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ORIGINAL ARTICLE

Noncontact intraoral measurement of force-related tooth mobility

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Abstract The aim of this pilot study was to measure force-related tooth mobility. Vertical and horizontal anterior tooth mobility in 31 healthy periodontal subjects was measured by a noncontact optical measurement technique. The subjects continuously increased the force on each tooth by biting on a load cell. An automated software program recorded tooth displacement at 9-N intervals. Vertical and horizontal displacements were subsequently measured. The vector of tooth mobility in the buccal direction was calculated using the Pythagorean theorem. The average displacements over all subjects for each tooth were determined. Global differences were assessed with the Wilcoxon test. There were no significant differences between contralateral teeth overall load stages. There were no significant differences in tooth mobility between the central and lateral incisors except for in the horizontal direction. However, there were significant differences between central incisor and canine and lateral incisor and canine teeth.

Keywords Tooth mobility · Photogrammetric measurement · Digital image correlation · Force impact · Intrusion

Introduction

In three dimensions, tooth mobility describes the resilience of an intact periodontium [1–4]. The periodontal ligament (PDL) is composed of connective tissue fibers that attach a tooth to the alveolar bone and control tooth mobility under physiological loads. The PDL shows viscoelastic behavior, due to the combination of fluid and elastic elements, its force responses are characterized by nonlinear displacement. In general, it is accepted that initial tooth mobility depends on the interaction of periodontal fibers, which are elastic and can elongate [1, 2]. Furthermore, the network of blood vessels that surround the teeth in their periodontal pockets can be compressed during movement. Likewise, a displacement of interstitial fluid takes place in the initial phase of tooth movement [5–8].

Several investigators have measured tooth mobility as the total buccolingual crown excursion of different groups of teeth [9–14]. After application of a horizontal force up to 5 N, incisors had the highest (100–120 µm) and molars had the lowest (40–80 µm) mobility [1, 13, 14]. When the force is increased, the tooth mobility progresses slowly. It is accompanied by the distortion of the buccal bone plate [1]. When the force is released, the tooth returns to its origin. The return is caused by the restoring forces of the surrounding bone and soft tissue, as well as the refilling of blood vessels and interstitial fluid [10, 12, 15]. After a period of fast restoration, a phase of slow movement follows, until the tooth returns to its original position.

Several techniques have been used for measuring tooth mobility. For in vitro simulations assessing orthodontic

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questions, electronic strain gages with accuracies up to 0.1 µm have been applied. Pedersen et al. [16] registered tooth movement in two dimensions on human cadaver bone with low force clip gages on three areas of the mandible. These measured values were used as a basis for finite element models. Hinterkausen et al. [17] used three laser diodes for measuring tooth mobility. The laser system was combined with a force inducer, and mobility was detected in the movements of the laser spots on the surfaces of the optical detectors. Using this technique, an accuracy of 9 µm was obtained. Kawarizadeh et al. [18] used comparable techniques to evaluate the initial tooth mobility in rat molars, and compared the results with finite element models in which tooth movement was simulated. Yoshida et al. [6, 19] developed an in vivo method in which a combination of eight magnetic sensors is fixed on a tooth, allowing real-time measurement. Castellini et al. [20] used a laser Doppler vibrometer as a noncontacting sensor for measuring tooth mobility. This technique is based on the manual application of impulses with an instrumental hammer on the crown. With an impulse of 10 N, the displacement reached a few microns. Several other research groups [21–24] used indirect techniques to assess displacement through dynamic excitation. Displacement values depended on tooth mobility, but predominantly on the damping characteristics of the periodontium [25].

The majority of currently published techniques for assessing tooth mobility are either limited to in vitro assessment or, in vivo, require highly complex instrumentation [16–18]. All existing measurement techniques for intraoral application use small forces or short force impacts on the teeth, resulting in low displacement ratios.

Photogrammetric measurement systems based on image correlation techniques have been used for deformation measurement, stress analysis, and displacement of different materials in industrial applications for years [26–28]. Some studies have assessed biomaterial-related questions [26, 29]. However there have been no in vivo applications.

Due to the lack of sound, quantitative in vivo data on the displacement of teeth by applying increasing loads, we have applied an alternative measuring technique. The aim of the present study was to test the clinical applicability of a photogrammetric measurement technique for quantifying tooth mobility. As tooth mobility is determined by overall root surface area in contact with bone, it was hypothesized that there would be no difference in tooth mobility between contralateral teeth, but between central and lateral incisor and canine teeth.

