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ORIGINAL ARTICLE

Quantitative tooth mobility evaluation based on intraoral scanner measurements

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Abstract

Background: Tooth mobility assessment is subjective and current techniques require the translation of a continuous variable to a categorical variable based on the perception of the examiner. The aim of this study was to evaluate the reliability of a novel technique to assess tooth mobility.

Methods: Three experienced periodontists were asked to push tooth #16 into a buccal position to in a typodont model with different mobility (M1−M2). Tooth position was obtained using an intraoral scanner and files were compared in metrology software. Mobility was calculated at three reference points at the cervical (C), middle (M), and occlusal (O) regions of the buccal surface of the tooth to determine the linear deviation in the three axes (x, y, and z). Reliability was determined by intraclass-correlation coefficient, differences between M1 and M2 determined by *t* test, and the analysis of variance (ANOVA) was used to compare the data at the C-M-O regions.

Results: Excellent reliability was assessed by Cronbach alpha >0.9 on the x-y-z axes for both mobility tested, except for M1-C X (0.85), M1-M Y (0.89), and M2-M Z (0.89). The correlation between the examiners demonstrated excellent (>0.90) or good (0.75> x <0.90) consistency, except for M1-C Y (0.73; examiner 1 **to** 2) and M1-M X (0.69; examiners 1 to 3). Significant changes were detected in all axes at the three reference points comparing M1 and M2, and a similar proportional change was observed between O-M-C reference points for M1 and M2.

Conclusion: A novel technique to assess tooth mobility based on intraoral scanner measurements provided reliable data in an in vitro experiment.

KEYWORDS

periodontal disease, precision medicine, quantitative evaluation, reliability of results, tooth mobility

1 | INTRODUCTION

Tooth mobility is a routine evaluation performed to support the diagnosis and prognosis of periodontal disease. Miller in 1938 proposed a classification based on the displacement of the crown and categorized tooth mobility according to horizontal and vertical thresholds.[1] Ramfjord in 1967 proposed a classification based on clinical aspects of tooth mobility, related to functional parameters, in attempt to overcome errors related to the lack of precision and accuracy of existing alternatives and to focus clinically relevant aspects.[2] The major problem of current tooth mobility techniques is not related to the classification but is the inherent subjective nature of the assessment that requires the translation of a continuous variable to a categorical variable, grouping together a broad range of values in subgroups based on the perception of the examiner.

Clinical data investigating tooth prognosis demonstrated the potential of tooth mobility measurements to define the treatment outcome. Fleszar et al. (1980) demonstrated that sites with moderate (4 to 6 mm) and deep (7 to 12 mm) probing depths experienced attachment loss (AL) associated with higher mobility compared with firm teeth after the first year following periodontal therapy.[3] The relevance of initial mobility on periodontal disease progression was highlighted in a 28 years retrospective study.[4] The patients with AL $\geq$2 mm had tooth mobility at baseline and during the follow-up, indicating that tooth mobility is a significant risk factor for future AL.[4] Wang et al. (1994) examined patients with furcation involvement after 8 years following periodontal therapy.[5] Molar teeth with mobility at baseline or 1 year had higher AL compared with molars without mobility, independent of furcation involvement. In contrast, sites treated with surgical and non-surgical periodontal therapy combined to occlusal adjustment demonstrated gain in clinical attachment level after 1 year independent of the initial mobility.[6]

Complex electronic and mechanical devices were developed to generate accurate measurements of physiological and pathological displacements of tooth. Parfitt developed an electronic device to measure the axial tooth displacement.[7] The author suggested that axial displacement would better relate to potential damage to all periodontal fibers, whereas bucco-lingual displacement was primarily related to the fibers in the cervical region. Muhlemann developed a mechanical device to measure bucco-lingual displacement in response to different loads providing quantitative outcomes.[8] Clinical data using the Muhlemann device successfully demonstrated a decrease in tooth mobility after non-surgical and surgical periodontal therapy.[9,10] However, the clinical application of such experimental devices was limited due to the time required to set-up and the overall patient experience. The effort to obtain reliable quantitative data on tooth mobility highlights the clinical relevance of such parameters. The development of a user-friendly concept based on objective measurements will provide the opportunity to establish reliable oral health outcomes to define the need to treat and evaluate patient's prognosis.

In the present study, we present a technique to determine tooth mobility based on intraoral scanner (IOS) measurements. The aim was to develop an accurate and precise technique to provide reliable three-dimensional (3D) quantitative oral health outcomes for physiological and non-physiological movements of the tooth.

2 | MATERIALS AND METHODS

2.1 | Images acquisition

The current method is based on the 3D comparison of digital models obtained with IOS.* A first digital impression of the typodont† on its original configuration was obtained and defined as the baseline. A series of digital impressions of the typodont was taken with the operators pushing the typodont's tooth to be analyzed into a buccal direction. The force was applied with the tip of the handle of a dental mirror placed in the lingual surface. The goal was to promote a movement in the tooth that simulates dental mobility commonly associated to periodontitis similar to the daily practice (Fig. 1).

A series of tests have been performed to develop the proposed method. In the current experiment, a typodont model was used to simulate the clinical environment and two different degrees of tooth mobility were created by changing the tightness of the screw holding tooth #16. Each operator was asked to push the tooth into a buccal position to promote the movement, with the use of the handle of a dental mirror (Fig. 1A). The operator was asked also to hold the instrument at the final position of tooth movement while a second operator performed the scanning. Three experienced periodontists evaluated two different mobility and repeated the measurements 10 times. The blinded operators were asked to simulate the same force and direction used in a clinical setting. No instructions were provided to the operators regarding direction and magnitude of the force during the experiment.

2.2 | Mobility evaluation

Digital impressions of the models were obtained and the STL files were exported from the IOS software‡ and compared using a comprehensive metrology platform.§ For the different evaluations, one baseline digital impression was obtained as reference and the different tested scenarios compared to generate the deviations at different pre-determined points in the crown (#16). The two models for each evaluation were then aligned using surfaces in the image not affected by the force applied to #16 (Fig. 1B). The aligned models were processed and the buccal surface of the tooth was oriented in the screen at 90° with the ground plane using regions not affected by the displacement of #16 (Fig. 1C). For the displacement analysis, three reference points at the buccal surface of the tooth were chosen to determine by linear deviation in the three axes (x, y, and z). The three areas chosen were in the cervical, middle, and occlusal third of the tooth crown (Fig. 2A).

* Trios 3, 3shape, Copenhagen, Denmark.

† Columbia Dentoform, New York, NY.

‡ Trios Dental System, 3Shape, Copenhagen, Denmark.

§ Geomagic Control X, 3D systems, Morrisville, NC.

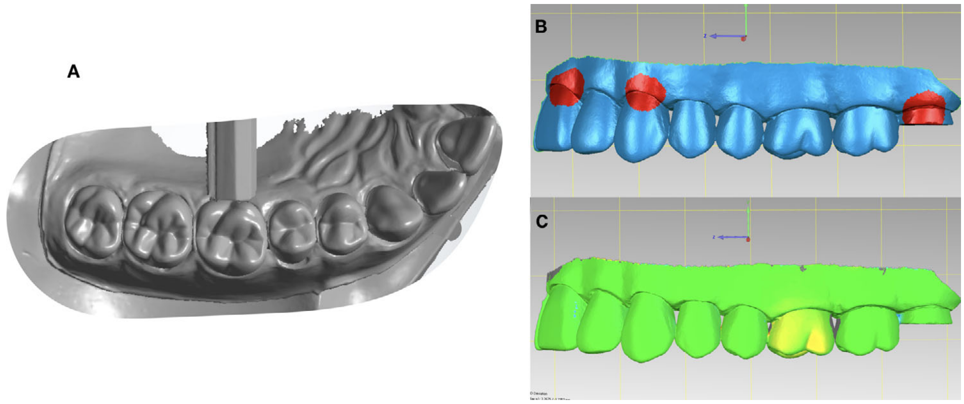

FIGURE 1 Illustration of how the intraoral scanning device can be used for detecting tooth mobility. (**A**) In vitro simulation of dental mobility in a similar way to what is done currently in a daily practice. The tip of a mirror handle pushed #16 to the buccal direction generating a displacement. (**B**) Alignment of the two digital models obtained by intraoral scanning. Three coincident areas were chosen as reference in each model for alignment. (**C**) Three-dimensional comparison of the two digital models aligned. The buccal surface of #16 shows different colors highlighting the displacement of the tooth, indicating the amount of deviation between baseline and mobility 1 or mobility 2 models

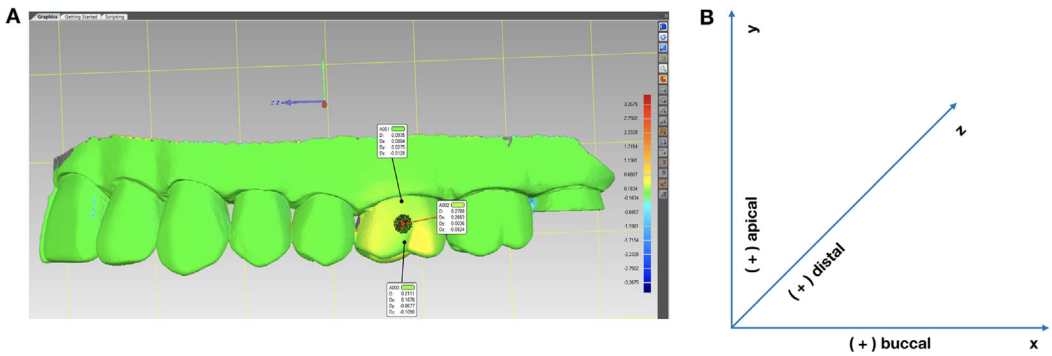

FIGURE 2 Demonstration of intraoral scanning device for recording three aspects of tooth mobility. **A**) Three different points were chosen to measure the linear movement in the three different axes. **B**) x, y, and z axes direction in relationship to the buccal-lingual, coronal-apical, and mesio-distal planes

The linear measurements of the movement in the three different axes were collected for statistical analysis. The x, y, and z axes represent the bucco-lingual, apical-coronal, and mesio-distal directions of the tooth anatomy. It was determined that a positive value during the analysis represented a change to the buccal, apical, and mesial aspects for the present evaluation, and a negative value would relate to the lingual, coronal, and distal aspects, respectively (Fig. 2B).

2.3 | Statistical analysis

The statistical analysis was performed to evaluate the following: 1) reliability; 2) differences between mobility 1 and mobility 2, and 3) the variation in the different regions (cervical, middle, and occlusal). The reliability was analyzed by intraclass correlation coefficient (ICC). ICC estimates and their 95% confidence intervals were calculated using statistical software.* Based on the 95% confidence interval of the ICC estimate, values <0.5, between 0.5 and 0.75, between 0.75 and 0.9, and >0.9 are indicative of poor, moderate, good, and excellent reliability, respectively.[11] In addition, the inter-item correlation was evaluated offering a paired analysis of the different examiners. Data from mobility 1 to 2 were analyzed by *t* test for each examiner (data not shown) or pooled to support a comprehensive interpretation. Data analysis among the cervical, middle, and occlusal points was performed by one-way analysis of variance (ANOVA). Significance level was set at 95%. Tooth displacement was calculated in microns (μm).

* SPSS, version 24, IBM, Armonk, NY.

3 | RESULTS

3.1 | Reliability

Tables 1 and 2 show the mean ± SD, inter-item correlation, Cronbach alpha, Cronbach alpha confidence interval (CI = 95%), and the *F* test for the ICC analysis. The reliability of the technique is supported by the high Cronbach alpha on the x, y, and z axes for both mobility tests that scored >0.9 in all

TABLE 1 Reliability analysis of the data obtained for mobility 1 in the three reference points analyzed (cervical, middle, and occlusal) reported by the axis (x, y, and z) and by examiners (1, 2, and 3)

		Mobility 1														
		Cervical					Middle					Occlusal				
Axis	Examiners	Mean ± SD	Inter-item correlation	C's α	CI (95%)	*F* test	Mean ± SD	Inter-item correlation	C's α	CI (95%)	*F* test	Mean ± SD	Inter-item correlation	C's α	CI (95%)	*F* test
x	1	124.3 ± 7.2	1 to 2 = 0.986	0.850	0.559 to 0.959	0.000	178.9 ± 17.3	1 to 2 = 0.961	0.972	0.918 to 0.992	0.000	211.3 ± 26	1 to 2 = 0.912	0.966	0.902 to 0.991	0.000
	2	132.4 ± 25.7	1 to 3 = 0.933				149.5 ± 21.2	1 to 3 = 0.929				145.2 ± 20.1	1 to 3 = 0.960			
	3	132.7 ± 13.3	2 to 3 = 0.901				178.4 ± 15	2 to 3 = 0.953				221.2 ± 22.1	2 to 3 = 0.885			
y	1	32.8 ± 4.7	1 to 2 = 0.944	0.931	0.798 to 0.981	0.000	−7.1 ± 11.5	1 to 2 = 0.963	0.891	0.681 to 0.971	0.000	−35.5 ± 0.11.7	1 to 2 = 0.961	0.982	0.946 to 0.995	0.000
	2	35.6 ± 9.4	1 to 3 = 0.976				−16.4 ± 12.7	1 to 3 = 0.791				−0.24.3 ± 14.4	1 to 3 = 0.987			
	3	33.6 ± 5.2	2 to 3 = 0.958				−19.2 ± 23.8	2 to 3 = 0.900				−38 ± 12.3	2 to 3 = 0.934			
z	1	−61.1 ± 7.9	1 to 2 = 0.982	0.954	0.866 to 0.988	0.000	−46.2 ± 17.8	1 to 2 = 0.859	0.961	0.885 to 0.989	0.000	−17.8 ± 21	1 to 2 = 0.963	0.942	0.829 to 0.984	0.000
	2	−59.4 ± 12.9	1 to 3 = 0.931				−41.7 ± 12.5	1 to 3 = 0.969				−1.5 ± 13.9	1 to 3 = 0.848			
	3	−63 ± 7.9	2 to 3 = 0.950				−47.8 ± 15.3	2 to 3 = 0.913				−4.3 ± 13.1	2 to 3 = 0.905			

Mean ± SD (μm), inter-item correlation among each examiner, C's α = Cronbach alpha for the three examiners, CI = Cronbach alpha confidence interval, and the *F* test for the Cronbach alpha.

TABLE 2 Reliability analysis of the data obtained for mobility 2 in the three reference points analyzed (cervical, middle, and occlusal) reported by the axis (x, y, and z) and by examiners (1, 2, and 3)

		Mobility 2														
		Cervical					Middle					Occlusal				
Axis	Examiners	Mean ± SD	Inter-item correlation	C's α	CI (95%)	*F* test	Mean ± SD	Inter-item correlation	C's α	CI (95%)	*F* test	Mean ± SD	Inter-item correlation	C's α	CI (95%)	*F* test
x	1	192 ± 33.7	1 to 2 = 0.848	0.949	0.852 to 0.986	0.000	291.1 ± 28.7	1 to 2 = 0.847	0.910	0.737 to 0.976	0.000	362.8 ± 36.1	1 to 2 = 0.857	0.937	0.816 to 0.983	0.000
	2	202.1 ± 26.7	1 to 3 = 0.836				265.4 ± 19.1	1 to 3 = 0.692				299.8 ± 30.8	1 to 3 = 0.945			
	3	215.4 ± 30.7	2 to 3 = 0.949				270.2 ± 24.9	2 to 3 = 0.917				268 ± 54.6	2 to 3 = 0.916			
y	1	49.7 ± 9	1 to 2 = 0.728	0.933	0.803 to 0.982	0.000	10.5 ± 15.6	1 to 2 = 0.843	0.931	0.799 to 0.981	0.000	−54 ± 8.8	1 to 2 = 0.953	0.976	0.928 to 993	0.000
	2	52.7 ± 8.4	1 to 3 = 0.819				−10.4 ± 21.2	1 to 3 = 0.888				−45.1 ± 7.6	1 to 3 = 0.928			
	3	51.3 ± 8.6	2 to 3 = 0.928				−18 ± 14.1	2 to 3 = 0.856				−45.9 ± 10.1	2 to 3 = 0.968			
z	1	−100.9 ± 18.1	1 to 2 = 0.807	0.940	0.825 to 0.984	0.000	−98.8 ± 33	1 to 2 = 0.860	0.892	0.685 to 0.971	0.000	−35.1 ± 33.6	1 to 2 = 0.876	0.906	0.724 to 975	0.000
	2	−102.3 ± 14.1	1 to 3 = 0.899				−79.8 ± 16	1 to 3 = 0.884				−24.9 ± 18.7	1 to 3 = 0.759			
	3	−108.4 ± 13.9	2 to3 = 0.881				−60.4 ± 18.4	2 to 3 = 0.882				−18.9 ± 22.4	2 to 3 = 0.926			

Mean ± SD (μm), inter-item correlation among each examiner, C's α = Cronbach alpha for the three examiners, CI = Cronbach alpha confidence interval, and the *F* test for the Cronbach alpha

TABLE 3 Change observed to mobility 1 and mobility 2 in the three axis and three points evaluated

Axis	Point	ΔM2−M1 (μm)	Direction	*P* value
X	Cervical	73	Buccal	<0.001
	Middle	107	Buccal	<0.001
	Occlusal	121	Buccal	<0.001
Y	Cervical	17	Apical	<0.001
	Middle	8	Apical	= 0.002
	Occlusal	−16	Coronal	<0.001
Z	Cervical	−43	Distal	<0.001
	Middle	−34	Distal	<0.001
	Occlusal	−18	Distal	<0.001

The mean value and resulted magnitude Δ(M2−M1) and direction of the displacement is reported.

groups, except for mobility 1 cervical x (0.850), mobility 1 middle y (0.891), and mobility 2 middle z (0.892). The analysis of the correlation between the examiners demonstrated excellent (>0.9) or good (between 0.75 and 0.9) consistency of the measurements, except for mobility 1 cervical on the y axis between examiners 1 and 2 (0.728), and mobility 1 middle in the x axis between examiners 1 and 3 (0.692). A graphic representation of the data demonstrates the consistency of the measurements obtained in the different axes (Fig. 3).

3.2 | Mobility 1 x mobility 2

Significant changes were detected in all axes at the cervical, middle, and occlusal points comparing mobility 1 and 2 (Table 3). For the x axis, higher displacement toward the buccal direction (P <0.001) was observed to mobility 2 compared with mobility 1 in the cervical, middle, and occlusal points. The y axis showed a significant displacement to the apical direction at the cervical (P <0.001) and middle (P = 0.002), whereas the displacement (P <0.001) at the occlusal was to the coronal direction, indicating a shift in resulting direction from mobility 1 to mobility 2 in the occlusal compared with the cervical and middle points. For the z axis, a displacement (P <0.001) at all points was observed to the distal direction.

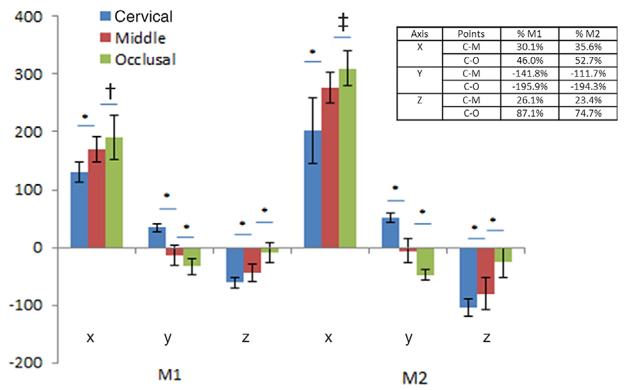

FIGURE 4 Different mobility observed along the cervical, middle, and occlusal points as reported in absolute values. *P <0.001, †P = 0.02, ‡P = 0.04. However, mobility ratio between the cervical-middle and cervical-occlusal followed a similar trend between M1 and M2

3.3 | Cervical (C) x middle (M) x occlusal (O)

The data reporting the values calculated in the different points along the x, y, and z axes are summarized in Figure 4. The x axis demonstrated a gradual increase for both mobility in the middle compared with cervical (P <0.001), and for occlusal compared with middle for mobility 1 (P = 0.02) and mobility 2 (P = 0.04). For the y axis, increased displacement to the coronal was observed to M compared with C (P <0.001) and O compared with M (P <0.001) for mobility 1 and 2. The z axis demonstrated higher displacement to the mesial for M compared with C (P <0.001) and O compared with M (P <0.001) for both mobility 1 and 2. Despite a significant difference in the values observed in mobility 1 compared with mobility 2, a similar change in percentages was observed between the cervical-middle and cervical-occlusal points, indicating a consistent movement in all points in all axes (Fig. 4).

4 | DISCUSSION

A novel concept to evaluate tooth mobility is presented based on IOS measurements using a typodont. An excellent reliability was obtained testing different mobility as

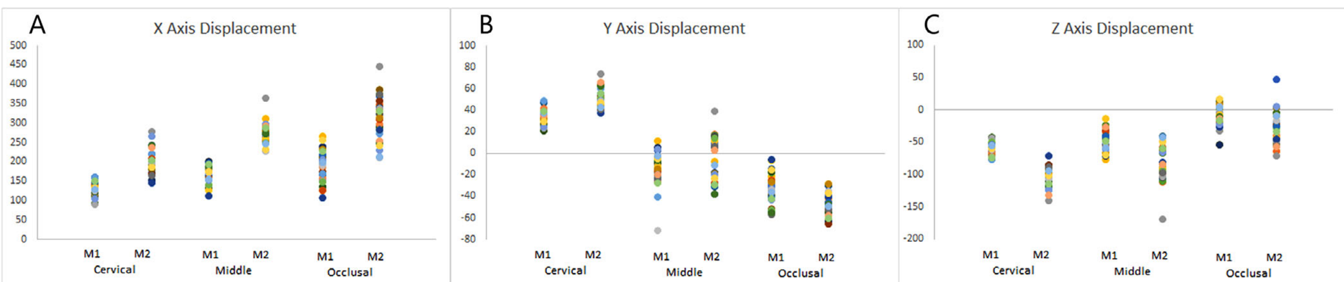

FIGURE 3 Scatter plot of the data obtained at different axes showing a limited dispersion of the data in the different reference points for mobility 1 (M1) and 2 (M2). Value reported in μm, n = 30. **A**) x-axis displacement. **B**) y-axis displacement. **C**) z-axis displacement

demonstrated by a high Cronbach alpha >0.9, and an inter-examiner correlation between 0.75 > x < 0.9 (good) or >0.9 (excellent). Previous evaluation of mobility data were obtained based on a categorical data using 5[12] or 2[13] scores. The data were reported lower Cohen k varying from poor (0.4) to moderate (0.6) between two examiners with 19 patients.[13] Higher values between two examiners based on the Pearson correlation coefficient of 0.86 was obtained with the first set of 26 patients and 0.98 with 24 patients after recalibration.[12] The agreement of the data reported by the analysis of correlation should be done with caution, since the coefficient shows the magnitude of the relationship, not the agreement. The reliability of the measurement depends on 1) the clarity of the criteria, 2) number of categories, and 3) training of the examiners.[13] We here propose a process based on an objective measurement excluding the factors 1 and 2 that will generate an outcome restricted to the magnitude and the direction of the force applied by the operator.

Persson and Svensson (1980) in a clinical study associated greater tooth mobility measurements in periodontally compromised individuals, using a loading/sensing device. The apparatus used at the time was complex and presented several limitations like one-dimensional recording possibility and no access to posterior teeth.[14] Schulte et al. (1992) examined the relationship between tooth mobility, assessed by means of the Periotest* (PTV value) and some clinical parameters of periodontal disease. The results showed that the percentage of bone loss was the parameter that was most highly correlated (r = 0.55) to the PTV value. Periotest instrument was also used in other studies, but a major limitation of this device is its restriction to only measure damping characteristics with a predefined frequency.[15,16] Increased tooth mobility at baseline of periodontal treatment was one of the factors strongly associated with high levels of additional attachment loss during maintenance.[4,5] Since tooth mobility could be a factor affecting severity, progression and therapeutic outcome of periodontal disease,[3,17] accurate measurement is of great interest. In this experiment, a significant difference in mobility from 8 μm in the y axis in the middle up to 121 μm in the x axis in the occlusal was successfully characterized. The displacement was significantly different within each examiner (data not shown) and with the data pooled (Table 3). The present technique is an accurate alternative for the measurement that could be correlated to periodontal clinical parameters allowing a precise evaluation of periodontally compromised patients.

Different approaches to monitor tooth mobility and to understand the behavior of the periodontal ligament were reported in previous studies. The majority of the methods described were limited to in vitro application and in vivo studies are very scarce.[18–20] Other studies implemented newly developed measurement systems in their investigations.[21,22] Konermann et al. 2017[21] developed a new device for in vivo measurement of tooth mobility. The authors demonstrated precision and validity in clinical use of the device, however it requires the construction of an individual splint for the maxilla of each patient for intraoral fixation of the device. Moreover the measurement performance demanded high precision from the investigator in terms of splint adaption and patient supervision to avoid unwanted movements potentially impacting the measurement results. The current approach is a user-friendly non-invasive technique that can be performed by the dentist and the dental hygienist.

A valid measurement approach recording tooth mobility upon displacement within the subtle range of physiological and non-physiological strains has not been developed. The introduction of digital dentistry and more recently the popularization of intraoral scanners helped clinicians to perform more versatile and precise dental procedures leading to more predictable treatment outcomes. The application of this new technology for treatment has been developed very quickly, however the application in the diagnosis and prognosis fields is in the early stages. The successful implementation of a device to monitor tooth mobility depends on the development of clinical data associated with physiological and disease thresholds accounting for individual values. It is a complex challenge since tooth mobility is a phenomenon related to several continuous and intermittent biologic and physical variants.[23] This first set of data obtained with a typodont model was able to detect a difference as low as 8 μm (Table 3), but the clinical significance of such subtle variation alone may not indicate progression or remission of disease compared with baseline values. Well established clinical parameters, such as clinical attachment level and radiographic bone loss will remain valid to classify the patient's disease and will be used to facilitate the interpretation of the scan results in future clinical experiments.

5 | CONCLUSIONS

Here, we introduce a novel digital approach based on intraoral scanner measurements that can be clinically applied to monitor tooth mobility during periodontal evaluation and treatment. Different from previous techniques, the current concept generates results as continuous variable, providing the opportunity to objectively assess the changes independent of the operator's perception.

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* Periotest, Siemens AG, Bensheim, Germany.

provisional patent based on the technique presented. Carlos Garaicoa-Pazmino, Shan-Huey Yu, and Hsun-Liang Chan report no conflicts of interest related to this study.

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