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3D tooth wear assessment in dentistry and orthodontics

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3D tooth wear assessment in dentistry and orthodontics

Thesis

Nikolaos Gkantidis

3D tooth wear assessment in dentistry and orthodontics

by Nikolaos Gkantidis

University Medical Center Groningen, University of
GroningenGroningen, The Netherlands

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3D tooth wear assessment in dentistry and orthodontics

PhD thesis

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 Rector Magnificus Prof. C. Wijmenga
 and in accordance with
 the decision by the College of Deans.

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Chapter 1

General introduction and aim of this thesis

Definition and prevalence of tooth wear

Tooth wear is expressed as superficial loss of dental hard tissues. It is a physiological process, starting by the time a tooth emerges into the oral cavity and it progresses slowly over time (Cunha-Cruz et al. 2010; Kuijpers et al. 2009; Schierz et al. 2014). However, in certain cases tooth wear might exceed normal levels due to various reasons (Kitasako et al. 2015; Schierz et al. 2014).

The prevalence of occlusal tooth wear in the general population is very high. All individuals are expected to develop a degree of tooth wear at a certain point in their lifetime. In terms of severity, anterior teeth exhibit greater wear (Ahmed et al. 2017; Awad et al. 2019; Liu et al. 2014; Marro et al. 2020; Schierz et al. 2014), expressed as vertical loss of dental hard tissues. Furthermore, between sexes, males are more prone to develop tooth wear both regarding the number of affected teeth, but also the severity of the condition (Cunha-Cruz et al. 2010; Schierz et al. 2014).

The currently available epidemiological data on tooth wear are primarily generated through qualitative studies that are subjective and lack precision. The information on the precise tooth wear amount, expected in a long-term period on a group of individuals, has not yet been adequately determined. Longitudinal, quantitative studies on medium- to long-term tooth wear occurrence are scarce (Ray et al. 2015; Korkut et al. 2020; O'Toole et al. 2020). Recently developed 3D superimposition methods that are relatively easy to apply on 3D digital models derived from intraoral scans can be used to obtain this important information (O'Toole et al. 2019; Stucki and Gkantidis 2020; Winkler and Gkantidis 2020).

Etiology of tooth wear

The etiology of tooth wear is multifactorial and usually a combination of factors is involved. Functional factors, such as gastroesophageal reflux, mastication pattern, or teeth grinding and environmental factors, such as highly acidic food, can act independently or synergistically causing tooth surface loss. Attrition, abrasion, and erosion processes, sometimes associated with pathological conditions, may contribute to the final tooth wear pattern that is clinically present (Kitasako et al. 2015; Schierz et al. 2014; Teixeira et al. 2017). In

individual patients, one of the factors reported above or any combination of them might be implicated (Goldfarb et al. 2020).

It has been shown that dietary habits, such as the regular consumption of acidic food, have a critical role in tooth wear development (Awad et al. 2019; Kitasako et al. 2015; Liu et al. 2014; Olley et al. 2015; Schierz et al. 2014). There are also occlusal components, such as overjet and anterior protected articulation, associated to occlusal tooth wear (Van't Spijker et al. 2015). Subjects with different malocclusions demonstrated different tooth wear patterns (Janson et al. 2010; Oltramari-Navarro et al. 2010). A relation of tooth wear to masticatory function has also been established (Meng et al. 2014). Furthermore, males, which have stronger musculature than females, show also higher amounts of tooth wear (Cunha-Cruz et al. 2010; Schierz et al. 2014).

Tooth wear and orthodontic treatment

Tooth wear, additional to that expected physiologically, might occur during orthodontic treatment, due to the continuously changing occlusal contacts, the contact of natural teeth with the orthodontic appliances or other factors (Mwangi et al. 2009; Janson et al. 2010; Oltramari-Navarro et al. 2010; Van't Spijker et al. 2015). Special reports highlight the risk of severe tooth wear when natural teeth are in contact with ceramic brackets (Karamouzios et al. 1997). Therefore, in the literature there are both qualitative (Kuijpers et al. 2009; Mwangi et al. 2009) and quantitative (Panos et al. 2011; Park et al. 2014; Jang et al. 2018) studies assessing the effect of orthodontic treatment on occlusal tooth wear. The studies report different amounts and patterns of tooth wear that might be related to orthodontic treatment. Treatment-related factors, such as treatment duration, extraction versus non-extraction treatment (Panos et al. 2011), or early versus late anterior crossbite correction (Jang et al. 2018) have also been shown to affect tooth wear. However, the current evidence is limited and in many cases contradictory. As a recent systematic review on the topic concluded (Makrygiannakis et al. 2018), among other methodological limitations, the existing studies lack precision and they do not include untreated control samples to enable the differentiation between tooth wear attributed to orthodontic treatment and that expected due to other factors.

Thus, at present, the relation of orthodontic treatment to tooth wear remains unclear.

Effects of tooth wear on individuals

Globally, life expectancy has increased considerably in recent years. This created the need for retention of natural teeth in a dentition for several decades. However, apart from the retention of a functional dentition throughout life, at the same time, patients' esthetic demands have also increased, generating the desire for presence of intact, esthetically pleasant teeth till the last years of life. These two facts, designated tooth wear as an important problem that contemporary dentistry is called to successfully manage (Lussi and Carvalho 2014).

The impact of tooth wear on a dental patient can be multilevel. The esthetic impact of tooth wear seems to be the major concern of the affected individuals, with sensitivity being the second one. A previous study identified an association between dentine hypersensitivity severity to occlusal tooth wear (Olley et al. 2015). On the contrary, functional problems and pain are present less often (Wazani et al. 2012). There are several studies supporting the negative esthetic impact of anterior tooth wear (Betrine Ribeiro et al. 2017; Machado et al. 2013; Sobral et al. 2019). Furthermore, a recent study on elder nursing home patients concluded that their quality of life was negatively affected by anterior tooth wear (Al-Allaq et al. 2018). In more severe cases, apart from the above, tooth wear may even alter facial morphology and speech, further impacting quality of life.

Accurate diagnosis of dental material wear, concerning restorations of missing or defected teeth, is also crucial for the assessment of the performance of these materials during clinical use. Dental restorations need to be fatigue resistant to maintain structural and form integrity over time and at the same time cause no damage to the antagonistic teeth (Heintze et al. 2008; Stober et al. 2016).

Advances in contemporary dentistry, including tooth wear management, enabled teeth maintenance till late stages of life, offering also various

possibilities to prevent or restore tooth and material wear (Loomans et al. 2017; Stober et al. 2016).

Tooth wear assessment

Early diagnosis is imperative for the timely management of tooth wear, to avoid subsequent problems and extensive restorations. Erosion has been found to progress more in individuals with previous signs of erosion, emphasizing the importance of early diagnosis (Hasselkvist et al. 2016). However, a recent study reported that dental patients might be unable to identify tooth wear and seek professional advice, even in severe cases (Goldfarb et al. 2020). Therefore, several previous studies have addressed the issue of tooth wear assessment and suggested various qualitative and quantitative approaches for this. Conventional qualitative methods have been found incapable of following precisely tooth wear progress over time, even when applied by dental professionals (Al-Omiri et al. 2013; Wulfman et al. 2018). To overcome this limitation, novel 3D approaches that are clinically applicable at reasonable time and costs have been recently suggested (O'Toole et al. 2019).

The conventional tooth wear assessment is performed through the use of indices that involve qualitative assessments of dental surface loss. Certain examples comprise the methods of Eccles (1979), Smith and Knight (1984), the New Tooth Wear Index (NTWI) (Hooper et al. 2004), or the Basic Erosive Wear Examination (BEWE) (Bartlett et al. 2008). These methods have gained popularity and are widely used primarily because of their simplicity, since they do not require any special equipment and they are not time consuming. Thus, they can be easily applied under clinical conditions or used in large-scale studies. There are several such indices suggested over the years, with each one having its own strengths and limitations. However, the main shortcoming of these approaches is the reduced precision (Al-Omiri et al. 2013; Wetselaar et al. 2016). Qualitative assessments are subjective and their sensitivity is limited, especially when considering small amounts of tooth wear that are usually expected within regular dental control periods (Al-Omiri et al. 2013).

In comparison, quantitative methods on dental models are more objective and can be highly accurate, detecting even minor tooth wear amounts in terms of tooth height or volume loss (Lee et al. 2012; Wulfman et al. 2018).

There are digital profilometry and 3D surface matching techniques, which can be highly reproducible, usually within 15–20 μm of vertical loss of tooth structure. Nevertheless, the trueness of most of these techniques has not been adequately investigated due to the absence of a gold standard reference (true value) to compare their outcomes with (Wulfman et al. 2018). Additionally, certain quantitative techniques are highly complex, requiring special equipment, considerable time, and expertise, as well as dental impressions and physical models to be applied. This increases the costs, induces errors, and limits the applicability of these methods in actual clinical conditions (Heintze et al. 2006; Rodriguez et al. 2011; Wulfman et al. 2018) or in large-scale research studies. In regard to these specialized techniques, we managed to identify only one study that applied a validated technique for 3D occlusal enamel wear measurement in a clinical setting (Pintado et al. 1997; Wulfman et al. 2018). All quantitative methods that use 3D digital dental models will benefit from the rapid advances in imaging techniques, which will facilitate their applicability by reducing costs, whereas at the same time enhancing accuracy.

In contemporary dentistry, the use of direct intraoral scanners to imprint the dentition is steadily increasing (Stucki and Gkantidis 2020; Winkler and Gkantidis 2020). The subsequent 3D digital dental models could provide the required tooth representations for quantitative 3D wear assessment enabling the *ex vivo* implementation of 3D superimposition techniques on regular clinical settings, through the use of relevant commercial or free software. A prerequisite to apply this technique and assess tooth wear over a certain time period, is the existence of an earlier obtained dental model. To date, the available *ex vivo* 3D wear assessment methods were based on serial tooth crown superimpositions on areas that were considered unaltered between two or more time points (Panos et al. 2011; Park et al. 2014, Tantbirojn et al. 2012; Wulfman et al. 2018). However, in actual clinical conditions, the selection of such areas is not easy. Furthermore, these methods have not been yet adequately validated against a gold standard measurement, which would provide the true tooth wear value (Wulfman et al. 2018). The accuracy of such 3D superimposition techniques can be affected by various factors, including tooth movement over the assessment period, the accuracy of the 3D surface

models, especially in difficult to scan areas, the reference areas used to register the serial surface models and the defined software settings.