Material and methods

A group of 31 dental students were randomly asked to participate (11 men, ages ranging from 21 yr to 29 yr, mean age 23.4 yr, and 20 women, ages ranging from 21 yr to 36 yr, mean 24.4 yr). Experimental measurements were undertaken with the understanding and written consent of every subject. The study was independently reviewed and approved by the University's ethical committee (Ethical Committee Re. No. 3673) and conducted in accordance with ethical principles according to the Declaration of Helsinki. Prior to load application, several periodontal parameters were assessed to verify healthy periodontal conditions. These included tooth mobility grade 0 (according to classification of the German Periodontal Association [30]), probing depth≤3 mm at four locations per tooth, vitality of teeth, no extended carious lesions or fillings, no endodontically treated teeth, and no prosthetic crown restorations.

Vertical and horizontal movements of central and lateral incisors and canines were measured. An optical inspection system (Aramis; GOM mbH, Braunschweig, Germany) based on photogrammetric principles was used for mobility analysis of the teeth. Digital image correlation is a noncontact optical method for displacement and strain measurement, which has been widely applied in various industrial and medical fields [26, 29, 31]. The key to a digital image correlation system is the tracking of changes in an applied random micropattern (stochastic pattern), rather than a projected pattern. [27, 32] This surface pattern changes when the object deforms or moves under an applied load, and is recorded by two cameras [27, 28].

The probands were seated in an upright position with their heads fixed to a headrest with an adaptable clamp to minimize unwanted movement. For photogrammetric measurements, all teeth were cleaned with alcohol (70%), and an adhesive tape with a stochastic surface pattern was fixed on each tooth surface. The stochastic pattern was obtained by using a nonreflective adhesive tape (Leukotape classic weiss, BSN medical GmbH, Hamburg, Germany), which was sprayed with graphite (Graphit Spray 33; CRC Industries Deutschland GmbH, Iffezheim, Germany). The unloaded initial configuration was defined as baseline. Patients were asked to bite on a custom designed loading device containing a subminiature load cell (ELFM 250 N; Measurement Specialties, Inc, Aliso Viejo, CA, USA). The loading device was calibrated to <1 N accuracy, and coupled to a trigger box (Aramis trigger box; GOM mbH; Fig. 1). The trigger released at 9 N load intervals up to 81 N to automatically take photographs. The procedure was stopped if pain prevented further loading. Photographs were made by a pair of synchronized high-resolution digital cameras with 2048×2048 pixel resolution (Aramis system 4 M; GOM mbH), arranged at an angle of 30° (Fig. 2). While the participant was biting, the load cell was maintained in position through magnets attached on a metal plate (Fig. 3). The plate was firmly fixed to the lower dental

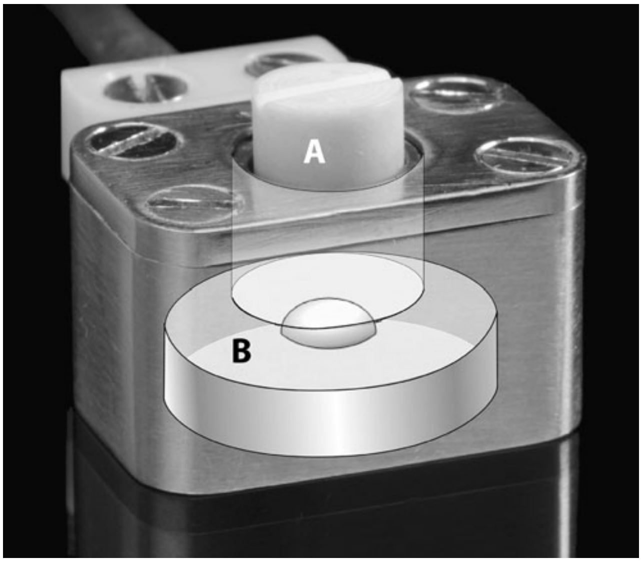

Fig. 1 Schematic drawing of custom loading device. Force is transferred via a cylinder (**a**) to a subminiature load cell (**b**) coupled to a trigger box, releasing photographs at 9-N load intervals

Fig. 3 Extraoral anterior view of experimental setup. The magnet retained loading device maintained in position by a metal plate that is attached to the mandibular teeth by silicone material. For hygiene reasons, the load device is covered with a single-use plastic cover. Adhesive tape with a stochastic surface pattern is fixed on all six anterior teeth. Surface pattern is tracked by digital image correlation system over all load stages. The *black rectangle* displays the 2×2 mm measurement area that was used for assessment of tooth mobility

arch with a polyvinylsiloxane silicone material (Futar D, Kettenbach GmbH & Co KG, Eschenburg, Germany). Measurements of each tooth were performed twice, with an intervening time period of 120 s to assure realignment.

