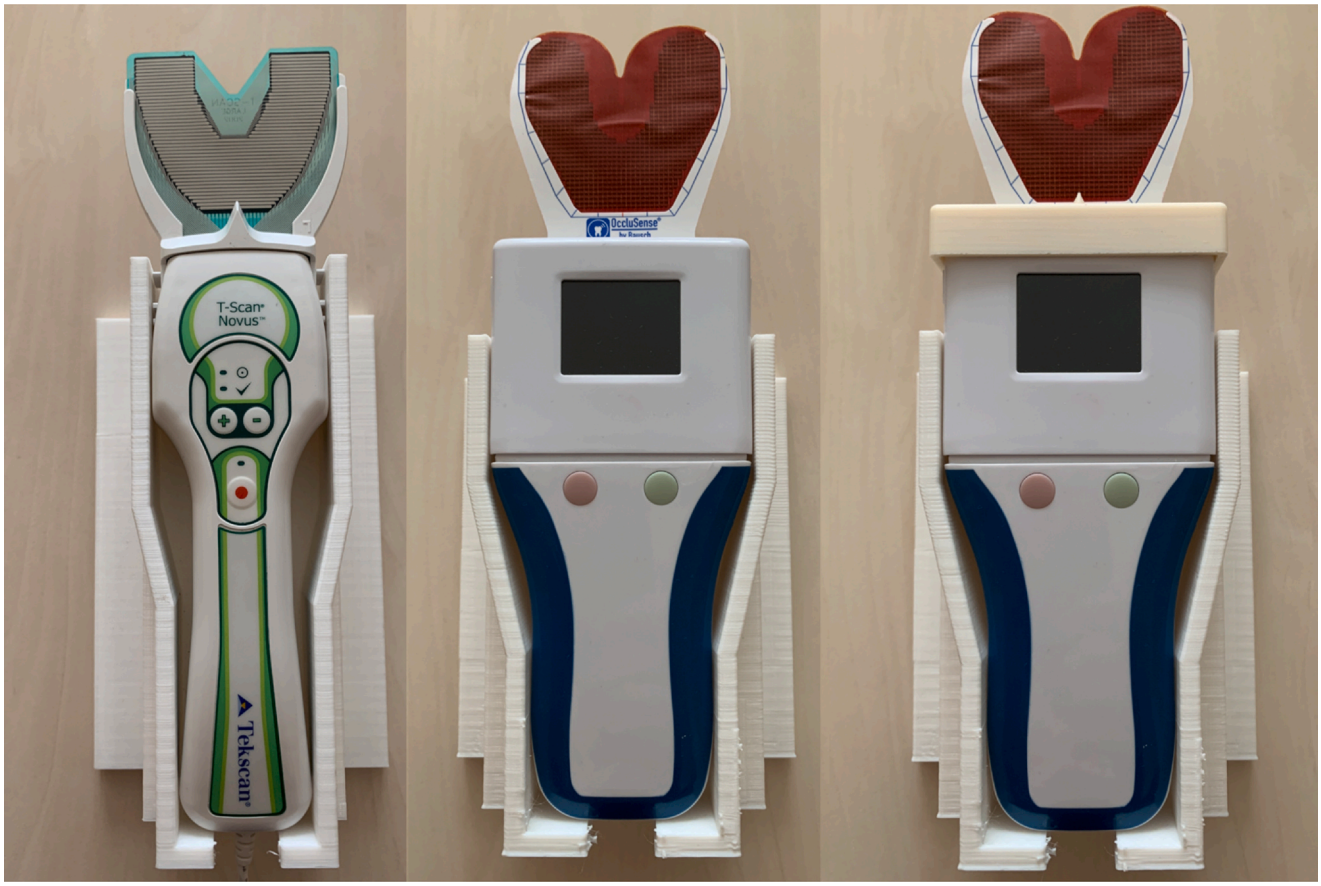

Figure 3. Three digital occlusal analyzer options tested (T-Scan; OccluSense; OccluSense with centering support) with piezoelectric film sensor attached.

film sensor in a reproducible way, whereas other digital occlusal analyzers, including the OccluSense, do not have a centering support.[15]

The purpose of this in vitro study was to determine and compare the repeatability and reproducibility for measuring the BOCFs obtained with 2 different digital occlusal analyzers. One of the digital occlusal analyzers had no centering support, so a custom centering support was designed and manufactured for it, and its precision with and without centering support was also determined and compared. The following reproducibility conditions were established for this in vitro study: same devices and operator but different articulated dental casts (equivalent to different patients) and sensor positioning (equivalent to different measurements over time). The null hypotheses tested were that no significant differences would be found in the repeatability and reproducibility of the 2 digital occlusal analyzers and that a centering support would not improve the repeatability and reproducibility of the digital occlusal analyzer.