Tooth wear management

Proper and timely diagnosis, through accurate monitoring of tooth wear progression and treatment outcome assessment, is the first step for successful tooth wear management (Loomans et al. 2017; Lee et al. 2012; Loomans and Opdam 2018) to avoid further tooth surface loss and associated esthetic or functional impairment (Huysmans et al. 2011; Lee et al. 2012). Wear monitoring at an individual level is important for dentists to enable the better understanding of the problem and allow timely targeted interventions for patients in need. These might be preventive, such as the prescription of mouth guards to limit grinding during sleep and the cessation of harmful habits that lead to tooth wear, or interceptive, such as the restoration of the lost tooth substance to stop the progress of the condition and improve esthetics and function. In the context of a multi-disciplinary approach, orthodontic treatment can in certain cases enable minimally-invasive tooth wear management, through the movement of selected teeth to avoid restoring the entire dentition (Mainjot and Charavet 2020). Following the placement of dental restorations, material wear monitoring is important for treatment outcome assessment at an individual clinical level, but also for the associated research on dental materials used for tooth restorations.

Aim of the thesis

The aim of the thesis is to develop accurate, clinically applicable 3D tooth wear assessment methods, through superimposition of serial digital dental models, and to apply them to assess long-term tooth wear progression in a treated orthodontic patient population.

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Chapter 2

An accurate and efficient method for occlusal tooth wear assessment using 3D digital dental models

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Abstract

Tooth or material wear in a dentition is a common finding that requires timely diagnosis for management and prevention of further loss or associated esthetic or functional impairment. Various qualitative and quantitative methods have been suggested to measure tooth or material wear, but they present with limitations, such as imprecision, subjectivity, or high complexity. Here we developed and assessed an efficient 3D superimposition method to accurately measure occlusal tooth wear on 3D digital dental models. For this purpose, teeth on plaster casts were manually grinded on their occlusal surfaces to simulate various degrees of tooth wear. The casts were scanned using a surface scanner. Grinded tooth crowns (T1) were segmented and compared to the original crowns (T0) using five 3D surface superimposition techniques and a gold standard technique (GS). GS measurements were obtained by using intact adjacent structures as superimposition references. The technique of choice (complete crown with 30% estimated overlap of meshes) showed the best reproducibility (maximum difference < 0.050 mm³) and excellent agreement with the GS technique (median difference: 0.032 mm³). The suggested 3D superimposition method offers a highly efficient and accurate tool for tooth wear assessment, which could be applicable to clinical conditions.

Introduction

Tooth wear in a dentition can be a result of attrition, erosion or abrasion and is expressed as loss of dental matter, especially of enamel. Timely diagnosis is necessary to manage this condition and avoid further tooth loss or other associated esthetic or functional impairment in the future [1,2]. Wear of dental materials is also critical since restorations have to be resistant to structural and form changes, without causing damage to the opposing teeth [3,4].

Over the past few years, various qualitative and quantitative methods have been suggested to measure tooth wear. Conventional approaches, such as those of Eccles [5], Smith and Knight [6], the New Tooth Wear Index (NTWI) [7], or the Basic Erosive Wear Examination (BEWE) [8] assess dental material loss qualitatively through the use of indices. The main shortcoming of such indices is that they are subjective and their sensitivity is unsatisfactory, especially when tooth wear is assessed in relatively short time-spans [9].

For this reason, quantitative methods on 3-dimensional (3D) dental models have been developed [10]. These are considered advantageous, since they are more objective and they provide more accurate estimation of the outcome, usually as tooth height or volume loss [11]. However, the utilization of such methods in vivo or ex vivo is usually rather complicated and time-consuming [12], and thus not feasible in a regular clinical basis or even for research purposes, if the required expertise and special equipment are not available. To our knowledge, when considering these specialized techniques, there is only one study that used a validated technique to measure the 3D occlusal enamel wear in a clinical setting [11,13].

The steadily increasing usage of intraoral scanners in contemporary clinical dentistry [14] could provide the required surface models for quantitative 3D wear assessment and the available software in the market could facilitate the ex vivo implementation of the relevant techniques on a regular clinical setting. Previous ex vivo wear assessment methods relied mostly on superimposition of tooth areas that were not considered to be affected by tooth wear between two or more time points [11,15–17]. However, the selection of such areas and the validation of these methods compared to a gold standard measurement, which would provide the true value, has not been adequately

investigated [11]. Numerous factors can influence wear assessment through these techniques, such as movement of teeth between two time points, the accuracy of the obtained 3D surface model, especially in areas that are inherently difficult to scan, the reference areas selected to register the serial surface models and the software settings used for the superimposition.

Thus, the aim of the present study was the development and in vitro assessment of the precision and trueness of a 3D superimposition method that can be used in a clinical setting to visualize and measure occlusal tooth wear in all dimensions of space.

Materials and Methods

Ethical approval

The research project is registered and approved by the Swiss Ethical Committee of the Canton of Bern (Protocol No. 2019-00326). The methods were carried out in accordance with the relevant guidelines and regulations. All participants signed an informed consent prior to the use of their data in the study.

Sample

For the needs of the study, sixteen dental plaster models (type IV plaster, white colour, Fujirock EP Premium, GC, Leuven, Belgium) with ($n = 8$; 4 maxillary and 4 mandibular) and without ($n = 8$; 4 maxillary and 4 mandibular) aligned dental arches were selected from the archive of the Department of Orthodontics and Dentofacial Orthopedics, University of Bern, Switzerland. The models depicted a full permanent dentition of all natural teeth, except for third molars, and no extreme morphology of the intraoral anatomical structures, assessed through visual inspection. Models with aligned dental arches were considered those with crowding less than 1 mm, whereas the models without well aligned dental arches had crowding between 4 and 10 mm. The detailed sample composition is provided in Supplementary Table S1.

Tooth wear simulation

Based on a predefined study setting, eighteen teeth of each tooth type (incisors, canines, premolars, and molars) that were equally distributed among the dental models (maxillary and mandibular, with and without crowding) were selected to be manually grinded on their occlusal surfaces. Various degrees of tooth wear

were simulated (mild, moderate and severe, corresponding to approximately 0.5, 1, and 2 mm of vertical loss, respectively), equally distributed within each tooth type (Supplementary Table S1). The predefined amount of tooth wear was first marked on the stone casts with a black pencil and then removed using a laboratory straight handpiece or a laboratory stone knife, to simulate normal tooth wear. Teeth were grinded both symmetrically and asymmetrically, aiming to simulate a variety of actual clinical conditions (Supplementary Figure S1). This setting allowed for presence of two intact teeth adjacent to each grinded tooth. The intact teeth, along with the adjacent gingival or palatal structures that were not artificially altered, comprised the stable superimposition reference areas that provided the gold standard measurement (true value).

3D model acquisition

The dental casts were scanned before (T₀) and after the occlusal tooth wear simulation process (T₁) using a high accuracy laboratory 3D surface scanner (stripe light/LED illumination; accuracy < 20 µm; Laboratory scanner D104a, Cendres+Métaux SA, Rue de Boujean 122, CH-2501 Biel/Bienne) to obtain the 3D Standard Tessellation Language (STL) models used in the study. The digitized 3D models were thereafter imported and analysed with Viewbox 4 software (version 4.1.0.1 BETA, dHAL Software, Kifissia, Greece, <http://www.dhal.com/viewboxindex.htm>).

Tooth wear volume measurement workflow

The crowns of the grinded teeth (T₁) were manually segmented and compared to the original crowns (T₀) using five test techniques and the gold standard technique.

The gold standard measurements (GS) were obtained by using the adjacent intact teeth and alveolar processes as superimposition reference areas (Fig. 1A). These were unaltered, identical structures, and thus, perfect congruence of the two surface models is expected in these areas following a best-fit superimposition. Thus, the amount of occlusal wear on the tooth of interest was accurately measured as described below.

The first group of measurements (PC: partial crown) were obtained using the part of the T₀ clinical crown that was considered intact as superimposition reference (Fig. 1B). For the second measurement group (CC:

complete crown), the complete To clinical crown was used as superimposition reference (Fig. 1C).

Figure 1. Reference areas used to measure tooth wear at the lower right canine. (A) Gold standard area (GS, blue). (B) Partial crown area (PC, yellow). (C) Complete crown area (CC, green). The upper row shows the buccal and the lower row the lingual view. All images were generated using Viewbox 4 software (version 4.1.0.1 BETA, <http://www.dhal.com/viewboxindex.htm>).

The To/T1 3D models of each patient were superimposed, in each reference area described above, using the software's implementation of the iterative closest point algorithm (ICP) [18], with different settings. In all cases, prior to the application of the ICP algorithm, the two objects were manually approximated to facilitate the automatic registration. For each registration, the whole process was repeated starting from the original initial position of the two models to be registered.

At first, the performance of three different ICP settings was tested. Setting (A) comprised: 100% estimated overlap of meshes, matching point to plane, exact nearest neighbor search, 100% point sampling, 50 iterations. Setting (B) was the same as (A), but with 80% estimated overlap of meshes. Setting (C) was the same as (A), but with the estimated overlap of meshes freely defined by the operator for each individual measurement, based on visual inspection of the overlap of the superimposed teeth, the adjacent intact structures and the relevant colour maps. The selected value for each case, obtained after various pilot superimpositions, was noted in an Excel sheet. A number close to the average of these values (average: 40.0, SD: 12.2, range: 20–75 estimated overlap of meshes) was used for a fourth setting (D), which was same as (A), but with 30% estimated overlap of meshes. We decided to use a value slightly lower than the average reported above, because further

assessment of individual cases showed that the lower values worked satisfactorily in all cases and were closer to the gold standard as compared to higher values. The specific techniques tested in this study (combinations of ICP settings and reference areas) are listed in Table 1.

Table 1. Superimposition techniques tested in the study.

Technique	Reference area	Estimated overlap
GS	Adjacent intact teeth and alveolar processes	100 %
PC(A)	Buccolingual surfaces	100%
PC(C)	Buccolingual surfaces	User defined
CC(B)	Complete crown	80%
CC(C)	Complete crown	User defined
CC(D)	Complete crown	30%

Following each superimposition, the registered 3D models of the crowns of interest were simultaneously sliced using one (gingival) to three planes (gingival, mesial, and distal), depending on the case. Prior to slicing, a colour coded distance map was created to ensure that no tooth wear surface was eliminated from the occlusal part of the tooth. The holes of each occlusal tooth part were then filled in through a specific process that ensured identical filling of both To and T1 tooth models (Fig. 2). To ensure that the holes got filled in exactly the same way, the contralateral points in sharp edges were connected, splitting the hole on the underside of the crowns in two or more parts. As a result, the edges of each subsequent hole lied on the same plane, so that the holes could be closed in only one way (irrespective of the software's algorithm) to create watertight To and T1 3D models of each tooth that differed only in their occlusal part, but were identical otherwise (Fig. 3). Thus, the difference of the volumes of the two resulting models represented the amount of the tooth wear at the entire occlusal/incisal surface.