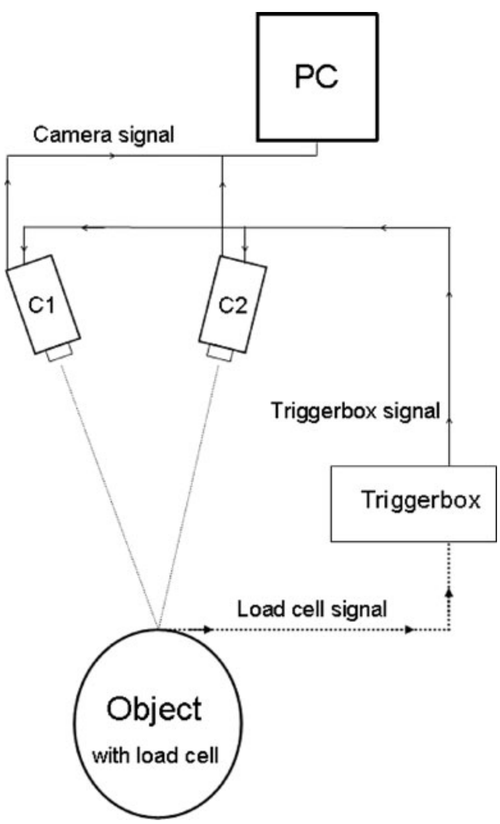

Fig. 2 Schematic illustration of study setup

Images were processed using a special software system (Aramis software; GOM mbH). Unique correlation areas (macroimage facets, 15 pixels square) were defined across the entire imaging surface [26–28]. For each area, the corresponding locations in all other images from the second camera, and all different loading situations, were automatically determined and tracked with subpixel accuracy [26, 28]. Subpixel resolution can be obtained in digital images by a special algorithm with an accuracy exceeding the nominal pixel resolution of that image [33–37]. Photogrammetric principles were then used to calculate the three-dimensional coordinates of the entire surface. The precision of the measurements of deformation and movement is±1 μm.

A 2 mm×2 mm area on the tooth surface at a 2-mm distance from the incisal edge of each tooth was defined for further analysis (Fig. 3). For maximum accuracy, the maximum calculable pixel number on this 4 mm^2 area was used and averaged. From the data recorded, the vertical and horizontal displacements of the teeth were calculated. For statistical analysis, the displacements in the vertical and horizontal dimensions were calculated in relation to immobile reference areas defined by unloaded contralateral teeth (Figs. 4 and 5). Thus, motions of the participant and related influences were eliminated from the measurements. The tooth motions in the buccal direction were calculated using "the Pythagorean theorem" (Fig. 6).

In addition to quantitative descriptive statistics, a nonparametric multivariate test (generalized Wilcoxon test) [38, 39] was applied to compare mean differences in vertical and horizontal displacements between types of teeth and contralateral teeth. The minimum level of statistical significance was set at $p \leq 0.05$. Statistical analysis

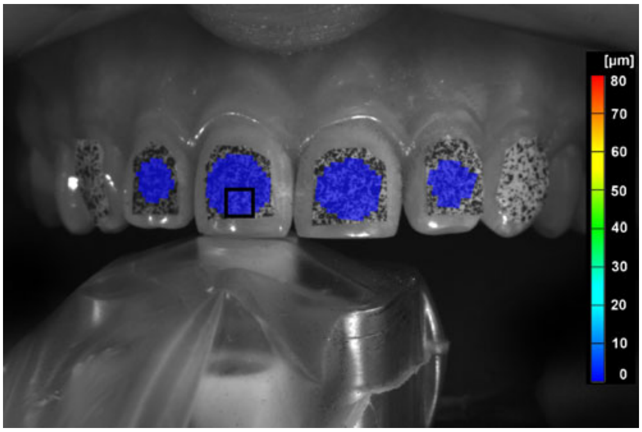

Fig. 4 Anterior screen image of surfaces as calculated by measurement system prior to load application. Displacement of teeth was measured against reference areas on adjacent unloaded teeth. *Color scale* on right depicts absolute displacement values in µm (blue: 0 µm; green: 40 µm; red: 80 µm)

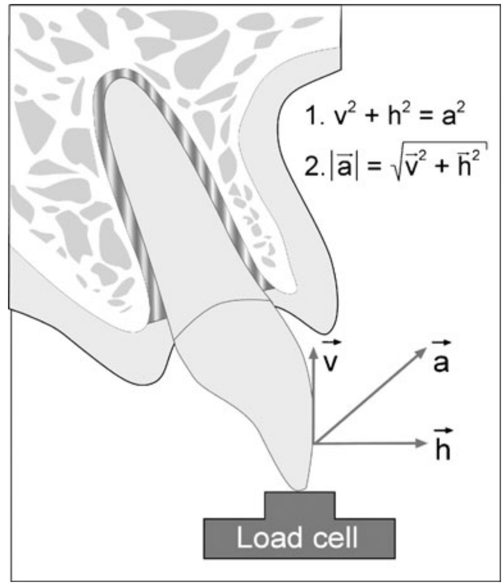

Fig. 6 Schematic drawing of absolute tooth displacement in the buccal direction calculated by using "the Pythagorean theorem" for vector calculation (*v* vertical displacement, *h* horizontal displacement, *a* absolute displacement vector)

used SPSS (SPSS Version 15; SPSS Inc, Chicago, USA) and SAS software (SAS Version 9; SAS, Heidelberg, Germany).

Results

The Wilcoxon test revealed no significant differences in the mean displacement amplitude between contralateral central or lateral incisors and canine teeth during horizontal, vertical, and absolute displacement values. Therefore, pooled data for contralateral teeth were used for subsequent statistical comparisons between central and lateral incisor and canine teeth.

There were no significant differences in vertical displacement between the central and lateral incisors at forces greater than 18 N. Comparisons between central incisor and canine teeth, as well as between lateral incisor and canine teeth demonstrated significant differences during all load steps. The absolute values of vertical tooth displacement at the various force steps are illustrated in Fig. 7.

Displacements of central and lateral incisor in the horizontal plane were significantly different at forces below 72 N. Significant differences in horizontal tooth displacement were found for all load stages between central incisor and canine teeth and between lateral incisor and canine teeth. Horizontal displacements at the various force steps are illustrated in Fig. 8. Using the values of the vertical and horizontal movements, the three-dimensional buccal displacement vector was calculated (Fig. 9). Vector comparison revealed significant differences in central and lateral incisor tooth displacement only for initial forces of 9 N and 18 N. Significant differences between central incisor and canine teeth and between lateral incisor and canine teeth in both the vertical and horizontal displacement were found ($p \leq 0.05$).

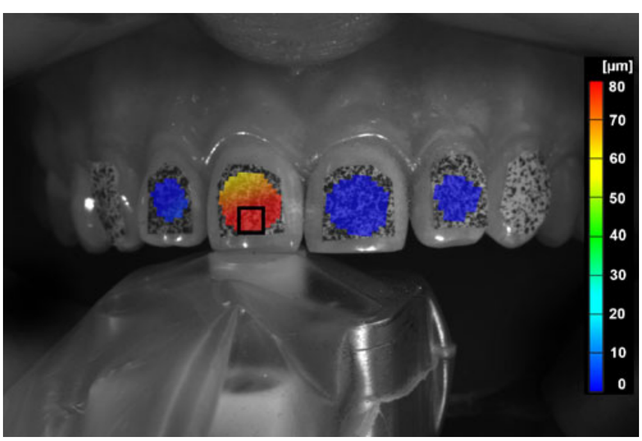

Fig. 5 Anterior screen image of surfaces as calculated by measurement system during load application; horizontal displacement at 54 N is shown exemplary (see color scale)

Discussion

In this pilot in vivo study, the tooth mobility of incisors and canine teeth in periodontally healthy subjects was investigated using a noncontact optical measurement technique. The hypothesis that contralateral teeth would reveal similar ranges of mobility was confirmed. Thus, results from contralateral teeth were pooled for further analysis. In the

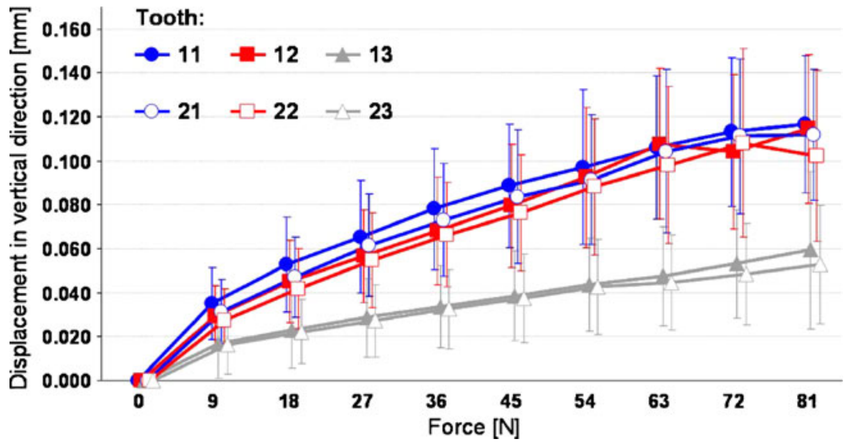

Fig. 7 Absolute values of vertical tooth displacement at various force steps

selected participants, no differences in mobility between central and lateral incisors were found except for in the horizontal direction. The root surface area and axis of rotation of incisors could be a reason for comparable movement. Compared to the mobility of canine teeth, however, significant differences were observed. This is most likely due to root surface area of canine teeth, compared to central and lateral incisors.

There are several published studies that measured initial tooth mobility [1, 13, 14]. Mühlemann [5] found that displacement of incisors reached up to 100–120 µm during an application of 5 N when teeth were pulled horizontally. In the present study, participants transmitted loads (up to 81 N) while biting vertically on a load cell. It can be assumed that much higher vertical forces have to be applied to reach the displacement values reported in previous studies. Using small forces, the initial type of tooth mobility is most likely a tipping around an axis of rotation inside the PDL [40]. When applying greater forces, the PDL is compressed and a continuing force increase leads to a displacement of both the alveolar bone and tooth [41, 42]. Further studies will be necessary to exactly determine the initial behavior of the tooth-bone complex. Here, low initial forces have to be applied only. Another aspect that must be considered is the fact that a 2×2 mm surface at a distance of 2 mm from the incisal edge was used for calculations. While a slight difference in absolute rotational values might exist in comparison to measuring a defined point on the incisal edge, this approach was selected for mathematical accuracy and stable calculation of surface area.

Other measurement techniques applied small forces and used magnetic sensors [6, 19], strain gage techniques [16], or laser measurements [20]. In the present study, load intensity and duration was increased to imitate clinical conditions. To obtain reproducible results, three repeated measurements were performed. Körber [10] and Parfitt [12] stated that a "return" to baseline of a tooth is not achieved immediately, but takes several seconds. After a phase of rapid elastic recovery, a slow asymptotic phase occurs, proportional to the magnitude and time of the load application. For this reason, 120-s intervals were maintained between repeated measurements. Even after manipulating teeth by fixing an adhesive tape with a stochastic

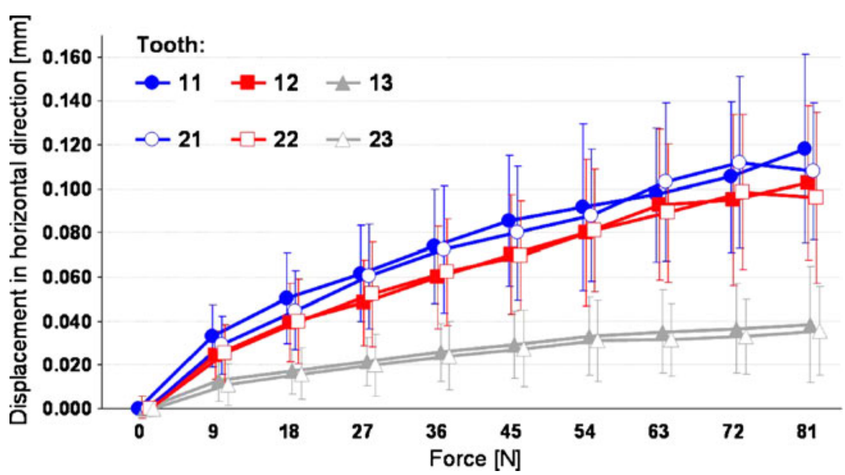

Fig. 8 Absolute values of horizontal tooth displacement at the various force steps

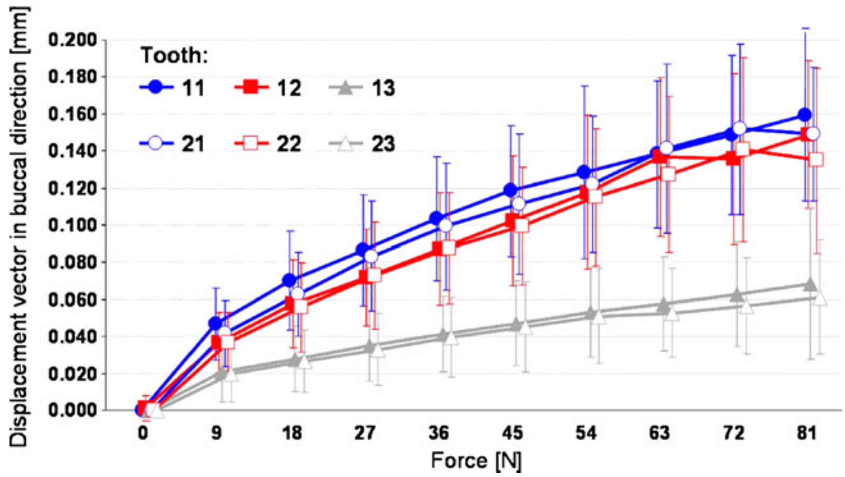

Fig. 9 Absolute values of the three-dimensional buccal displacement vector at the various force steps

surface pattern to the surfaces, a 3-min waiting period for the tooth to return to its original position was observed.

Other investigators [1, 5, 10, 11, 43] induced forces by pulling or pushing on teeth with mechanical appliances to guarantee a reproducible linear force application. In the present study, load application varied between subjects, and no linear force application was guaranteed. However, for simulating intraoral, clinically relevant situations, linear force is inappropriate. In fact, biting on the load cell simulated natural load transmission, as expected during mastication.

A significant advantage of the applied technique is that the mobility of a tooth is compared to an immobile reference area. Movement of the subjects, therefore, has no influence on measurements.

Mühlemann and Zander [1] observed, while pulling on teeth in a horizontal direction, that tooth displacement is not linearly related to the magnitude of the force applied. It was shown that tooth mobility is divided into two parts—the so-called initial tooth mobility (ITM) and secondary tooth mobility (STM) [1, 5]. The first part describes a high displacement of the tooth while applying small forces up to 1 N. It can be assumed that this corresponded to movement of the root within the periodontal pocket. When the force increases, tooth movement progresses slowly. It is most likely accompanied by distortion of the cortical bone plate. Parfitt [12] and Körber [10] described the curve of tooth displacement as a logarithmic pattern. Considering the diagrams in this study, a curve with a logarithmic form can be recognized. While applying initial forces, the displacement increased much faster than when greater forces were exerted. Calculation of gradients could provide information about ITM and STM. Displacement of teeth was recorded in 9-N intervals in this initial clinical study. To obtain more precise results especially in the initial phase of force application, images can be triggered in 0.5 or 1-N intervals in future investigations.

A current limitation of the applied optical measurement technique is the field of view of the camera system. Only anterior teeth up to the canine/first bicuspid were assessed. To obtain information on bicuspids and molars, the surface alterations of the objects have to be developed.

The most prominent advantage of the applied noncontact measuring technique is that obtained data can be used for finite element models. Being able to provide in vivo clinical data that can subsequently be used for mathematical calculation reduces the number of necessary assumptions and will result in more precise calculations and clinically relevant data. The measurement technique is not limited to tooth mobility but can be applied to other clinical aspects of relevance such as implant micromovement upon load application or the clinical progress of regenerative techniques to maintain teeth in future investigations.

Conclusions

Within the limitation of this pilot in clinical study, the following conclusions can be drawn.

1. The present optical image correlation technique can be applied for intraoral measurement of tooth mobility.
2. Absolute vertical and horizontal tooth mobility upon load application can be assessed.
3. Contralateral teeth have no significant differences in mobility in periodontally healthy persons.

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Conflict of interest The authors declare that they have no conflict of interest

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