MATERIAL AND METHODS

The repeatability and reproducibility for measuring BOCFs were determined and compared for 2 different digital occlusal analyzers: T-Scan (T-Scan Novus; Tekscan Inc) and OccluSense (OccluSense; Dr. Jean Bausch GmbH & Co KG). Since the OccluSense does not have a centering support for the piezoelectric film sensor, 1 was custom designed and manufactured.

The study was approved by the university ethical committee (M10_2019_254). Ten pairs of dental casts were mounted in MIP on a semi-adjustable articulator (Artex CN; Amann Girrbach AG). Before mounting the casts, the articulator was calibrated with a magnetic plate system to a precision of less than 10 μm. An experienced clinician made the impressions with a high- and low-viscosity polyvinyl siloxane impression material (3 M ESPE Express 2 Putty Soft and Light Body Standard; 3 M). The same clinician obtained the interocclusal records at MIP with polyvinyl siloxane material (3 M Imprint 4 Bite; 3 M) and facebow records (Artex

Figure 4. Assembly of elements used for tests.

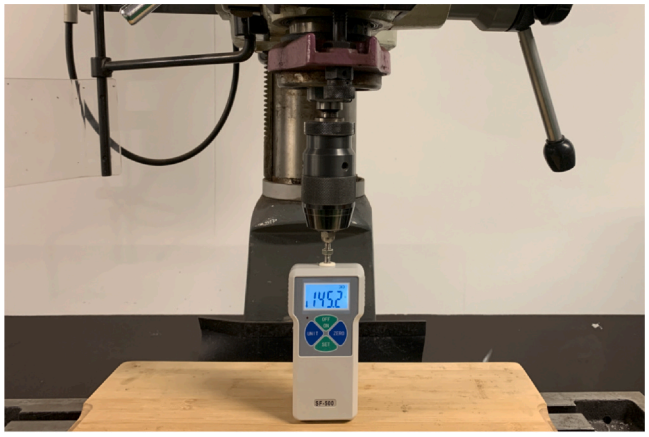

Figure 5. Vertical drill and input force of constant magnitude of 145 N.

facebow; Amann Girrbach AG). The dental casts were produced and mounted on the semi-adjustable articulator by a dental laboratory technician.

For each articulated dental cast, the BOCFs were measured using the T-Scan, the OccluSense, and the OccluSense with the centering support (Fig. 3). For each digital occlusal analyzer, the piezoelectric film sensor was placed centrally between each of the articulated maxillary and mandibular casts. A custom fixed support was used to fix the position of each of the digital occlusal analyzers (Fig. 4).

To measure the BOCFs, the corresponding fixed structure was placed on a vertical drill press table (OPTI F30; Optimum) (Fig. 4), designed to reproduce the trajectory and position the tool with respect to its table. An input force of 145 N, equivalent to masticatory force,[10–12] previously measured with a digital dynamometer (Beslands Push-pull Force Gauge SF-500; Beslandstool) (Fig. 5), was applied perpendicular to the Frankfurt plane from a Ø12.5 mm spherical tip. The force was applied at the same point on the upper arm of the semi-adjustable articulator, which was set by using a printed grid attached to the articulator (Fig. 4). Each time an input force was applied, the BOCFs were measured as per the manufacturer's protocol.[12] For each of the 10 articulated dental casts, 24 measurements were made in each of the 3 ways, repositioning the piezoelectric film sensor every 6 measurements (720 in total) (Table 1).

All measurements were recorded in a spreadsheet software program (Microsoft Excel 2016 with Real Statistics Resource Pack; Microsoft Corp.). The GRR test was used to determine and compare the repeatability and reproducibility of the 3 ways of measuring BOCFs. The GRR tests quantified the variability of the 240 BOCF measurements obtained with each of the measuring methods. This test separated the variability into 3 components: the repeatability of the measuring method, the reproducibility of the measuring method, and the variation of articulated dental casts (equivalent to patient variation). The precision of the measuring method was represented in terms of variations in its repeatability and reproducibility. Within the GRR test, an ANOVA test was performed to measure the interaction between the positioning of the piezoelectric film sensor and articulated dental casts to determine whether this variation was due to the repeatability or the reproducibility of the measuring method (α=.05).[28]

RESULTS

The ANOVA within the GRR test revealed that the articulated dental casts (part in GRR tests), the positioning of the piezoelectric film sensor (operator in GRR tests), and the iteration of both of them (operator×part in GRR tests) had a statistically significant influence on the variability of the measurements of the BOCFs obtained through the 3 measurement ways used (P<.05) (Tables 2–4). According

Table 1. Experimental protocol for BOCFs measurement

	T-Scan Device				OccluSense Device				OccluSense Device With Centering Support			
	SP 1	SP 2	SP 3	SP 4	SP 1	SP 2	SP 3	SP 4	SP 1	SP 2	SP 3	SP 4
ADC 1	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R
ADC 2	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R
…	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R
ADC 10	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R	6 R

ADC, articulated dental cast (part of gage repeatability and reproducibility test); BOCFs, balance of occlusal contact forces; R, repetition of measures; SP, sensor positioning (operator of gage repeatability and reproducibility test).

Table 2. GRR test results for T-Scan device

GRR (With Interaction) for T-Scan						
ANOVA				Alpha	.05	
	SS	DF	MS	F	*P*	Sig.
Part	6.728	9	0.748	1059.615	<.001	
Operator	0.007	3	0.003	3.450	.030	
Operator*part	0.019	27	<0.001	6.194	<.001	Yes
Repeatability	0.023	200	<0.001			
Total	6.777	239	0.028			
Variation					AIAG Classification	
	Variance		SD		Range	Evaluation
Total GRR	0.024%	0.8%	1.6%	8.8%	<10%	Good
- Repeatability	0.011%	0.4%	1.1%	6.0%	<10%	Good
- Reproducibility	0.013%	0.4%	1.1%	6.4%	<10%	Good
– Operator	0.003%	0.1%	0.5%	3.0%		
– Op*part	0.010%	0.3%	1.0%	5.6%		
Part-to-part	3.112%	99.2%	17.6%	99.6%		
Tot variation	3.136%	100.0%	17.7%	100.0%		
No. of categories:		16				

AIAG, Automotive Industry Action Group; DF, degree of freedom; F, Fisher statistical; GRR, Gage repeatability and reproducibility; MS, mean square; SD, standard deviation; SS, sum of squares.

to the GRR test, the variability between the positioning of the piezoelectric film sensor and the articulated dental casts used was a component of the reproducibility of the measurement method used.

According to the GRR test, the variance of 0.8% of the measurements obtained with the T-Scan was caused by its repeatability and reproducibility (0.4% repeatability, 0.4% reproducibility) (Table 2). The repeatability and reproducibility of the OccluSense caused 12% of the variance of the measurements obtained with it (2.2% repeatability, 9.8% reproducibility) (Table 3). However, when using the OccluSense with the centering support, the variance caused by its repeatability and reproducibility decreased to 6.4% (2.8% repeatability, 3.6% reproducibility) (Table 4). According to the AIAG classification,[28] the repeatability and reproducibility of the T-Scan were good (standard deviation below 10%) (Table 2), those of the OccluSense poor (standard deviation above 30%) (Table 3), and those of the OccluSense with the centering support medium (standard deviation above 10% but below 30%) (Table 4). The coefficient of variation of the repeatability and reproducibility (calculated as the standard deviation due to the repeatability and reproducibility divided by the mean value of the corresponding measurements) was 2.97% for the T-Scan, 9.72% for the OccluSense, and 8.57% for the OccluSense with the centering support (Table 5).

DISCUSSION

This in vitro study determined and compared the repeatability and reproducibility for measuring the BOCFs of 2 different digital occlusal analyzers: the T-Scan and

Table 3. GRR test results for OccluSense device

GRR (With Interaction) for OccluSense						
ANOVA				Alpha	.05	
	SS	DF	MS	F	*P*	Sig.
Part	4.562	9	0.507	35.626	<.001	
Operator	0.028	3	0.009	0.660	.584	
Operator*part	0.384	27	0.014	27.701	<.001	Yes
Repeatability	0.108	200	<0.001			
Total	5.077	239	0.021			
Variation					AIAG Classification	
	Variance		SD		Range	Evaluation
Total GRR	0.280%	12.0%	5.3%	34.6%	>30%	Poor
- Repeatability	0.051%	2.2%	2.3%	14.8%	10%-30%	Medium
- Reproducibility	0.229%	9.8%	4.8%	31.3%	>30%	Poor
– Operator	0.000%	0.0%	0.0%	0.0%		
– Op*part	0.229%	9.8%	4.8%	31.3%		
Part-to-part	2.053%	88.0%	14.3%	93.8%		
Tot variation	2.332%	100.0%	15.3%	100.0%		
No. of categories:		3				

AIAG, Automotive Industry Action Group; DF, degree of freedom; F, Fisher statistical; GRR, Gage repeatability and reproducibility; MS, mean square; SD, standard deviation; SS, sum of squares.

Table 4. GRR test results for OccluSense with centering support

GRR (With Interaction) for OccluSense With Centering Support						
ANOVA				Alpha	.05	
	SS	DF	MS	F	*P*	Sig.
Part	6.114	9	0.679	93.618	<.001	
Operator	0.015	3	0.005	0.667	.580	
Operator*Part	0.196	27	0.007	8.705	<.001	Yes
Repeatability	0.167	200	<0.001			
Total	6.492	239	0.027			
Variation					AIAG Classification	
	Variance		SD		Range	Evaluation
Total GRR	0.190%	6.4%	4.4%	25.2%	10%-30%	Medium
- Repeatability	0.083%	2.8%	2.9%	16.7%	10%-30%	Medium
- Reproducibility	0.107%	3.6%	3.3%	18.9%	10%-30%	Medium
– Operator	0.000%	0.0%	0.0%	0.0%		
– Op*part	0.107%	3.6%	3.3%	18.9%		
Part-to-part	2.800%	93.6%	16.7%	96.8%		
Tot variation	2.991%	100.0%	17.3%	100.0%		
No. of categories:		5				

AIAG, Automotive Industry Action Group; DF, degree of freedom; F, Fisher statistical; GRR, Gage repeatability and reproducibility; MS, mean square; SD, standard deviation; SS, sum of squares.

Table 5. Comparative of precision results of 3 digital occlusal analyzer options

Comparative Values of GRR Tests	**T-Scan**	**OccluSense**	**OccluSense With Centering Support**
Mean value of 240 measurements	52.29%	54.40%	50.90%
Total variance of 240 measurements	3.136%	2.332%	2.991%
Variance due to repeatability and reproducibility	0.024%	0.280%	0.190%
(% respect total variance)	(0.8%)	(12.0%)	(6.4%)
Variance due to repeatability	0.011%	0.051%	0.083%
(% respect total variance)	(0.4%)	(2.2%)	(2.8%)
Variance due to reproducibility	0.013%	0.229%	0.107%
(% respect total variance)	(0.4%)	(9.8%)	(3.6%)
Standard deviation due to repeatability and reproducibility divided by standard deviation of 240 measurements	8.8%	34.6%	25.2%
Classification of the precision according to the AIAG	Good	Poor	Medium
Coefficient of variation of repeatability and reproducibility (standard deviation due to repeatability and reproducibility divided by the mean value)	2.97%	9.72%	8.57%

AIAG, automotive industry action group; GRR, Gage repeatability and reproducibility.

the OccluSense. Given that in clinical practice it is common for the same clinician to perform different occlusion measurements on the same patient with the same device at different appointments, the reproducibility conditions tested were the same devices and operator but different articulated dental casts (equivalent to different patients) and sensor positioning (equivalent to different measurements over time). In addition, since the OccluSense does not have a centering support to assist in the positioning of the piezoelectric film sensors, measurements with that device were performed without a centering support and with a custom-designed centering support to analyze whether such a support would improve the reproducibility of the device. The results revealed that the repeatability and reproducibility of the T-Scan were better than those of the OccluSense and that the reproducibility of the OccluSense improved with a centering support. Therefore, both null hypotheses were rejected.

The results revealed that only 0.8% of the variance of the measurements obtained with the T-Scan was from its repeatability and reproducibility, 0.4% from repeatability, and 0.4% from reproducibility (that is, by differences in the positioning of the piezoelectric sensor film) (Table 2). Thus, according to the results, 99.2% of the variance of the measurements obtained with the T-Scan was caused by differences between the articulated dental casts used (equivalent to differences between patients). With these results, according to the AIAG classification, the repeatability and reproducibility of the T-Scan were considered to be good. These results were consistent with those of previous studies, including Kerstein et al,[12] which also concluded that the T-Scan was repeatable for measuring the BOCFs. In addition, Lee et al[11] concluded that the T-Scan was repeatable for measuring the total force value. Cerna et al[10] concluded that the T-Scan was reliable and repeatable for measuring the total force when using sensors of the same manufacturing series. In addition, the coefficient of variation of the BOCFs measured with the T-Scan in this study (2.97%) was similar to the magnitudes of total contact forces and the center of contact force positions

measured with the T-Scan by Jauregi et al[14] (3.70% and 0.37%, respectively).

In contrast, the results revealed that 12.0% of the total variance of the measurements obtained with the OccluSense was from repeatability and reproducibility with 2.2% repeatability and 9.8% reproducibility (Table 3). According to the AIAG classification, the repeatability and reproducibility of OccluSense were considered poor. The fact that the variance from reproducibility was much larger than from repeatability suggested that positioning the piezoelectric film sensor of the OccluSense in a reproducible manner in the patient's mouth is problematic. When the OccluSense was tested with the centering support to help position the piezoelectric film sensor, the variance of the measurements from repeatability and reproducibility decreased to 6.4% (2.8% repeatability, 3.6% reproducibility) (Table 4). The decrease in the variance of the measurements from the repeatability and reproducibility of the OccluSense was due to the decrease in the variance from reproducibility, indicating that a centering support for the piezoelectric film sensor could improve the repeatability and reproducibility of the OccluSense. With this support, the repeatability and reproducibility of the OccluSense were acceptable, according to the AIAG classification. This improvement in the repeatability and reproducibility of the OccluSense is clinically significant, especially considering that the OccluSense device is considerably less costly than the T-Scan.[28]

The coefficient of variation of the measurements obtained with the T-Scan was 2.97%, and those of the measurements obtained with the OccluSense with and without centering support were 8.57% and 9.72%, respectively (Table 5). These comparable values, according to the results of the GRR tests, indicated that the first version of the OccluSense with or without the centering support had significantly less precise results than the current version of the T-Scan and that the OccluSense was more precise with the centering support.

Limitations of the present study included the in vitro design and that only the precision of the digital occlusal analyzers for measuring the BOCFs at MIP was determined and compared. The authors were unaware of the existence of methods for analyzing the trueness of digital occlusal analyzers for measuring the BOCFs at MIP, so truenees was not analyzed. Therefore, further studies are needed to develop a procedure to determine its trueness. Procedures to determine and compare the accuracy of digital occlusal analyzers for measuring other data such as the contact force percentage over time or the position of the center of forces should also be developed. Future research should be carried out in vivo, since under those conditions, the placement of the piezoelectric film sensor could be more complicated and the results of the GRR tests could be worse. Such studies should consider that the magnitude and balance of human masticatory forces are not as repeatable as in an in vitro study[14,30] and that this could also affect the GRR test results.

CONCLUSIONS

Based on the results of this in vitro study, the following conclusions were drawn:

1. The T-Scan digital occlusal analyzer was significantly more precise than the OccluSense digital occlusal analyzer for measuring the right- and left-side balance of occlusal contact forces.
2. The precision of the OccluSense digital occlusal analyzer for measuring the right- and left-side balance of occlusal contact forces was significantly improved by using a centering support for the piezoelectric film sensor. Although its precision was still lower than that of the T-Scan, it could be acceptable, especially considering that it is much more affordable than the T-Scan.

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CRediT authorship contribution statement
Mikel Jauregi: Conceptualization, Methodology, Software, Investigation, Writing - original draft. **Xabier Amezua:** Investigation, Writing - original draft, Visualization. **Mikel Iturrate:** Formal analysis, Data curation, Visualization. **Eneko Solaberrieta:** Validation, Writing - review and editing, Supervision, Project administration, Funding acquisition.

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