Figure 2. Tooth wear measurement process in an upper canine. (A) Tooth before (yellow) and after (red) tooth wear. (B) Superimposed tooth crowns using the complete crown technique and setting D. (C) Color coded distance map showing the tooth wear. (D) Level (grey) used to simultaneously slice the two crowns. (E) Sliced tooth crowns. (F) Holes filled to create watertight models, and thus, calculate volumes.

Figure 3. Tooth wear measurement process in a lower molar. (A) Tooth before (yellow) and after (red) tooth wear. (B) Superimposed tooth crowns using the complete crown technique and setting D. (C) Color coded distance map showing the tooth wear.

(D) Levels (grey) used to simultaneously slice the two crowns. (E) Sliced tooth crowns. (F) Connected contralateral points in sharp edges (red line), splitting the hole in two parts to ensure identical hole filling process. (G) Holes filled to create watertight models, and thus, calculate volumes. All images were generated using Viewbox 4 software (version 4.1.0.1 BETA, <http://www.dhal.com/viewboxindex.htm>).

The amount of tooth wear that was detected through the gold standard technique and expressed as volume loss of tooth structure (mm³) was then compared to the test techniques.

For intra- and inter-operator error testing (reproducibility), the whole process was repeated for 20 teeth on four randomly selected models, two maxillary and two mandibular (one with and one without crowding, each) by two operators, following a 1-month washout period.

Statistical analysis

Statistical analysis was carried out by using the IBM SPSS statistics for Windows (Version 25.0. Armonk, NY: IBM Corp). Raw data were tested for normality through the Kolmogorov-Smirnov and Shapiro-Wilk tests and did not have a normal distribution in certain cases. Thus, non-parametric statistics were applied.

Agreement between different techniques with the gold standard technique (trueness) in tooth wear assessment was shown in box plots. Zero median value implies perfect trueness, whereas the larger the deviation from zero the lower the trueness of the technique. The range of deviation of individual values from the median value within techniques shows the precision of each technique. Differences in trueness and precision among different techniques were tested in a paired manner through Friedman's test. In case of significant results, pairwise comparisons were performed through Wilcoxon's signed rank test.

Potential effects of presence of crowding, tooth type, or tooth wear amount on the trueness and precision of each technique were explored through visual inspection of relevant plots and unpaired mean comparison tests within techniques.

Intra- and inter-operator error (reproducibility) of each technique on tooth wear measurement was assessed through Bland Altman plots, with

markers set by tooth category. Any deviation from zero shows imprecision of the technique. Differences in the reproducibility of the techniques were tested in an unpaired manner through Kruskal-Wallis test. In case of significant results, pairwise comparisons were performed through Mann-Whitney U test.

In all cases, a two-sided significance test was carried out at an alpha level of 0.05. In case of multiple comparisons, a Bonferroni adjustment was applied to the level of significance to avoid false positive results.

Results

The hole filling process used to create watertight models was repeated in 20 randomly selected teeth and always provided identical volumes.

There was a consistent pattern of tooth wear amounts in each tooth type, measured through the gold standard technique, verifying the study setting (Supplementary Figure S2).

Bland Altman plots for intra- and inter-operator error showed consistent results. There was no systematic error in any technique since mean measurements were always not significantly different from 0 (one sample t-test, $p > 0.05$). There was no evidence that the difference between repeated measurements was increasing by an increase in the amount of tooth wear. Tooth type also did not seem to affect reproducibility. The gold standard measurement and technique CC(D) showed the best reproducibility, overall and in individual measurements (max difference $< 0.050 \text{ mm}^3$). Interestingly the repeatability of the CC(D) technique was slightly better even compared to the GS technique (Fig. 4). However, the GS technique showed also optimal trueness (Supplementary Figure S3).

All tested techniques, except for PC(A) and PC(C), differed significantly to each other in their trueness (Friedman test: $p < 0.001$; Wilcoxon signed rank test: $p < 0.001$; Fig. 5). The CC(D) technique showed excellent agreement with the GS technique in all cases (median difference: 0.032 , max: 0.262 mm^3), suggesting this technique as appropriate for highly accurate tooth wear assessment.

Tooth type affected the trueness and precision of all techniques that use the complete crown as superimposition reference (CC; Kruskal-Wallis test, $p <$

0.01), with the premolars and molars showing the highest differences to the GS measurements (Fig. 6A). On the contrary, there was no difference between the trueness of each technique as measured in models with and without crowding (Mann-Whitney U test: $p > 0.05$). The amount of tooth wear affected significantly only the results of technique CC(B) (Kruskal-Wallis test, $p = 0.001$; Fig. 6B).

The difference of the technique of choice CC(D) from the GS technique in tooth wear measurements was always small for any tooth type or amount of tooth wear (Supplementary Figure S4). Significant differences were detectable only between canines and molars, with molars showing reduced trueness and precision (Mann-Whitney U test, $p < 0.001$). There was also a slight tendency for reduced trueness and precision when the amount of tooth wear was increased (Supplementary Figure S4, B).

Figure 4. Reproducibility of tooth wear measurement with all techniques. (A) Bland Altman plots showing intra-operator error. (B) Bland Altman plots showing inter-operator error. The axes length represents the true range of measured tooth wear values. The continuous horizontal line shows the mean and the dashed lines the 95% confidence intervals.

Figure 5. Box plots showing in the y-axis the difference of each technique with the gold standard technique in tooth wear measurements. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value (trueness). Zero value indicates perfect agreement with the gold standard. The vertical length of each plot indicates precision.

Figure 6. Box plots showing in the y-axis the difference of each technique with the gold standard technique in tooth wear measurements, (A) by tooth type, and (B) by amount of tooth wear. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value (trueness). Zero value indicates perfect agreement with the gold standard. The vertical length of each plot indicates precision.

Discussion

This study presents an accurate and efficient method to assess tooth wear using hardware and software applications that are convenient to use and can be easily incorporated to the contemporary armamentarium of a regular clinical practice. The method is essentially a superimposition method, and the result can be visualized in all dimensions of space and quantified according to the clinician's needs, as a linear or volumetric quantity. Apart from tooth wear, the present technique is expected to be suitable for dental material wear assessment, especially on the occlusal/incisal tooth surfaces, but this remains to be tested.

Previous studies questioned the laboratory defined performance of materials to that occurring clinically, among others also regarding tooth wear. This has primarily been attributed to the inadequacy of laboratory tests to simulate clinical conditions [19,20]. However, the lack of accurate clinical tooth wear assessment methods *in vivo* or *ex vivo* [11] might have also confounded this relationship. The overall accuracy of the previously available wear assessment techniques has been reported to vary from 15 to 20 μm , regarding vertical loss, with high variation per tooth, per patient, and per study [11]. The presented technique showed an accuracy of 0.032 mm^3 , which is superior to previous techniques, considering that it refers to a volumetric measurement. The relation of volumetric to vertical loss is evident in Supplementary Figure S2. According to these data, the 0.032 mm^3 volume loss would correspond to approximately 9 μm of vertical loss.

According to a recent systematic review, most previous studies on tooth or dental material wear used special technical equipment and/or materials for the assessment of dental or material tooth wear *in vivo*, increasing the costs, the complexity, and the feasibility of the process, as well as the operator- or material-dependent effects on the outcomes [11,12]. Furthermore, these methods require the use of replicas and possibly indexes bonded to teeth, which add cost and error to the process [11]. The large amount of unusable data reported in previous studies is also indicative of the limitations of the currently available techniques [11]. Thus, apart from the high precision and trueness of the present technique, its major advantage concerns its applicability in everyday clinical conditions, since the required surface models can now be

easily obtained by intraoral scanning. Numerous surface matching software applications have also become widely available, though their performance for such outcomes has to be individually tested.

The quality of the surface models inevitably affects the validity of tooth wear outcomes. Currently the intraoral scanners available on the market offer a global accuracy of approximately 30–50 μm [21,22]. However, errors are reduced when smaller structures, such as single teeth, which are required for the suggested technique, are considered [22,23]. The scanner used in the present study was a highly accurate ($<20 \mu\text{m}$) laboratory scanner in order to limit the effect of the scanner inaccuracy factor on the results. This accuracy is comparable or superior to that obtained from previously used techniques, such as profilometry [11]. The surface distance between corresponding points of repeatedly scanned dental models by this scanner is always less than 5 μm in all areas of the model. This accuracy level is slightly higher to the one that can be obtained from the currently available intraoral scanners, under actual clinical conditions. However, this design allowed for a gold standard measurement that provided the true value, which would have not been otherwise available [22]. In any case, with the very rapid advancement of intraoral scanners, it is expected that higher accuracy, which is preferable for valid 3D surface model superimposition outcomes [24], will be achieved in the near future.

The matching software can be another important factor affecting tooth wear outcomes [11]. When registering identical 3D models, the software used in this study achieves accuracy higher than 0.1 μm . This software has been extensively tested previously for the processing and superimposing of surface models [22,24–26] and proved to perform satisfactorily. The high repeatability of tooth wear measurements observed in the present study confirmed this finding.

A recent systematic review showed that most previous studies on tooth or dental material wear assessment reported 2D outcomes and mainly the vertical height loss [11]. It has been argued that 2D measurements might be more clinically relevant since they are not affected by tooth size [27]. We decided to report here volumetric measurements, since they provide higher

amount of information. However, with the present technique and namely by the visualization of lost tooth structure through color coded distance maps, thousands of 2D measurements on the entire affected surface are available to the operator, both for visual assessment and quantification.

Moreover, although we tested here tooth wear assessment on the entire occlusal surface, the present technique is suitable for measurements at selective surfaces. These can be performed by isolating the volume of interest through slicing levels and hole filling processes that are similar to those reported here for the entire occlusal surface.

Regarding the reference areas used to register the serial 3D digital dental models, previous clinical studies followed various approaches, which primarily included the use of lingual or buccal surfaces or of occlusal surfaces that were considered free of occlusal contacts, based on the inspection of intraoral photographs [11,28]. Other researchers used software based approaches to detect stable superimposition reference areas, performing a quantitative or qualitative assessment of the distances between corresponding models, following an initial matching [5,11]. However, the validity of such approaches might be questioned, since proper reference area selection or serial 3D model matching cannot be guaranteed and it was not tested against a gold standard evaluation. Furthermore, most of the previous techniques included impression procedures, stone model construction, and special scanning equipment, which might, additionally, introduce bias to the outcomes. In the present study, after testing various potentially eligible reference areas and software settings towards a gold standard assessment it became evident that with certain settings, the complete tooth crown should be selected as a reference area to achieve results that are similar to the actual values. Thus, the operator-effect on the measured outcomes is expected to be minimized, since the reference area selection is straightforward and the matching process fully automated. Indeed, the operator effect was minimal as shown by the intra- and inter-operator reproducibility of the gold standard and the selected technique. The operator effect was evident in the present study, through the high variation of repeated measurements obtained using setting C and its lower trueness and precision compared to setting D. Although superimpositions with setting C were

performed while viewing the overlap of intact structures, setting D, which was standardized, showed better performance.

Limitations

The main limitation of the study was that the proposed technique was tested in vitro and not on actual patient data. However, the main problem with actual patient data is that a gold standard reference that provides the true condition, cannot be obtained. Thus, in vitro testing is so far the only way to test the validity of the technique. As discussed previously, we expect that the proposed technique will perform satisfactorily on actual patient data. Another limitation of the technique is that it may not be suitable for teeth that underwent morphological alterations over time, in parts of the crown other than the occlusal surface, which are used as superimposition references. Such circumstances could occur due to erosion, restorations, decay, or fixed retainer placement at the tested teeth. We suggest that during the superimposition process, the operator should assess this by testing the overlap of the superimposition reference areas through visualization of relevant color coded distance maps. In cases such as the one mentioned above, the registration of the subsequent models might not be optimal, and thus, the outcome might not be accurate. Future studies are needed to test the performance of the suggested technique in presence of such conditions.

Conclusion

Utilizing 3D dental model surface data and standard 3D surface-based superimposition techniques we developed and tested here an efficient approach for in vivo occlusal tooth wear assessment, which can be easily implemented both for clinical and research purposes, using data obtained from high-performance intraoral scanners.

The study tested various superimposition reference areas and software settings and confirmed that these factors significantly affect the wear outcome.

According to our findings, the complete tooth crown should be selected as superimposition reference, using certain settings on a specific commercial software. The method is straightforward, easy to use and it shows increased

accuracy when used on teeth that are not expected to undergo significant morphological alterations in parts other than the occlusal surface.

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Competing interests

Author D. Halazonetis owns stock in dHAL Software, the company that markets Viewbox 4. Authors N. Gkantidis, K. Dritsas, Y. Ren, and C. Katsaros declare no competing interests.

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Supplementary material

Supplementary Table S1. Detailed report of the used dental models and teeth to simulate tooth wear.

Model No	Jaw	Aligned dental arches	Worn teeth				
			Tooth number (Wear amount in mm)				
1	Maxilla	No	15 (0.5)	13 (1)	11 (1)	24 (2)	26 (1)
2	Maxilla	No	16 (2)	13 (0.5)	11 (0.5)	22 (1)	26 (0.5)
3	Maxilla	No	15 (1)	13 (2)	22 (2)	24 (0.5)	
4	Maxilla	No	16 (1)	14 (2)	12 (1)	23 (1)	
5	Maxilla	Yes	16 (0.5)	12 (0.5)	21 (1)	23 (0.5)	25 (0.5)
6	Maxilla	Yes	14 (1)	11 (2)	22 (0.5)	24 (2)	
7	Maxilla	Yes	16 (2)	14 (0.5)	12 (2)	21 (0.5)	23 (2)
8	Maxilla	Yes	16 (1)	21 (2)	24 (1)	26 (2)	
9	Mandible	No	46 (0.5)	43 (1)	33 (0.5)	35 (2)	
10	Mandible	No	46 (2)	43 (0.5)	41 (2)	33 (1)	36 (1)
11	Mandible	No	46 (1)	44 (2)	42 (1)	33 (2)	36 (0.5)
12	Mandible	No	45 (1)	43 (2)	31 (0.5)	33 (1)	36 (2)
13	Mandible	Yes	45 (0.5)	43 (1)	34 (2)	36 (1)	
14	Mandible	Yes	46 (0.5)	42 (0.5)	33 (0.5)	35 (0.5)	
15	Mandible	Yes	46 (2)	43 (0.5)	41 (1)	33 (2)	35 (1)
16	Mandible	Yes	45 (1)	43 (2)	31 (2)	36 (0.5)

Supplementary Figure S1. Examples of teeth before (left) and after (middle) simulated tooth wear and colour coded distance maps (right) showing the missing tooth structure in each case. The colour maps were constructed following the superimposition of each before and after tooth wear condition, with the gold standard reference method used in the study. (A, B) Upper incisors. (C) Mandibular molar. (D) Maxillary molar. (E, F) Mandibular incisors. (G) Maxillary canine. (H) Mandibular canine. (I) Maxillary premolar. (J) Mandibular premolar. All images were generated using Viewbox 4 software (version 4.1.0.1 BETA, <http://www.dhal.com/viewboxindex.htm>).

Supplementary Figure S2. Box plots showing in the y-axis tooth wear measurements by tooth type, measured with the gold standard technique. Colours show the planned vertical height reduction of the tooth cusps. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value. Note the consistent pattern of the measured tooth wear in each tooth type, according to the study setting.

Supplementary Figure S3. Superimposed models before (red) and after (yellow) tooth wear using tooth 14 as superimposition reference. (A) Gold standard superimposition technique. Note the even distribution of the two colours in the whole surface suggesting the optimal registration of the two models in all areas. (B) Complete crown, setting D superimposition technique. Note that for tooth 14, which was used as reference, the overlap of the two models is satisfactory, but in other areas of the models the registration is inferior to that obtained with the gold standard technique. All images were generated using Viewbox 4 software (version 4.1.0.1 BETA, <http://www.dhal.com/viewboxindex.htm>).

Supplementary Figure S4. Box plots showing in the y-axis the difference of the technique of choice (complete crown, setting D) from the gold standard technique in tooth wear measurements (A) by tooth type and (B) by amount of tooth wear. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value (trueness). Zero value indicates perfect agreement with the gold standard. The vertical length of each plot indicates precision.

Chapter 3

3D occlusal tooth wear assessment in presence of limited changes in non-occlusal surfaces

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Abstract

The study aimed to develop an accurate and convenient 3D occlusal tooth wear assessment technique, applicable when surfaces other than the occlusal undergo changes during the observation period. Various degrees of occlusal tooth wear were simulated in vitro on 18 molar and 18 premolar plaster teeth. Additionally, their buccal and lingual surfaces were gently grinded to induce superficial changes and digital dental models were generated. The grinded and the original tooth crowns were superimposed using six different 3D techniques (two reference areas with varying settings; gold standard: GS). Superimposition on intact structures provided the GS measurements. Tooth wear volume comprised the primary outcome measure. All techniques differed significantly to each other in their accuracy ($p < 0.001$). The technique of choice (CCD: complete crown with 30% estimated overlap of meshes) showed excellent agreement with the GS technique (median difference: 0.045, max: 0.219 mm³), no systematic error and sufficient reproducibility (max difference < 0.040 mm³). Tooth type, tooth alignment in the dental arches, and amount of tooth wear did not significantly affect the results of the CCD technique ($p > 0.01$). The suggested occlusal tooth wear assessment technique is straightforward and offers accurate outcomes when limited morphological changes occur on surfaces other than the occlusal.

Introduction

Tooth wear is the loss of tooth structure that occurs during time; it has very high occurrence in the population. It is of multifactorial etiology and it can be a result of normal function, parafunction, or of environmental factors, such as highly acidic food. Apart from dental esthetic impairment, excessive tooth wear may even alter facial morphology or speech, negatively impacting quality of life. In contemporary societies, tooth wear is considered an important problem since the increased human life span and patient demands led to the need for presence of natural teeth in the dentition for several decades [1]. Progress in dental sciences has facilitated this purpose and also offered various opportunities for prevention, as well as restoration, of tooth wear [2,3].

Proper and timely diagnosis, through accurate monitoring of tooth wear progression and treatment outcome assessment, is the first step for successful tooth wear management [2,4]. Therefore, several previous studies have addressed this issue and suggested various qualitative and quantitative approaches to assess tooth wear. The qualitative approaches, such as the Eccles index, the Tooth Wear Index, the Lussi index, or the Basic Erosive Wear Examination, are commonly used, since they are relatively simple, they do not require special equipment, and thus, they can be easily incorporated in large-scale studies or used for clinical screening. However, apart from the specific strengths and limitations of each individual index, the main shortcoming of qualitative approaches is the reduced accuracy, including reproducibility [5,6]. On the other hand, there are highly reproducible quantitative techniques, such as digital profilometry and 3D surface matching techniques, but their trueness was, in most cases, not assessed due to the absence of a gold standard reference (true value) [7]. Furthermore, certain methods are too complicated to be applied in clinical practice, because they require special equipment, as well as impression taking and construction of physical models. This increases costs and sources of error and reduces the applicability of these methods [7–9]. For any quantitative method that uses digital models at any stage, advances in imaging techniques over time facilitate its applicability through the enhancement of accuracy and the reduction of costs.

In previous studies, we suggested accurate 3D superimposition methods to assess tooth wear on intraorally obtained serial digital dental models, using techniques applicable under various clinical conditions [10,11]. Due to the rapid incorporation of intraoral scanners in contemporary dentistry [12,13], these approaches can be easily applied in clinical settings, through the use of relevant software. One previous study tested wear assessment in teeth where all crown surfaces, apart from the worn occlusal aspects, remained intact over time [10]. Another previous study tested the scenario of extensive changes over time, on non-occlusal surfaces, additionally to the occlusal tooth wear. Such changes were simulated by the placement of a wire retainer on the lingual aspects of the tested teeth [11]. However, these conditions do not cover the whole spectrum of possible clinical occurrences. Tooth crown morphology might also be subjected to limited changes in non-occlusal surfaces, by dental caries, fillings, tooth wear, or other factors [14–16]. Such conditions may complicate the superimposition procedure and affect the outcomes. Thus, in the present study, the in vitro methodology that was previously developed, validated and applied to assess tooth wear under different clinical scenarios [10,11], was used to define a 3D superimposition method that can accurately measure occlusal tooth wear on teeth that undergo limited changes in non-occlusal crown surfaces, additional to the occlusal wear.

Materials and Methods

Sample

The study sample comprised 16 dental plaster models (type IV plaster, white color, Fujirock EP Premium, GC, Leuven, Belgium) depicting dental arches of both jaws, with varying alignment status. More specifically, eight models with crowding ≤ 1 mm (four maxillary and four mandibular) and an additional eight models with crowding ranging from 4 to 10 mm (four maxillary and four mandibular) were retrieved from the archive of the Department of Orthodontics and Dentofacial Orthopedics, University of Bern, Switzerland. The eligibility criteria included the presence of all permanent teeth till the second molars and no extreme morphological variation, assessed through visual inspection. More details on sample composition and characteristics were reported previously [10].

Tooth Wear Simulation

According to a modified previously published protocol [10,11], 18 premolars and 18 molars, equally distributed among the dental models, comprised the testing material. On these, various degrees of tooth wear, in terms of vertical reduction (approximately 0.5, 1, and 2 mm), were simulated through manual grinding of the occlusal tooth surfaces [10,11]. Additionally, a small amount of buccal and lingual surface wear was generated by removing a slight layer of these tooth surfaces from the posterior test teeth. This was performed through a slight touch with a laboratory straight handpiece. The removed substance from each tooth surface had a maximum extent of 3 to 5 mm and a vertical depth of approximately 100–250 µm (Supplementary Figure S1). Two intact teeth, bilaterally distributed besides each grinded tooth, along with additional unaltered adjacent anatomical structures, comprised the superimposition reference areas to obtain the gold standard (true) value. These areas were identical in the before and after tooth wear simulation models, and thus, a perfect registration of the two models was possible, allowing for the determination of the true amount of occlusal tooth wear [10,11,13,17].

3D Model Acquisition

A reliable 3D surface scanner (accuracy < 20 µm; Laboratory scanner D104a, Cendres+Métaux SA, Biel/Bienne, Switzerland) was used to scan the dental casts prior (To) and following the tooth wear simulation process (T1). Each entire dental model consisted of 600.000–900.000 triangles, with a premolar clinical crown consisting of approximately 17.000 triangles. Subsequently, the digitized 3D Standard Tessellation Language (STL) models were imported for further processing and analysis in Viewbox 4 software (version 4.1.0.1 BETA, dHAL Software, Kifissia, Greece, <http://www.dhal.com/download.htm>, accessed on 15 March 2021).

Tooth Wear Measurement

To assess the volume of occlusal tooth wear, the grinded tooth crowns (T1) were selected through manual segmentation and were compared with the original crowns (To). This process was performed applying the gold standard and five test techniques.

To obtain the gold standard (true) measurements (GS), the segmented To and T1 crown models were superimposed on the intact adjacent teeth and alveolar processes (Figure 1a). Thus, the perfect congruence of the two models in these areas after the application of the best-fit algorithm, ensured the accurate 3D occlusal tooth wear assessment [10,11,13,17].

Figure 1. Superimposition reference areas for tooth wear assessment at a maxillary first permanent molar. **(a)** Gold standard area (GS, blue). **(b)** Partial crown area (PC, green). **(c)** Complete crown area (CC, orange). Buccal aspects are shown at the upper row and palatal aspects at the lower row.

Parts of the buccal and palatal To tooth crown surfaces were used as superimposition references for the first group of measurements (PC: partial crown) (Figure 1b). The buccal and lingual surfaces were used, irrespective of buccolingual wear for two reasons. First, to simulate real life conditions, where buccolingual tooth wear is usually undetectable with natural vision. Secondly, in cases where an extended buccal or lingual surface area would have been affected, there would be no other alternative. The second group of measurements was performed using the whole To clinical crown as superimposition reference (CC: complete crown; Figure 1c).

Corresponding To and T1 3D models were superimposed on each reference area using different settings of an iterative closest point algorithm (ICP) [18]. A manual approximation of the two objects always preceded the automatic algorithm application, to facilitate the process. Each registration was performed, always starting from the original initial position. For each superimposition session, the registration process was applied repeatedly (usually four to five times), until the minimum possible distance between the superimposed models was reached.

Firstly, the outcomes of four different ICP settings were assessed. Setting (A) consisted of 100% estimated overlap of meshes, exclude overhangs, matching point to plane, exact nearest neighbor search, 100% point sampling, and 50 iterations. Setting (B) was defined at 80% estimated overlap of meshes, with all other parameters set as in setting (A). In setting (C), the operator defined freely, for each individual measurement, the estimated overlap of meshes, in an iteratively improved superimposition process regarding the superimposed teeth and the adjacent intact structures. All other parameters were set as in (A). The value used for each case to provide the best possible overlap, was noted in an Excel sheet (Microsoft Excel, Microsoft ©, Richmond, WA, USA). A fourth setting (D), which was otherwise same as (A), was defined in 30% estimated overlap of meshes, based on the average of these values (average: 34.0, SD: 9.3, range: 15–50% estimated overlap of meshes). The specific value was chosen because further assessment of individual cases showed that the lower values provided satisfactory results in all cases and approximated better the gold standard measurements than the higher values [10,11]. Table 1 provides an overview of all techniques assessed in this study (combinations of ICP settings and reference areas).

Table 1. Superimposition techniques tested in the study.

Technique	Reference Area	Estimated Overlap
GS	Adjacent intact teeth and alveolar processes	100%
PC(A)	Buccolingual surfaces	100%
PC(C)	Buccolingual surfaces	User defined
CC(B)	Complete crown	80%
CC(C)	Complete crown	User defined
CC(D)	Complete crown	30%

Based on a previously published protocol [10,11], after each superimposition, the acquired To/T1 3D tooth crown models were simultaneously sliced using one (gingival) to three slicing planes (gingival, mesial, and distal). The number of the required planes was defined by the need to slice each crown through straight lines, without leaving any uneven margins on the sliced surface model. In advance of the slicing, the planes were

positioned with the help of a color map in such way that the occlusal tooth wear surface was included, but the buccolingual tooth wear surfaces were excluded or kept to a minimum. Afterwards, a specific hole filling process was applied on both T0 and T1 occlusal tooth parts, aiming to fill them identically (Figure 2). Certain cases required more than one slicing plane, to ensure identical filling of both models. There, the contralateral points of sharp edges had to be connected, to split the hole of each crown model resulting from slicing. Consequently, the edges of each pair of T0/T1 holes lied on a single plane, allowing for a unique hole closure each time (irrespective of the software's algorithm), through a flat surface. Thus, the subsequent T0 and T1 watertight 3D models of the superimposed teeth differed only occlusally, being otherwise identical (Figure 3). The volumetric difference of the resulting two models provided the occlusal wear amount of each tooth.

Figure 2. Workflow of tooth wear assessment in a mandibular first molar. **(a)** Tooth crown before (yellow) and after (green) wear simulation at the occlusal and the buccolingual surfaces. **(b)** Tooth crowns superimposed through the complete crown technique with setting D (30% estimated overlap). **(c)** Tooth wear from the buccal (left) and the lingual (right) aspect shown using a color coded distance map. **(d)** Simultaneous slicing of the two crowns using one level (grey). **(e)** Sliced tooth crown parts. **(f)** Watertight models created after the hole-filling process, used to calculate volumes.

Figure 3. Workflow of tooth wear assessment in a maxillary first premolar. **(a)** Tooth crown before (yellow) and after (green) wear simulation. **(b)** Tooth crowns superimposed through the complete crown technique with setting D (30% estimated overlap). **(c)** Color coded distance map showing the tooth wear from the buccal (left) and the lingual (right) side. **(d)** Two levels (grey) used to simultaneously slice the two crowns. **(e)** Sliced tooth crowns with connected contralateral points (blue) in sharp edges (red line), splitting the hole in two parts to ensure identical hole-filling process. **(f)** Holes filled to create watertight models and, thus, calculate volumes.

The tooth wear amount detected through the gold standard technique (volume loss of tooth structure in mm^3) was then compared to that of the test techniques.

A thorough assessment of intra-and inter-operator of similar techniques were published previously [10]. Here, we tested the intra-operator error of the gold standard technique and the technique of choice by repeating the whole process for 10 randomly selected teeth, 1-month after the first set of measurements.

Statistical Analysis

The present statistical approach, performed using IBM SPSS statistics for Windows (Version 25.0, IBM Corp, Armonk, NY, USA), is identical to a previously published by our group in a similar study [10]. Certain deviations from normality (Kolmogorov–Smirnov and Shapiro–Wilk tests) designated the use of non-parametric statistics.

Box plots were used to show the agreement of different techniques with the gold standard technique (trueness) in tooth wear measurement. Any deviation from zero indicates reduced trueness. For each technique, individual

value variation from the median indicates precision. Friedman's test was used to test differences in trueness and precision among different techniques. This was followed by Wilcoxon's signed rank test for pairwise comparisons, when significant results were evident.

Within each technique, visual inspection of relevant plots and unpaired comparative tests were performed to assess potential effects of crowding status, tooth type, or tooth wear amount on trueness and precision.

Bland Altman plots of tooth wear measurements were created to assess intra-operator error. Deviations from zero indicate reduced precision. The Mann–Whitney U test was applied to assess differences in the reproducibility between techniques.

In all cases, a two-sided significance test was carried out at an alpha level of 0.05. In case of multiple comparisons, a Bonferroni adjustment was applied to the level of significance to reduce the probability of false positive results.

Results

There was no systematic error between the repeated measurements performed through the gold standard technique and the CC(D) technique of choice (one sample t-test, $p > 0.05$). Tooth type or amount of tooth wear did not seem to affect reproducibility. The gold standard measurement and technique CC(D) showed sufficient and comparable reproducibility, overall ($p > 0.05$) and in individual measurements (max difference $< 0.040 \text{ mm}^3$) (Supplementary Figure S2).

All tested techniques differed significantly to each other in their trueness, except for PC(C) with all CC techniques (Friedman test: $p < 0.001$; Wilcoxon signed rank test: $p < 0.001$; Figure 4). There were differences in precision among techniques (Figure 4). The CC(D) technique provided accurate tooth wear assessment, since it consistently showed excellent agreement with the GS technique (median difference: 0.045 , max: 0.219 mm^3).

Figure 4. Difference of each technique from the gold standard technique in tooth wear assessment shown in box plots (y -axis, mm^3). The upper limit of the black line represents the maximum value, the lower limit the minimum, the box the interquartile range, and the horizontal black line the median value (trueness). Outliers are shown as black circles (°) or asterisks (*), in more extreme cases, with a step of $1.5 \times \text{IQR}$ (interquartile range). Zero value (dashed horizontal line) indicates perfect agreement with the gold standard. Precision is indicated by the vertical length of each plot. The blue box on the right image indicates the area of the graph shown in the left image in a larger scale.

Tooth type affected the trueness and precision only of CC(B) technique (Mann–Whitney U test, $p < 0.01$), with molars showing slightly higher differences to the GS measurements (Figure 5a). Tooth alignment in the dental arches affected only the results of the PC(C) technique (Mann–Whitney U test: $p < 0.01$). Tooth wear amount affected significantly only the results of the CC(B) and CC(C) techniques (Kruskal–Wallis test, $p < 0.01$; Figure 5b), with differences from the GS measurements increased with increasing tooth wear amount.

Figure 5. Difference of each technique with the gold standard technique in tooth wear measurements, (a) by tooth type, and (b) by amount of tooth wear, shown in box plots. The upper limit of the black line represents the maximum value, the lower limit the minimum, the box the interquartile range, and the horizontal black line the median value (trueness). Outliers are shown as black circles (°) or asterisks (*), in more extreme cases, with a step of $1.5 \times \text{IQR}$ (interquartile range). Zero value (dashed horizontal line) indicates perfect agreement with the gold standard. The vertical length of each plot indicates precision.

The technique of choice CC(D) did not differ considerably from the GS technique for any tooth type or wear amount (Supplementary Figure S3). There was a tendency for lower trueness and precision for molars (Mann–Whitney U test, $p = 0.088$) or with increasing amount of tooth wear (Kruskal–Wallis test, $p = 0.062$), but the differences were not statistically significant.

Discussion

The present study validated a 3D superimposition method for occlusal tooth wear assessment on teeth that undergo limited additional changes in non-occlusal surfaces. The method was previously developed to visualize and quantify occlusal tooth wear on teeth that remain intact in all surfaces, apart from the occlusal [10]. Several modifications in the superimposition reference areas and settings were tested, but the previously defined approach [10] provided the most favorable outcomes, also in the newly tested clinical scenario. Thus, the applicability of the existing highly accurate technique in cases of intact non-occlusal surfaces [10] is expanded to cases that undergo limited additional changes in non-occlusal surfaces. The technique is applicable under regular clinical conditions, since it uses mainstream software

applications and 3D digital dental models, which can be easily obtained through intraoral scans [13]. Furthermore, it requires the existence of two intraoral models, obtained at different time points, to monitor tooth or material wear that occurred during this time. For this reason and due to the very high occurrence of tooth wear in the population [19–21], it is recommended that a dental scan should be obtained, if possible, in all patients, at the early permanent dentition. This scan, can then be superimposed to scans obtained at later stages. Similarly, immediately after placement of any restoration that needs to be monitored, an intraoral dental model should be obtained. The time span between consecutive diagnostic scans should be defined by the dentist on an individual basis, depending on the needs and the risk factors of each case. Conventional impressions and subsequent stone models can be scanned afterwards, and might also serve this purpose, but apart from material costs and storage needs, they can also be subjected to dimensional changes over time [22].

In a previous report [10], we validated this method for teeth that were not affected in any other surface than the occlusal. However, alterations of the buccal or palatal tooth surfaces can also occur during function. These can be due to bacteria, erosion, or dental interventions, including fillings, tooth whitening, or removal of orthodontic bracket bonding agents. Additionally, the scanner error itself can be a source of such morphological differences [13,17]. A recent study on surface-based 3D superimposition in palatal areas [17] showed that even small artifacts might significantly affect superimposition outcomes. Thus, our previously suggested technique might have not been suitable for teeth subjected to slight morphological changes in non-occlusal surfaces. Following thorough testing of various modifications, it became evident that the previous technique [10] also performed favorably in these cases. Thus, this technique is suitable for occlusal wear assessment in cases that have either no or limited changes in non-occlusal surfaces. Providing that serial crowns are adequately and similarly superimposed in both the above mentioned cases, we also suggest the technique as suitable to assess buccal or lingual tooth wear, at least of a similar amount and pattern to that tested here. In individual patients, such occurrences can be verified following visualization of color coded distance maps of superimposed crowns. Lack of congruence of the two models indicates worn

surfaces. It should be noted here that, according to another previous study by our group, certain modifications of the applied 3D superimposition settings should be made in case of extensive changes on non-occlusal tooth surfaces, additional to occlusal wear [11].

The accuracy of the superimposed tooth surface models directly affects the trueness of the wear assessment. Previous studies have shown that the accuracy of an intraoral scan is affected by several factors, such as the scanner, the type, extent, and irregularity of the scanned surface, the software used to process the images and create the final 3D model, and others [13,23–25]. The dental surface models of the present study were acquired using a high accuracy laboratory scanner. With this scanner, the distance between superimposed corresponding surfaces, obtained from repeatedly scanned single jaw models, is consistently smaller than 5 μm [11]. For small structures, such as single natural teeth, this scanner is comparable to the current high-end intraoral scanners [13]. Thus, the clinical applicability of the suggested technique, which is applied in individual tooth crown models, is not questioned for natural teeth. However, in cases of restored teeth, the tooth model to be superimposed might show reduced trueness. In such cases, if the model error is comparable to the simulated buccolingual surface wear in this study, the accuracy of the suggested method is expected to be similar to that detected here. In contrast, in cases of larger error, the superimposition outcomes might be affected considerably. The laboratory scanner was used to assure negligible effects of scanner inaccuracy on the gold standard outcome, obtained using a more extended superimposition reference area. According to the study design, this area was not changed during tooth wear simulation, and thus, identical surfaces were available in both pre- and post-wear models. These identical surfaces were perfectly superimposed, and thus, revealed the true crown morphology changes due to tooth wear. This is only feasible under the present experimental conditions, but it provides the true wear values to be compared with those of the single crown techniques that were tested here and are clinically feasible. The matching software used in the present study shows a difference smaller than 0.001 μm between identical duplicates of a surface model, superimposed with the methodology used here [11].

In actual clinical conditions, the gingival margin area may also change over time [15], leading to differences in the adjacent clinical crown surfaces, captured by the scanner each time. This does not affect the performance of the technique if, as suggested, the “exclude overhangs” option is selected. With the proposed settings, the software ignores any surfaces that exceed the outer limits of one surface model over the other, when applying the best fit algorithm. This issue was extensively tested previously, by selecting small reference areas only in one model and superimposing them to much larger models, and it always worked properly [10,11,13,17,26–28]. Therefore, it is suggested that, in actual clinical data with large differences in clinical crown sizes over time, the smaller clinical crown should be selected as a superimposition reference. Depending on the time between subsequent models and on individual case characteristics, this might be the initial model, in cases of severe gingival recession development, or the final model, in cases of severe tooth wear.

Apart from proper registration, accurate volume measurements presuppose proper hole filling of the crown parts that are compared. The hole filling process used to create watertight models—a prerequisite for volume measurement—was tested previously [10] and consistently provided identical volumes. The level of crown slicing is also important considering the reproducibility of the measurements, which proved to be high in our study. However, the slicing process does not affect the accuracy of the technique, since following a valid superimposition of serial tooth crown models, the operator can define the type of measurement (point/area distance or volume) and the area where differences need to be measured. A problem might arise in studies including patients with extensive tooth wear in multiple surfaces. In this case, the consistent selection of an anatomically defined area of interest or the consistent slicing at the same anatomical level among various individuals, in order to obtain comparable measurements, might be more challenging.

Tooth wear simulation was performed at three different levels, representing approximately 0.5 to 2 mm vertical loss. This approach aimed to test varying degrees of wear severity, in the presence of clinically significant tooth structure loss. The high performance of the technique was consistent, independent of the different tooth wear amounts or tooth types tested. This was

also evident in previous studies [10,11]. Smaller amounts of occlusal tooth wear were not simulated here, though they might be present in actual patients. We decided to test this range, since the performance of the ICP algorithm would be equally good, if not better, with smaller alterations than the one tested here (Supplementary Figure S3B) [11]. It is important to note that the suggested technique also performs perfectly in cases where the serial tooth crown models are identical (Supplementary Figure S4) [13,17,26]. Existing clinical studies, as well as clinical experience, suggest that, taken together, the above scenarios might cover the majority of cases to be managed in a conventional dental practice [29,30]. Although quantitative data regarding the prevalence, type, and amount of wear in buccal and lingual tooth surfaces are scarce, the same seems to apply for the limited buccal and lingual surface changes simulated in this study [14].

So far, several methods were suggested in the literature for tooth wear monitoring [7,31–33]. Qualitative methods usually suffer from reduced precision. On the other hand, the main shortcoming of most previous quantitative methods is that they were not tested against a true measurement [7,34]. Most previous studies focused on reproducibility and some based their assessments only on differences between group means. The assessment of differences in means is inadequate when testing the performance of methods that should work properly in every single case [35]. Furthermore, reproducibility, even if it is high, does not guarantee the trueness of a measurement. In agreement with previous studies [10,11,17], the superimposition of serial models on intact structures accomplished perfect registration in the present study, and thus, provided the true measurement. This would not be possible in an *in vivo* design, where no neighboring structure could be considered intact. Thus, through this design, we developed a clinically applicable superimposition technique that can provide a measurement quite similar to the true. Furthermore, differences were assessed between group means, but also for individual cases, testing both precision and trueness.

There are certain quantitative techniques with comparable accuracy to that of the present method, but they require complex, expensive equipment, and expertise to be properly applied [7]. This limits the applicability of these

techniques. On the contrary, we present a technique that can be incorporated in everyday clinical practice, provided that specific software is available and short training is performed. Following this, the application of the method to measure the wear of one tooth requires approximately 2–3 min. In case of time limitations, such as in large-scale studies or in a busy practice, the use of index teeth might be a viable solution, as suggested recently [30]. Furthermore, most previous techniques assessed vertical loss of tooth structure [7]. However, this information is quite limited compared to the assessment of tooth loss in the original whole crown 3D space. With the suggested method, results can be visualized through color-coded distance maps and quantified as desired by the operator. For example, the vertical loss at any point, the mean vertical loss of a selected surface area, or any volume loss can be easily measured, following proper registration of two or more serial tooth models. A freeware and easy to use software (Wear Compare; leeds-digitaldentistry.com; accessed on 22 March 2021) [36] for serial tooth surface model superimpositions to assess occlusal tooth wear was also recently suggested. This performed perfectly when duplicated surfaces were superimposed, but relatively large errors became evident when the original position of the duplicated models changed or when actual patient data were considered [36]. Furthermore, its robustness in the presence of changes in non-occlusal surfaces that are used as superimposition references has not been tested yet against a gold standard. A recent study testing the agreement of this method to a qualitative one (BEWE index) reported limited sensitivity and specificity [37]. Nevertheless, the latter finding should be interpreted with caution, since the qualitative approaches do not allow for an accurate wear quantification [5,6,38]. Thus, their use as a reference to test highly accurate methods, as the one reported here, might not be appropriate.

The present study implemented an in vitro design, which allowed the acquisition of the gold standard measurement (true value) to be compared with the outcomes of other clinically applicable methods. Currently, there is no reliable way to obtain the true wear value using intraoral scanners in vivo. Although this might be a limitation of the study, for reasons discussed in detail in the manuscript and are based on current evidence, we believe that the present design allows for direct transfer of our findings to actual conditions.

The study focused on posterior teeth since these are round-shaped and this might restrain the performance of the best-fit algorithm [10], in contrast to the more rectangular anterior teeth. The performance of similar techniques on anterior teeth was thoroughly tested previously and proved highly reproducible [10,11,13,17,26]. Thus, if the present method is valid for posterior teeth, it is expected to work equally good, if not better, in the anterior dentition [10,11,17,26]. Reproducibility was tested for the gold standard and the technique of choice. The other techniques were not tested, since they showed reduced trueness. Thus, even if they were highly reproducible [10], this does not assure that they would provide valid assessments. Furthermore, the reproducibility of similar techniques was thoroughly tested previously and consistently provided satisfactory results [13,17,26]. Finally, this study tested the performance of 3D superimposition techniques to assess occlusal tooth wear in presence of limited changes in non-occlusal surfaces. When larger changes occur, such as when a bonded wire retainer is placed during the assessment period [16] or when severe tooth wear occurs in the buccal or lingual tooth surface [14,21], specific modifications should be applied [11].

Conclusions

The present in vitro study tested the trueness and precision of various tooth crown superimposition techniques, used to assess occlusal wear in presence of limited morphological changes on non-occlusal surfaces. The results indicate that the high performance of a previously suggested technique, for teeth with isolated occlusal surface changes, is also robust in this case. Furthermore, the technique is also suitable to assess non-occlusal wear, at least of limited extent.

The present technique offers a highly accurate 3D tooth wear assessment and can be applicable in a clinical environment, provided that easily acquired skills and usually already available equipment is required.

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Conflicts of Interest

Author D.H. owns stock in dHAL Software, the company that markets Viewbox 4. Authors N.G., K.D., C.K., and Y.R. declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Supplementary material

Supplementary Figure S1. Color coded distance maps showing the buccal and lingual aspects of superimposed tooth crowns, prior and after tooth wear simulation, using the gold standard technique. Patterns of tooth wear simulation are shown from the buccal (left) and the lingual (right) aspects of: **(a, b)** two maxillary molars, **(c)** one mandibular molar, **(d, e)** two maxillary premolars, and **(f)** one mandibular premolar. The teeth shown were randomly selected from the total sample.

Supplementary Figure S2. Intra-operator error on tooth wear measurement (mm³) assessed through Bland Altman plots. **(a)** Gold standard (GS) technique. **(b)** Technique of choice (complete crown with 30% estimated overlap). The true range of measured tooth wear values is represented in the axes length. The continuous horizontal line shows the mean and the dashed lines the 95% confidence intervals.

Supplementary Figure S3. Difference in tooth wear measurement between the technique of choice (complete crown, setting D) and the gold standard technique by **(a)** tooth type and **(b)** tooth wear amount. In the box plots, the upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value (trueness). Perfect agreement with the gold standard is indicated by zero value (horizontal dashed line). The vertical length of each plot indicates precision.

Supplementary Figure S4. Superimposition of identical surface models of a maxillary molar (left) and a maxillary premolar (right). **(a)** Original tooth (yellow) and duplicate (red). **(b)** Superimposed tooth crowns using the complete crown technique and setting D (30% estimated overlap) shown from the buccal aspect. **(c)** Color coded distance maps of the superimposed crowns, shown from the buccal (above) and the palatal (below) aspect.

Chapter 4

3D method for occlusal tooth wear assessment in presence of substantial changes on other tooth surfaces

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Abstract

Early diagnosis and timely management of tooth or dental material wear is imperative to avoid extensive restorations. Previous studies suggested different methods for tooth wear assessment, but no study has developed a three-dimensional (3D) superimposition technique applicable in cases where tooth surfaces, other than the occlusal, undergo extensive morphological changes. Here, we manually grinded plaster incisors and canines to simulate occlusal tooth wear of varying severity in teeth that received a wire retainer bonded on their lingual surfaces, during the assessment period. The corresponding dental casts were scanned using a surface scanner. The modified tooth crowns were best-fit approximated to the original crowns using seven 3D superimposition techniques (two reference areas with varying settings) and the gold standard technique (GS: intact adjacent teeth and alveolar processes as superimposition reference), which provided the true value. Only a specific technique (complete crown with 20% estimated overlap of meshes), which is applicable in actual clinical data, showed perfect agreement with the GS technique in all cases (median difference: -0.002, max absolute difference: 0.178 mm³). The outcomes of the suggested and the GS technique were highly reproducible (max difference < 0.040 mm³). The presented technique offers low cost, convenient, accurate, and risk-free tooth wear assessment.

Introduction

Tooth wear characterizes the superficial loss of tooth matter over time. In humans, tooth wear occurs as a consequence of normal function, parafunction, or environmental factors, such as very acidic food. The main issue of concern, when excessive tooth wear occurs, is impaired dental esthetics. However, it may also affect facial morphology and speech, impacting patients' quality of life. In recent years, the need for retaining natural teeth intact for several decades has arisen due to the increase in life expectancy. This, along with increased patient esthetic demands has designated tooth wear as an important problem that needs to be addressed [1]. Advances in the dental field, including tooth wear management, enabled teeth maintenance till late stages of life [2].

Early diagnosis is imperative for the timely management of tooth wear, to avoid subsequent problems and extensive restorations [2,3]. To facilitate tooth wear assessment, several previous studies have suggested a variety of qualitative and quantitative methods. Qualitative approaches are subjective and usually suffer from reduced precision and reproducibility [4–6]. On the contrary, certain quantitative techniques have shown adequate reproducibility, usually within the range of 15–20 μm , concerning vertical loss of tooth structure. However, the trueness of these techniques remains questionable, since studies lack a gold standard reference for comparison [7]. Other shortcomings include the high complexity of these techniques that need special equipment and expertise to be applied properly, as well as the dental impressions and physical models required. The above increase the costs, the inaccuracies, and the applicability of the techniques in actual clinical conditions [7–9].

A highly accurate three-dimensional (3D) superimposition technique has been suggested recently for occlusal tooth wear assessment using serial digital dental models [10]. Assuming that relevant software and hardware is accessible, which is realistic for a contemporary practice, this technique is applicable under regular clinical conditions. The existence of a previous dental model, obtained at a certain point in the past, is a prerequisite to apply this technique. The rapid incorporation of intraoral scanners in contemporary dentistry [11] and the use of relevant software for various applications facilitates

this purpose. The aforementioned previous study [10] focused on occlusal tooth wear assessment in cases that only the occlusal tooth surfaces were subjected to changes over time, offering an accuracy of 0.033 mm³, which corresponds to approximately 9 µm of vertical tooth loss [10]. This accuracy level is much higher than any level that might be considered clinically significant. However, other tooth surfaces might also be affected by function, pathology, or due to iatrogenic interventions [12–14]. This might complicate occlusal tooth wear assessment through serial 3D surface model superimpositions. To our knowledge, there is no study in the literature that has addressed this issue. A common instance where tooth surfaces, other than the occlusal, undergo extensive morphological changes regards the placement of bonded wire retainers. Such retainers might be bonded following orthodontic treatment, to stabilize teeth after trauma, or in periodontally compromised patients [14–17]. Thus, the purpose of the present study was to develop and validate a 3D occlusal tooth wear assessment technique, applicable when the anterior teeth crown morphology is highly altered during the testing period, in non-occlusal surfaces.

Experimental Section

Ethical Approval

The research project is registered and approved by the Swiss Ethical Committee of the Canton of Bern (Protocol No. 2019-00326). All experiments were performed under the relevant regulations and according to the pre-specified protocol. All participants signed an informed consent prior to the use of their data in the study.

Sample

The present sample was derived from an existing material, which was previously generated and thoroughly described [10]. In this study, sixteen dental plaster models (type IV plaster, white color, Fujirock EP Premium, GC, Leuven, Belgium) with (n = 8; 4 maxillary and 4 mandibular; crowding ≤ 1 mm) and without (n = 8; 4 maxillary and 4 mandibular; crowding: 4–10 mm) well aligned dental arches were used. These were retrieved from the archive of the Department of Orthodontics and Dentofacial Orthopedics, University of Bern, Switzerland. The models represented individuals with natural permanent

dentition and no extreme morphological variation in oral structures (visual inspection).

Tooth Wear Simulation

According to a pre-specified and previously validated protocol, eighteen canines and eighteen incisors, equally distributed among the dental models described above, were manually grinded to simulate occlusal tooth wear of varying severity (approximately 0.5, 1, and 2 mm of vertical loss, respectively) [10]. Grinding was performed both symmetrically and asymmetrically, using a dental laboratory straight handpiece or a dental laboratory stone knife, to simulate a variety of normal tooth wear patterns. Additionally, for the needs of the present study, a fixed retainer that is usually bonded following orthodontic treatment or to stabilize highly mobile teeth following trauma or severe periodontally compromised teeth, was simulated in the anterior teeth. For this, a twisted white coated ligature wire (0.3 mm initial diameter, Dentaureum, Ispringen, Germany) was placed on the middle of the lingual surfaces of the test anterior teeth. A white modeling compound (Play-Doh putty, Hasbro, Pawtucket, RI, USA) was used to stabilize the wire on the teeth during scanning and simulate the bonding material placed in vivo. Both materials were selected after pilot testing that confirmed sufficient material surface acquisition by the scanner. The setting resulted in two intact teeth adjacent to each grinded tooth that received the retainer. The intact teeth and other adjacent anatomical structures that were not artificially altered, were used as superimposition reference areas to provide the gold standard (true) measurement [10,18].

3D Model Acquisition

The dental casts of the before (T0) and after wear simulation plus retainer placement (T1) conditions, were scanned using a laboratory 3D surface scanner (stripe light/LED illumination; full dental arch accuracy < 20 µm; Laboratory scanner D104a, Cendres+Métaux SA, Biel/Bienne, Switzerland). Repeated single jaw model scans with this scanner, show a distance between corresponding surfaces always smaller than 5 µm. The subsequent binary 3D Standard Tessellation Language (STL) models were imported in Viewbox 4 software (version 4.1.0.1 BETA, dHAL Software, Kifissia, Greece) to apply the

methods tested in the study. Each such maxillary or mandibular full dental arch model consisted of 600.000–900.000 triangles.

Tooth Wear Volume Measurement Workflow

Following 3D superimpositions through seven test techniques and the gold standard technique, the crowns of the grinded teeth (T1) were manually segmented and compared to the segmented original crowns (To).

For each tested tooth, the gold standard (GS) measurements were obtained through To/T1 model superimpositions on intact adjacent teeth and alveolar processes (Figure 1a). Perfect matching is expected in these areas following a best-fit superimposition, which enables accurate occlusal tooth wear assessment [10,11,18].

Measurements were performed according to a modified, previously published protocol [10]. The first group of measurements (PC: partial crown) was obtained using part of the To clinical crown as superimposition reference (Figure 1b–d). This aimed to include crown areas that could be considered unaffected from occlusal wear or retainer placement. On the other hand, the complete To clinical crown was used as a superimposition reference for the second group (CC: complete crown) (Figure 1e). Each time, the To/T1 3D models of each patient were superimposed using the software's implementation of the iterative closest point algorithm (ICP) [19], with predefined settings that are described below. The whole process always started from the original initial position of the models. Thus, the first step included the manual approximation of the two objects to facilitate rapid automatic registration through the ICP algorithm. For the same reason, following the manual approximation, in cases of a setting that included less than 50% estimated overlap of meshes, a partial approximation of the two models was always performed, using 100% estimated overlap of meshes, before applying the predefined setting.

Figure 1. Reference areas used to measure tooth wear at the right maxillary permanent central incisor. **(a)** Gold standard area (GS: blue). **(b–d)** Partial crown areas (PC: green, orange, red). **(e)** Complete crown area (CC: purple). The upper row shows the buccal and the lower row the palatal view. The letters within the parentheses indicate the settings applied for each reference area.

Based on previous experience [10] and pilot testing, the performance of different ICP settings was assessed using the superimposition reference areas described above (Figure 1). The eight specific techniques applied in the study (combinations of ICP settings and reference areas) are listed in Table 1. The basic setting consisted of 100% estimated overlap of meshes, matching point to plane, exact nearest neighbor search, 100% point sampling, exclude overhangs, and 50 iterations. Other ICP settings were identical to the basic setting, but with user defined, 40%, or 20% estimated overlap of meshes. The user defined estimated overlap of meshes was freely chosen by the operator for each individual measurement, through an iterative process. Each time, following various adjustments of the specific setting, the user aimed to achieve the maximum overlap of the superimposed teeth and, primarily, of the adjacent intact structures. The selected value that provided the best overlap of intact structures in each case, was noted in an Excel sheet. For each reference area, the average of these values, provided the additional estimated overlap settings to be tested. It should be noted that the case-specific, user defined setting is impossible to be obtained in actual patient data, since there are no absolutely intact structures in the mouth between two time points [11]. Thus, this approach allowed the determination of a setting that might work properly, while being applicable in actual clinical conditions.

Table 1. Superimposition techniques tested in the study.

Technique	Reference Area	Estimated Overlap
GS	Adjacent intact teeth and alveolar processes	100%
PC(A)	Buccal surface	100%
PC(B)	Buccolingual surfaces without composite	User defined
PC(C)	Complete crown without composite	User defined
PC(D)	Complete crown without composite	40%
CC(A)	Complete crown	40%
CC(B)	Complete crown	User defined
CC(C)	Complete crown	20%

GS: gold standard; PC: partial crown; CC: complete crown.

The superimposed 3D tooth crown models through each technique described above, were simultaneously sliced using one (gingival) to three planes (gingival, mesial, and distal), based on a previously published protocol [10]. For each pair of teeth, the slicing planes were positioned to include the complete occlusal wear surface. At the same time care was taken to avoid significant differences between the two models at the edges of the crown parts to be sliced. This was verified through the visualization of relevant color coded distance maps. Consequently, identical filling of the holes of each occlusal part of the sliced To and T1 crown models was achieved (Figure 2). In certain cases, the hole created from slicing had to be split to two or more parts, through manual connection of contralateral points in sharp edges. This ensured that the edges of each hole to be filled, through the application of the software's algorithm, were located on the same plane. Thus, it ensured identical hole filling and creation of watertight To and T1 3D models that were matching at all parts, apart from the occlusal part that was the one to be assessed (Figure 3). Following this approach, occlusal tooth wear was defined as the difference between these two superimposed crown parts. The wear amount, expressed as volume loss of tooth structure (mm^3), that was detected through the gold standard technique, was then compared to that of the test techniques.

To assess the error of Viewbox 4 software on volumetric assessments, the volumes of ten tooth parts similar to those used for the study were measured using Viewbox 4, Artec Studio 12 Professional (Artec 3D, Luxembourg), and MeshLab 2016.12 [20] and compared. The error attributed to the used surface

scanner was measured in ten teeth of various types, located on ten different models that were scanned twice. Following superimposition of the corresponding identical teeth derived from repeated scans, volumes similar to those tested in the study were calculated. Zero difference in corresponding volumes would indicate perfect superimposition of the repeated models and zero scanner error. Reproducibility of tooth wear assessment techniques was tested through repeated measurements of ten teeth, on four randomly selected models, two maxillary and two mandibular (one with and one without crowding each) by one operator, following a 1-month period.

Figure 2. Tooth wear measurement process in a maxillary central incisor. **(a)** Tooth before (yellow) and after (green) tooth wear and retainer simulation. **(b)** Superimposed tooth crowns using the complete crown technique and setting C (20% estimated overlap) shown from the buccal (left) and the lingual (right) aspect. **(c)** Color coded distance map showing the tooth wear from the buccal (left) and the lingual (right) side. **(d)** Level (grey) used to simultaneously slice the two crowns. **(e)** Sliced tooth crowns. **(f)** Holes filled to create watertight models, and thus, calculate volumes.

Figure 3. Tooth wear measurement process in a mandibular canine. **(a)** Tooth before (yellow) and after (green) tooth wear and retainer simulation. **(b)** Superimposed tooth crowns using the complete crown technique and setting C (20% estimated overlap) shown from the buccal (left) and the lingual (right) aspect. **(c)** Color coded distance map showing the tooth wear from the buccal (left) and the lingual (right) side. **(d)** Two levels (grey) used to simultaneously slice the two crowns. **(e)** Sliced tooth crowns with connected contralateral points (blue) in sharp edges (red line), splitting the hole in two parts to ensure identical hole filling process. **(f)** Holes filled to create watertight models, and thus, calculate volumes.

Statistical Analysis

The statistical approach followed here is comparable to that of a previous similar study [10]. Statistical analysis was carried out by using the IBM SPSS statistics for Windows (Version 26.0. IBM Corp: Armonk, NY, USA). Non-parametric statistics were applied based on abnormal distribution of the raw data of certain variables (Kolmogorov–Smirnov and Shapiro–Wilk tests).

Agreement between different techniques with the gold standard technique (trueness) regarding tooth wear, was shown in box plots. Perfect trueness is indicated by zero median value, whereas the larger the deviation from zero the lower the trueness. Within techniques, the range of deviation of individual values from the median value shows precision. Differences in trueness and precision among different techniques were tested using Friedman's test, followed, where applicable, by Wilcoxon's signed rank test for pairwise comparisons [10].

Potential effects of presence of crowding, tooth type, or tooth wear amount on the trueness and precision of each technique were explored through

visual inspection of relevant plots and unpaired comparative tests within techniques [10].

Intra-operator error (reproducibility) of the gold standard and the technique of choice was assessed through Bland Altman plots, with markers set by tooth category. Any deviation from zero shows imprecision of the technique. Differences in the reproducibility of the two techniques were tested in an unpaired manner through Mann–Whitney U test [10].

For all tests, a two-sided significance test was carried out at an alpha level of 0.05. When multiple pairwise comparisons were performed, the level of significance was altered according to the Bonferroni adjustment.

Results

Regarding the volumetric assessment of tooth crown parts of interest, all three tested software provided identical values for all tested models. Following superimposition of corresponding single teeth, derived from repeated scans, with the CC(C) technique, the median volume difference was 0.0115 mm³ (range: 0.0003, 0.0350 mm³) when all differences were transformed to absolute values. The original position of the second scan was randomly altered prior to these tests. This value indicates the scanner plus the superimposition error regarding tooth wear assessment using single teeth. Repeated tooth wear measurements with the gold standard technique and the CC(C) technique of choice showed no systematic error (one sample *t*-test, $p > 0.05$). The amount of tooth wear and the tooth type did not seem to affect reproducibility. The outcomes of both techniques were considered highly reproducible overall and in individual measurements (max difference < 0.040 mm³) (Figure 4). There was no difference in the reproducibility of the gold standard and the technique of choice ($p = 0.94$). The superimposition error of the gold standard technique that provided the reference measurements is shown in Figure 4a and it was on average less than 0.005 mm³ and in all cases less than 0.020 mm³.

There were significant differences in the trueness of the tested techniques (Friedman test: $p < 0.001$). PC(A) and PC(B) differed clearly from all other techniques. Among the rest, all techniques differed significantly to each other apart from CC(A) vs. PC(D), CC(B) vs. PC(C), CC(B) vs. CC(C), and CC(C) vs.

PC(C) (Wilcoxon signed rank test: $p < 0.01$; Figure 5). Analogous differences in precision were evident among all techniques (Figure 5). The CC(C) technique was the only technique that showed perfect agreement with the GS technique in all cases (median difference: -0.002 , max absolute difference: 0.178 mm^3) and is applicable in actual clinical conditions.

Tooth type did not affect the trueness of each technique (Mann–Whitney U test, $p > 0.05$). However, measurements in canines tended to be more precise compared to those of incisors (Figure 6a). Tooth alignment in the dental arches also did not affect the outcomes of any technique (Mann–Whitney U test: $p > 0.05$). Tooth wear amount did not show any significant effects (Kruskal–Wallis test, $p > 0.01$), though there was a tendency for slightly reduced trueness and precision in the group with the highest amount of tooth wear (Figure 6b).

The difference between the CC(C) technique of choice and the GS technique was always small for any tested tooth type or amount of tooth wear (Supplementary Materials Figure S1). However, there was a tendency for decreased precision in case of 2 mm vertical height loss of tooth structure (Kruskal–Wallis test, $p = 0.029$). Pairwise comparisons showed a significant difference only between the 0.5 mm and the 2 mm groups (Mann–Whitney U test, $p < 0.01$).

Figure 4. Bland–Altman plots showing intra-operator error on tooth wear volume measurements. **(a)** Gold standard (GS) technique. **(b)** Technique of choice: complete crown (CC) with 20% estimated overlap. The axes length represents the true range of measured tooth wear values. The continuous horizontal line shows the mean and the dashed lines the 95% confidence intervals.

Figure 5. Box plots showing in the Y-axis the difference of each technique with the gold standard technique in tooth wear measurements. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value (trueness). Outliers are shown as black circles or asterisks, in more extreme cases, with a step of $1.5 \times \text{IQR}$ (interquartile range). Zero value (dashed horizontal line) indicates perfect agreement with the gold standard. The vertical length of each plot indicates precision. The blue box on the left image indicates the area of the graph shown in the right image in a larger scale. PC: partial crown; CC: complete crown.

Figure 6. Box plots showing on the Y-axis the difference of each technique from the gold standard technique in tooth wear measurements, (a) by tooth type, and (b) by amount of tooth wear. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value (trueness). Outliers are shown as black circles or asterisks, in more extreme cases, with a step of $1.5 \times \text{IQR}$ (interquartile range). Zero value (dashed horizontal line) indicates perfect agreement with the gold standard. The vertical length of each plot indicates precision. PC: partial crown; CC: complete crown.

Discussion

Additional to proper diagnosis, easily applicable methods that facilitate accurate assessment of tooth wear will support the scientific community in better understanding potential causes, acting mechanisms, and contributing factors. Material wear is also very important for materials science when conducting in vitro tests, but also to clinically test the real-life performance of materials [21,22]. