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An evaluation of the Periotest® method as a tool for monitoring tooth mobility in dental traumatology

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Abstract – *Background/aim*: The Periotest® method is a technique for the objective assessment of tooth mobility. The aims of this study were to determine normal Periotest® values in the vertical and horizontal dimensions of periodontally healthy teeth in individuals aged 20–35 years and investigate the reliability of Periotest® in terms of intra-series and inter-series reproducibility before and after applying a dental trauma splint *in vivo*. *Materials and methods*: Periotest® values were measured in periodontally healthy dental students ($n = 33$; mean age 24.7 years) at reproducible measuring points in the vertical and horizontal dimensions, before and after splint insertion. Three readings were taken per series to observe the intra-series reproducibility; three series were measured to test inter-series reproducibility (Friedman-test; $P \leq 0.001$). Two different wire-composite splints, 0.45 mm Dentaflex and 0.8×1.8 Strengtheners, were inserted and the Periotest® values were measured. *Results*: The median Periotest® values before splinting were: canines -2.5, lateral incisors -0.9, and central incisors 0.0 for the vertical dimension, and canines 1.1, lateral incisors 3.2, and central incisors 3.6 for the horizontal dimension. The intra-series and inter-series Periotest® values were highly reproducible. *Conclusion*: The Periotest® method provides highly reproducible results. Focused on dental trauma, the method can be applied diagnostically during the splint and follow-up period and for evaluating splint rigidity.

Tooth mobility assessment is often applied as a diagnostic tool for clinical monitoring and follow-up, as well as for treatment outcome evaluation in periodontology, prosthodontics, implantology, orthodontics, and dental traumatology (1–8). Methods for measuring tooth mobility can be classified as subjective or objective. One subjective method was introduced by Miller; the tooth is deflected between two instrument handles (4) and the amplitude is described using a four-step index (9). This method is widely accepted and mainly applied in clinical routine because it is fast and easy to perform. The disadvantage is that reproducibility is inconsistent and is operator-dependent (9). Objective tooth mobility assessment is necessary. Some methods evaluate periodontal pulsation or tooth mobility free of contact (10, 11). However, most techniques are based on the principle of the direct application of a defined load for tooth deflection, which can be measured. Examples are periodontometry (12–14), the mobilometer (15), dental holographic interferometry (16, 17), laser vibrometry (18), the device developed by Persson and Sevensson (19) in which the deflecting force is generated by compressed air. These methods are time consuming and use complex technical equipment therefore, they are more applicable for scientific investigations than routine clinical use (20). An exception is the Periotest® method (21, 22) which is a well established and accepted technique for measuring tooth mobility *in vivo* and *in vitro* in periodontology (6, 23, 24), implantology (25, 26), orthodontics (4, 8, 15) and dental traumatology (1, 2, 27–29). The advantages of the Periotest® are easy application, the ability to measure both the horizontal and vertical dimensions, as well as reproducible results (2, 27, 30–32).

The treatment of teeth with injuries to the periodontal ligament or root fractures should involve repositioning followed by splinting to facilitate the positioning of displaced teeth or fragments in their original location. Splints should ensure adequate fixation, prevent accidental ingestion or inhalation, and should protect teeth against traumatic forces during the vulnerable healing period (28, 33, 34). Splints should also allow the transmission of physiological load to injured teeth. Studies concerning splinting time and splint rigidity have shown that the application of physiological load to teeth that suffered dentoalveolar trauma leads to better healing results than long-term rigid tooth immobilization (35, 36). Modern tooth splinting is based predominantly on the principles of adhesive bonding using the acid etching technique (37) with resin composite alone (27, 38), as well as with different reinforcement wires (27, 28, 33, 34, 39) or commercially available splinting systems (27, 29, 39). Splint rigidity can be influenced by the selected resin composite material, the type of reinforcement, the splint position, and the dimension of the adhesive points (15).

This study had two specific objectives. Our first objective was to determine normal Periotest® values (PTV) in the vertical (v) and horizontal (h) dimensions of periodontally healthy teeth in individuals aged 20–35 years. The second objective was to investigate the reliability of the Periotest® (PTV v and PTV h) in terms of intra-series (within one measuring cycle) and inter-series (between different measuring cycles) reproducibility before and after applying dental trauma splints.

Material and methods

Volunteer selection

The study design was approved by the Ethics Commission of the University of Erlangen-Nuremberg (#3673), and the investigation was carried out according to the Helsinki Declaration. The study was conducted on 33 dental students (13 males, 20 females) with a mean age of 24.7 years (range 19.8–36.5 years). All volunteers received written and oral information about the procedure and signed a consent form. All potential participants were asked about medical history and underwent a clinical examination (pocket depth, recessions, bleeding on probing, tooth loosening, sensibility, and percussion – pain and sound). The teeth were scanned for enamel cracks, restorations, and endodontic treatment. The volunteers had to fulfill the following criteria: no periodontal disease (pocket depth < 3 mm, no loosening or inflammation), no orthodontic treatment or anterior crowding at the time of investigation, no restorations or root canal treatment on maxillary incisors or canines, no general health problems or medical contraindications, and no signs or history of dental trauma.

After the clinical examination, a maxillary dual-phase polyvinyl siloxane impression (Panasil® Binetics Putty and Panasil® contact plus, Kettenbach, Eschenburg, Germany) was taken and two casts made (GC FujiRock EP, Muenchen, Germany). One cast was used to prepare a vacuum splint (Erkodur 1.0/120 mm, Erkodent, Pfalzgrafenweiler, Germany) for placing reproducible measuring points on the teeth. A small hole on the labial aspect of all incisors (middle of the tooth, 4 mm from the incisal edge) and a second hole, in the middle of the incisal edge, were made. The second cast was used to prepare and passively adjust the wires before splinting.

Splint preparation and application

The two wire-composite splints (WCS) tested were prepared using 0.45 mm Dentaflex® (Dentaurum, Pforzheim, Germany) for WCS1 and 0.8 × 1.8 mm Denture Strengtheners (Dentaurum, Pforzheim, Germany) for WCS2. The wires were cut to the desired length from the left to right lateral incisor and were extra-orally adjusted to the patient's cast until they passively fit.

The maxillary incisors were cleaned using pumice with a rubber cup and the slurry was removed. After placing cotton rolls in the vestibule, the teeth were rubbed with an alcohol soaked cotton pellet and air dried. The prepared wire splints were bonded to the middle third of the labial surface using Tetric flow® chroma (Ivoclar Vivadent, Schaan, Liechtenstein). After this primary fixation, the wire and the attached adhesive dots were removed using a hand scaler. The tooth surface was again cleaned with alcohol and dried. A small amount of Tetric flow® chroma was applied to the bottom of each adhesive dot and the splint reattached to the tooth. The resin composite was again light-cured for 40 s.

After the Periotest® procedure the splints were removed using a hand scaler. The tooth surfaces were than cleaned with pumice and polished, followed by the application of Elmex® fluid (GABA AG, Loerrach, Germany).

Measuring tooth mobility and splint effect

The Periotest® device (Gulden, Modautal, Germany) consists of a handpiece with a tapping rod inside. During the measuring procedure, the rod taps against the vestibular or occlusal surface of the tooth 16 times in 4 s (force 8 g, velocity 0.2 m s^{-1}). The deflection time is measured and a computer, inside the device, converts it to a scaled number between -8 and 50. Negative values represent maximal fixation, as in osseo-integrated implants or ankylosed teeth, whereas high values represent loose objects, such as periodontally affected teeth or dental trauma (6, 24, 33).

To ensure reproducible measuring points, the previously prepared vacuum splint was used as a template to transfer the vertical and horizontal reading points, for each tooth, onto a dry surface using a waterproof pencil.

The Periotest® device (Gulden, Bensheim, Germany) was used to measure the vertical and horizontal mobility of all maxillary incisors and canines before splinting and for all incisors while the splint was in situ, per the manufacturer's instructions. Three Periotest® readings were taken in both, vertical and horizontal, dimensions for each tooth per series. The time elapsed between the beginning of each series was 15 min therefore, the measurements for each specific tooth took place at 15-min intervals. All readings were taken by the same experienced operator.

Periotest® values before splinting (PTVpre)

Before applying WCS1, three series with a total of nine readings in the horizontal (PTV (h) pre S1) and vertical (PTV (v) pre S1) dimensions were measured. Before fixing WCS2, only one series with a total of three readings in the horizontal (PTV (h) pre S2) and vertical (PTV (v) pre S2) dimensions was measured.

Periotest® values after splinting (PTVpost)

Three series for WCS1 (PTVpost S1) and WCS2 (PTVpost S2), including a total of nine readings per tooth in the horizontal and vertical dimensions, were measured.

Statistical analysis

Data were recorded using individually developed acquisition sheets and transferred to SPSS 14.0 (SPSS Inc., Chicago, IL, USA) for statistical analysis. The horizontal and vertical PTVpre and PTVpost were not normally distributed (Kolmokorov-Smirnow test, $P \leq 0.001$); thus, non-parametric tests were applied. For evaluating intra- and inter-series reproducibility, the Friedman-test for paired samples ($P \leq 0.001$) was used. To compare the Periotest® values before splinting with WCS1 and WCS2, the Wilcoxon test for paired samples ($P \leq 0.001$) was applied. The Wilcoxon test was also used for comparing PTVpre and PTVpost ($P \leq 0.001$).

Results

Mobility measurements

We recorded a total of 9504 values, 288 per individual, including 3564 values for PTVpre S1, 1188 for PTVpre S2, and 2376 for PTVpost S1 and S2.

Descriptive statistics for the vertical and horizontal PTVpre showed a statistical spread (Table 1). Thus, PTVpre were used as a covariate for analyzing the splint effect. In the vertical dimension the median PTVpre for canines was -2.5 (range -5.8–10.7), -0.9 (range -4.9–5.8) for the lateral incisors and 0.0 (range -4.7–7.0) for the central incisors. The median PTVpre in the horizontal dimension for canines was 1.1 (range -2.6–5.9), 3.2 (range -0.8–11.2) for the lateral incisors, and 3.6 (range -0.5–13.7) for the central incisors.

Vertical PTVpre and PTVpost

Comparing vertical PTV before and after splinting showed a decrease in vertical tooth mobility after splinting. There were significant differences between PTVpre and PTVpost for all teeth ($P \leq 0.001$), with the exception of WCS2 on tooth 12.

Horizontal PTVpre and PTVpost

Compared to the changes in vertical mobility, there were more considerable reductions detected in horizontal mobility (WCS1 < WCS2). Both inserted splints caused a significant change in lateral tooth mobility ($P \leq 0.001$).

Comparison of PTVpre (h + v) for WCS1 and WCS2

Applying the Wilcoxon test to the comparison of PTV before the insertion of WCS1 and WCS2 no significant differences for all tested teeth, in either dimension were detected.

Intra-series reproducibility of PTVpre

The Friedman-test found that the three readings, per series, in the vertical dimension were highly reproducible for all tested teeth (Table 1). In the horizontal dimension, all incisors showed highly reproducible results. Significant differences between the three measurements per series were detected only for the canines ($P \leq 0.001$).

Intra-series reproducibility of PTVpost

After splinting, the PTV per series was highly reproducible for the vertical and horizontal measurements for both WCS (Table 2).

Inter-series reproducibility of PTVpre

The three PTV of series 1 (t = 0 min), series 2 (t = 15 min), and series 3 (t = 30 min) were averaged per series, and the Friedman-test ($P \leq 0.001$) was applied to compare series values. The measurements were highly reproducible in the vertical and horizontal dimensions (Table 3). The only exception was found for PTV (h) pre on tooth 21 as significant differences were detected between the series ($P \leq 0.001$).

Inter-series reproducibility of PTVpost

The inter-series reproducibility for PTVpost was lower in the vertical dimension than the horizontal, however, no significant differences were found (Table 4). Slight differences were observed in the vertical dimension for teeth 12, 11, and 21 after inserting WCS1 and for tooth 22 after inserting WCS2. There were also slight differences observed on tooth 11 in the horizontal dimension after splinting with WCS1.

Discussion

Methodological factors

There are various *in vitro* and *in vivo* models for evaluating tooth mobility or rigidity of dental trauma splints (27–29, 38, 40) and orthodontic retainers (15, 20). *In vitro* models include commercially available acrylic resin models (27). Tooth mobility can be easily manipulated by placing silicon rubber pieces between the root and alveolar socket but, the absence of the periodontal ligament could be considered a disadvantage. Individual custom-made models have also been introduced (15, 40). In previous *in vitro* studies, dissected sheep mandibles were utilized to test splint rigidity (38). The advantage of this approach is the presence of a periodontal ligament and natural enamel. The form, size, and crown-root relationship of sheep incisors are similar to those of human teeth. Sheep incisors are normally very loose and may simulate injured teeth well, but they cannot accurately represent uninjured teeth. Other possible disadvantages are the potential risk of prion transmission from Scrapie infected sheep and the extensive variability between the specimens. Different *in vivo* studies have reported tooth mobility evaluations and trauma splint rigidity testing in human volunteers with uninjured (1, 2, 15, 20, 29, 31) or injured (1, 28) human teeth. The main advantage is the presence of a periodontal ligament, providing normal or pathological tooth mobility. Another advantage is the ability to bond splints to human enamel; however, the potential for damage to the

Table 1. Intra-series reproducibility of all three Periotest® measurements (M) in the vertical and horizontal dimension before splinting with WCS1 or WCS2

		Tooth 13			Tooth 12			Tooth 11			Tooth 21			Tooth 22			Tooth 23		
		M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
WCS 1 vertical	Median	−2.5	−2.5	−2.8	−1.0	−1.1	−1.3	0.0	0.1	0.0	0.3	0.2	0.2	−0.8	−0.6	−0.5	−2.4	−2.3	−2.3
	Min.	−5.6	−5.8	−5.1	−4.4	−4.4	−4.7	−4.1	−4.4	−4.5	−4.5	−4.7	−4.5	−4.7	−4.9	−4.9	−5.6	−5.7	−5.6
	Max.	7.5	10.7	8.	3.	3.8	2.4	5.3	5.1	5.9	6.4	7.0	7.0	3.8	4.8	5.8	7.4	6.7	6.3
	IQR	2.6	2.8	3.1	2.7	2.7	2.7	2.6	3.8	3.2	2.8	2.6	2.6	2.7	3.0	2.6	2.3	2.9	3.2
	Variance	5.465	6.423	6.211	3.278	3.324	3.254	4.712	5.780	5.797	5.670	5.372	5.255	3.413	3.990	4.041	2.993	5.790	5.762
	n	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.842			0.068			0.853			0.484			0.213			0.306		
	df	2			2			2			2			2			2		
	χ^2	0.344			5.378			0.319			1.452			3.095			2.370		
WCS 1 horizontal	Median	1..3	1.6	1.8	3.1	2.9	3.1	3.9	3.8	3.7	3.1	3.0	3.0	3.0	3.0	3.0	0.3	0.5	0.6
	Min.	−2.6	−2.3	−2.1	−0.7	−0.8	−0.8	−0.5	−0.4	−0.1	−0.4	−0.2	−0.4	−0.5	−0.1	−0.1	−2.5	−2.4	−2.3
	Max.	4.7	4.8	5.9	11.2	8.8	9.4	13.7	12.9	12.9	11.9	11.6	10.9	9.4	10.3	9.9	4.3	4.6	4.7
	IQR	2.9	2.8	2.8	3.6	4.0	3.9	3.0	2.6	2.5	2.7	2.9	2.7	3.3	3.4	3.3	2.8	3.0	2.9
	Variance	2.793	2.872	3.176	5.525	5.332	5.028	7.865	8.041	7.852	5.036	5.443	5.387	4.708	4.820	4.574	3.116	3.065	2.904
	n	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
	P	<0.001			0.104			0.303			0.575			0.363			<0.001		
	dF	2			2			2			2			2			2		
	χ^2	32.814			4.526			2.386			1.107			2.028			16.312		
WCS 2 vertical	Median	−2.9	−2.5	−3.0	−1.8	−1.2	−1.6	−0.7	−1.1	−0.7	0.6	0	0.5	−0.8	−0.6	−0.7	−2.4	−2.1	−2.3
	Min.	−5.5	−5.6	−5.1	−4.3	−4.1	−4.1	−3.8	−4.4	−4.5	−4.3	−4.2	−4.0	−4.2	−4.1	−4.5	−5.0	−5.2	−5.6
	Max.	7.1	7.2	7.8	3.2	3.3	2.2	5.3	5.1	5.9	5.6	3.6	5.2	3.8	3.2	3.96	5.1	5.3	4.9
	IQR	2.2	2.7	2.7	2.6	3.0	2.3	2.8	4.0	3.9	2.8	2.6	2.4	2.3	2.3	2.0	3.2	3.4	3.3
	Variance	5.273	5.659	6.294	3.178	3.228	2.815	5.239	6.335	6.401	5.169	4.086	4.412	2.993	3.661	3.371	6.879	5.231	5.743
	n	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33
	P	0.976			0.258			0.224			0.030			0.862			0.253		
	df	2			2			2			2			2			2		
	χ^2	0.048			2.713			2.992			6.992			0.297			0.752		
WCS 2 horizontal	Median	1.1	1.4	1.5	3.1	3.1	3.1	3.8	3.7	3.6	2.8	2.9	3.1	3.0	2.8	2.9	0.5	0.6	0.6
	Min.	−2.6	−2.3	−1.2	−0.7	−0.8	−0.8	0.1	−0.4	0.3	−0.4	−0.1	−0.4	−0.3	0.5	1.0	−2.5	−2.4	−2.3
	Max.	4.0	4.3	5.0	11.2	8.4	9.4	11.4	12.0	11.6	10.0	9.9	10.4	8.1	7.9	7.8	4.0	4.1	4.2
	IQR	3.1	2.8	3.7	3.5	3.8	3.3	2.6	2.1	2.3	2.8	3.0	2.8	3.2	3.1	3.1	3.1	3.2	2.9
	Variance	2.968	2.988	3.808	6.134	5.362	5.175	7.219	7.320	7.341	5.001	5.338	5.837	4.586	4.020	3.729	2.795	2.912	2.648
	n	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33
	P	<0.001			0.542			0.452			0.238			0.889			0.145		
	df	2			2			2			2			2			2		
	χ^2	15.578			1.226			1.590			2.869			0.234			3.864		

The Chi-squared test was used to detect differences between M1, M2 und M3

Table 2. Intra-series reproducibility of all three Periotest® measurements (M) in the vertical and horizontal dimension after splinting with WCS1 or WCS2

		Tooth 12			Tooth 11			Tooth 21			Tooth 22		
		M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
WCS 1 vertical	Median	−1.2	−1.3	−1.3	−0.8	−0.7	−0.3	−0.3	−0.2	−0.3	−1.4	−1.3	−1.2
	Min.	−4.9	−5.1	−5.2	−4.9	−5.3	−4.7	−4.8	−5.0	−4.5	−3.9	−4.4	−8.0
	Max.	3.1	2.7	4.2	4.5	4.3	5.1	4.4	3.6	4.2	2.8	3.3	3.2
	IQR	2.1	2.2	2.4	2.4	2.5	2.5	2.1	2.1	2.2	1.7	2.2	2.0
	Variance	2.738	2.613	2.855	3.302	3.357	3.968	3.268	3.127	3.417	2.008	2.473	3.033
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.557			0.192			0.947			0.250		
	df	2			2			2			2		
	χ^2	1.170			3.305			0.109			2.773		
WCS 1 horizontal	Median	2.6	2.9	2.7	2.4	2.3	2.3	1.7	1.6	1.6	1.8	1.7	1.8
	Min.	0.3	0.1	−0.6	−1.4	−2.1	−2.1	−2.2	−2.1	−2.6	−4.5	−5.1	−3.1
	Max.	8.0	7.7	7.7	8.5	8.2	9.4	6.9	4.8	5.3	8.0	8.7	7.9
	IQR	2.7	3.1	2.7	2.3	2.5	2.7	2.0	1.9	2.0	2.5	2.6	2.4
	Variance	3.097	2.955	2.834	3.902	3.771	4.121	2.694	2.655	2.750	4.381	4.525	4.176
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.732			0.218			0.182			0.183		
	df	2			2			2			2		
	χ^2	0.624			3.048			3.403			3.401		
WCS 2 vertical	Median	−1.7	−1.9	−1.5	−1.6	−1.6	−1.6	−1.9	−2.0	−1.8	−1.4	−1.5	−1.6
	Min.	−4.8	−5.4	−5.4	−5.3	−5.5	−5.8	−5.1	−5.6	−5.6	−4.9	−5.0	−5.1
	Max.	2.9	2.6	2.5	6.1	5.3	6.1	2.4	3.2	2.5	2.8	3.4	3.0
	IQR	1.6	2.8	2.9	1.7	2.5	2.4	2.4	3.3	3.6	2.9	2.8	3.0
	Variance	2.279	2.809	3.661	4.394	4.222	4.241	2.258	3.747	4.325	3.426	3.529	3.792
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.018			0.892			0.598			0.120		
	df	2			2			2			2		
	χ^2	8.064			0.229			1.029			4.245		
WCS 2 horizontal	Median	2.3	2.3	2.3	1.2	1.1	1.2	0.7	0.7	0.6	1.4	1.5	1.4
	Min.	−2.7	−1.4	−1.4	−1.5	−1.6	−1.9	−2.5	−2.5	−2.4	−0.2	−0.3	−0.5
	Max.	6.6	7.5	9.5	5.8	5.1	5.2	4.5	4.4	4.1	6.5	6.6	6.7
	IQR	2.7	2.2	2.7	2.0	2.3	2.1	1.5	1.7	1.6	1.8	2.0	1.8
	Variance	4.251	3.417	3.796	1.980	1.586	1.849	1.810	2.111	1.934	1.892	1.954	2.377
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.180			0.794			0.405			0.395		
	df	2			2			2			2		
	χ^2	3.425			0.462			1.806			1.856		

The Chi-squared test was used to detect differences between M1, M2 und M3.

enamel during splint removal and the absence of traumatically loosened teeth can be considered a disadvantage.

The majority of dentoalveolar injuries happen in the period between 8 and 12 years (41). Andresen et al. (2) and Mackie et al. (31) measured physiological horizontal Periotest® values and tested the method's reliability in the age group 8–16 years. Further investigations need to focus on vertical PTV in this age group. In our investigation, we selected volunteering dental students, aged 20–35 years, to investigate the reproducibility of the Periotest® method before and after insertion of different dental trauma splints. Beside the commonly used horizontal measurements, we focused also on the vertical dimension because in our prospective the vertical Periotest® values are more meaningful for assessing and interpreting the healing process. In our clinic, we use the Periotest®method as a standard procedure in all dental trauma cases as well as an extra diagnostic tool in endodontic cases. We have found that the vertical Periotest® values respond earlier and more sensitive to pathological changes than the horizontal measurements. There is no prospective study published that proves this fact, further studies have to be conducted on this topic. For both dimensions, it is essential that single values are insignificant, however, values taken at different appointments over the healing period can, beside other diagnostic methods, provide valuable information about the tooth condition. Normally, the Periotest® values in both dimension decrease from the time of injury over a certain period to physiological values when healing without complication occurs. In the case of flexible splinting, the horizontal values can be used to help decision-making about the timing of splint removal. Reduced or negative vertical values are often an early indicator for ankylosis which can be transient (PTV increase after 2–6 weeks again) or permanent (PTV remain reduced or decrase further); the decrease of the horizontal PTV follows delayed (42). Increased vertical values, compared to the reference tooth, after completion of periodontal and osseous healing, can be an indicator for apical breakdown.

For our investigation, we selected two types of WCS with different rigidity characteristics (27). The flexible

Table 3. Inter-series reproducibility of the three serials (S) of the vertical and horizontal Periotest® values before splinting with WCS1

		Tooth 13			Tooth 12			Tooth 11			Tooth 21			Tooth 22			Tooth 23		
		S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
WCS 1 vertical	Median	−2.6	−2.4	−2.5	−0.9	−1.3	−1.4	0.2	−0.1	−0.2	0.4	0.0	0.4	−0.8	−0.6	−0.3	−2.3	−2.6	−2.3
	Min.	−5.6	−4.9	−5.8	−4.5	−4.6	−4.7	−4.5	−4.0	−4.4	−4.3	−4.0	−4.7	−4.5	−4.3	−4.9	−5.6	−5.2	−5.7
	Max.	10.7	7.8	4.9	3.8	3.3	1.9	5.7	5.7	5.9	7.0	7.0	5.6	5.8	2.8	3.1	7.4	7.0	4.4
	IQR	2.9	2.9	2.8	3.1	2.9	2.2	3.2	3.2	3.5	2.7	2.5	3.1	3.3	2.9	2.0	3.2	3.3	2.6
	Variance	7.566	6.217	4.357	3.887	3.391	2.538	5.255	5.131	5.884	5.742	5.289	5.244	4.743	3.345	3.356	6.903	6.278	5.246
	n	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.650			0.154			0.391			0.685			0.405			0.928		
	df	2			2			2			2			2			2		
	χ^2	0.862			3.745			1.876			0.758			1.808			0.150		
WCS 1 horizontal	Median	1.7	1.3	1.6	3.2	3.1	2.9	3.7	3.9	3.7	3.1	3.0	2.9	3.1	3.0	2.9	0.5	0.5	0.4
	Min.	−2.0	−2.6	−2.1	−0.7	−0.8	−0.1	−0.4	−0.3	−0.5	0.0	−0.3	−0.4	−0.5	0.2	−0.3	−2.3	−2.5	−2.5
	Max.	4.8	4.7	5.9	9.3	9.9	11.2	13.7	12.7	12.8	11.9	9.8	10.4	8.1	9.7	10.3	4.3	4.7	4.2
	IQR	2.6	3.0	2.9	4.1	3.8	3.4	2.5	2.5	3.4	2.7	3.4	2.8	3.2	3.1	3.5	2.9	3.0	3.1
	Variance	2.717	3.084	3.120	5.279	5.295	5.320	7.767	7.600	8.375	5.478	5.277	5.085	4.538	4.664	4.898	2.639	3.314	3.131
	n	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.489			0.290			0.025			<0.001			0.318			0.014		
	df	2			2			2			2			2			2		
	χ^2	1.429			2.476			7.351			15.597			2.291			8.480		

The Chi-squared test was used to detect differences between S1. S2 und S3

Table 4. Inter-series reproducibility of the three serials (S) of the vertical and horizontal Periotest® values after splinting with WCS1 or WCS2

		Tooth 12			Tooth 11			Tooth 21			Tooth 22		
		M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
WCS 1 vertical	Median	−1.4	−1.1	−1.3	−0.3	−0.4	−1.1	−0.3	0.0	−0.3	−1.2	−1.2	−1.5
	Min.	−4.0	−4.9	−5.2	−4.5	−4.5	−5.3	−5.0	−4.2	−4.2	−4.6	−3.9	−8.0
	Max.	4.2	2.5	3.1	5.1	4.5	3.0	4.4	4.2	3.6	2.0	2.9	3.3
	IQR	2.3	2.5	2.1	2.5	2.9	2.2	2.2	2.4	2.0	2.3	2.0	1.8
	Variance	2.644	2.991	2.536	3.608	3.572	3.270	3.668	3.112	2.999	2.050	2.527	2.966
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.017			0.003			0.042			0.053		
	df	2			2			2			2		
	χ^2	8.097			11.526			6.341			5.880		
WCS 1 horizontal	Median	2.8	2.7	2.8	2.2	2.4	2.3	1.7	1.6	1.7	1.7	1.7	1.8
	Min.	0.0	0.3	−0.6	−1.2	−1.4	−2.1	−1.7	−1.9	−2.6	−5.1	−3.3	−4.5
	Max.	7.5	8.0	6.1	8.4	9.4	8.2	5.0	4.5	6.9	7.2	8.7	8.0
	IQR	2.8	2.6	2.6	2.7	2.3	2.5	2.0	2.0	2.2	2.4	2.5	2.8
	Variance	3.039	3.229	2.609	3.991	4.025	3.839	2.491	2.380	3.235	3.736	4.554	4.793
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.433			0.011			0.945			0.666		
	df	2			2			2			2		
	χ^2	1.672			9.109			0.112			0.812		
WCS 2 vertical	Median	−1.8	−1.6	−1.7	−1.6	−1.4	−1.2	−1.9	−2.0	−1.6	−1.5	−1.2	−1.6
	Min.	−4.4	−5.0	−5.4	−5.8	−5.4	−5.3	−5.5	−5.0	−5.6	−4.6	−4.6	−5.1
	Max.	2.9	2.7	2.2	4.7	4.7	6.1	3.2	2.0	2.4	3.0	3.4	2.7
	IQR	2.3	2.3	2.6	2.2	2.6	2.0	2.8	2.1	2.3	2.9	2.6	2.7
	Variance	2.870	2.936	3.112	4.200	4.021	4.701	3.389	2.595	2.758	3.530	3.778	3.806
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.076			0.096			0.691			0.027		
	df	2			2			2			2		
	χ^2	5.146			4.679			0.738			7.218		
WCS 2 horizontal	Median	2.3	2.0	2.1	1.2	1.1	1.1	0.7	0.7	0.7	1.4	1.4	1.5
	Min.	−2.7	−1.2	−0.2	−1.4	−1.6	−1.9	−2.5	−2.1	−2.5	−0.5	−0.3	−0.2
	Max.	6.9	9.5	6.1	5.2	5.2	5.8	4.5	4.4	4.1	6.2	6.2	6.7
	IQR	2.3	1.7	2.2	2.0	1.5	1.8	1.4	1.2	1.5	1.8	1.6	1.7
	Variance	3.743	3.577	2.812	1.771	1.654	2.093	1.918	1.586	1.643	2.037	1.927	2.069
	n	99	99	99	99	99	99	99	99	99	99	99	99
	P	0.238			0.184			0.664			0.659		
	df	2			2			2			2		
	χ^2	2.874			3.388			0.820			0.833		

The Chi-squared test was used to detect differences between S1, S2 und S3

splint is indicated in all injuries involving the periodontal ligament and in cases with intra-alveolar root fractures (43, 44). Semi-rigid or rigid splinting is applied after alveolar process fractures or in cervical root fractures when flexible splinting is not stable enough (33). Wire-composite splints, as well as the titanium ring splint (TRS) and titanium trauma splint (TTS), fulfill most of the demands of splinting after dental trauma (27–29, 34, 38). The advantage of WCS is that the required materials are inexpensive and usually available in dental offices (29, 39). Concerning the possible tooth damage while removing WCS attached using the conventional acid etching technique, preliminary experiments were conducted to find a bonding technique that guarantees secure attachment during the measurement process with concomitant easy removal without damage. Different potential bonding materials and techniques were tested *in vitro* on bovine deciduous teeth using the shear bond strength test. Because of the finding of these experiments, one promising method was further tested *in vivo*. Both splint types were applied using this technique and 20 Periotest® measurements were taken in the vertical and horizontal dimensions to determine the bonding ability under test conditions. To reveal possible de-bonding or to detect gaps between the tooth surface and the resin composite after the Periotest® procedure, dye was applied around the fixing points. No loosening or de-bonding was found in any cases, and splint removal was easy without visible damage to the enamel. Therefore, this technique was selected for splint application in the main study. The preliminary results as well as the results of the main study proved that the splints were securely attached to all supporting teeth over the whole test period. These findings lead to the presumption that the splint mechanics should not be influenced by this bonding technique, compared to the acid etch technique.

To mark reproducible measuring points, in this investigation, impressions were taken from each volunteer to prepare the vacuum splint as template. In the clinical situation, after an injury, it is not recommended to take impressions or Periotest® readings of the injured area to avoid further traumatization. Instead, at the first appointment, we form an individual key covering the palatal tooth surface and part of the labial surface up to the splint wire using polyvinyl siloxane putty impression material. This replaceable mould can be utilized during further appointments to place reproducible measuring points.

Study outcome

Within the test group, high inter-individual variabilities for PTV (v) pre and PTV (h) pre were found. It seems reasonable to express the physiological PTV for each tooth group as range, rather than a value. Andresen et al. (2) found similar results, but the mean PTV (h) pre in our study was considerably lower. They investigated a group of children aged 8–12 years, whereas we focused on individuals aged 20–23 years. The difference in bone structure, periodontal ligament, and tooth development explains the lower PTV found in our study. In dental trauma cases, the measurement of the uninjured contralateral tooth is recommended to determine the comparative physiological PTVpre.

Because the comparison between the PTVpre of WCS1 and WCS2 revealed no significant differences, only one series with three measurements was taken for PTVpre WCS2 to reduce volunteers' inconvenience.

The comparison of PTVpre and PTVpost, irrespective of the splint type, showed a significant reduction of tooth mobility after splint application. This finding corresponds with the results of other studies (15, 27, 29). We observed that the reduction was higher in the horizontal dimension than the vertical, which could be explained by the higher PTV (h) pre compared to PTV (v) pre.

Statistical analysis revealed considerable intra-series reproducibility for PTVpre and PTVpost. Less reproducible results were found for PTV (h) pre with both canines. The more convex surface of these teeth compared to the almost flat surface of the incisors complicates the Periotest® measurement. The high reproducibility could be explained by, in addition to the features of the Periotest® device, the marking of defined measuring points. A second factor could be that all Periotest® measurements were made by the same experienced operator to reduce inter-examiner variability. These findings are in contrast to reports from Andresen et al. (2) and Mackie et al. (31), who found significant differences between the first and second readings. This discrepancy can be explained by differences in the significance levels used in both studies. Another factor is the experimental design. In our study, three Periotest® readings were taken without pausing between the measurements, whereas Mackie et al. (31) waited for 10 min and Andresen et al. (2) paused for 5–60 min between the measurements. Considering these factors, a future study will aim to investigate the influence of operator experience, the utilization of reproducible measuring points, and the time between measurements.

We also found high inter-series reproducibility. Similar to intra-series reproducibility, the use of defined measuring points and the operator's experience can be positive influence factors. In an *in vitro* study, Chai et al. (45) found no inter-examiner differences; however, the position of the measuring points significantly influenced the results. Van Steenberghe et al. (32) found acceptable inter-series reproducibility resulting in slight differences with five measurements taken over a 24-h period. These differences may be caused by a lack of reproducible measuring points. Clinically, the second series would be measured during the first recall after 1 or 2 weeks; in this study, the second series was measured after 15 min. This timing may positively influence reproducibility. Future investigations will focus on this factor.

Splint rigidity can be influenced by the attachment point extension (15). To reduce variability, all splints were applied by the same operator. Special attention was paid to ensure similar attachment point dimensions and splint localization.

We found that WCS1 caused less tooth mobility reduction compared to WCS2. These differences were expected because of the different material properties of the selected wires. In previous *in vitro* studies, WCS1 was also found to be more flexible than WCS2 (27).

Conclusion

This *in vivo* study indicates that the Periotest® method provides highly reproducible results for PTVpre and PTVpost measurements in the vertical and horizontal dimensions in adult test persons. The results could be positively influenced by the fact that the measurements were performed by a single examiner along with the use of reproducible measuring points. Focusing on dental trauma, the Periotest® can be applied as a sensitive and reliable diagnostic tool during the splinting and the follow-up period to receive additional information during and after the healing process. Because of the high inter-individual variability, physiological tooth mobility should be expressed as a PTV range, and the uninjured contralateral tooth should always serve as a reference.

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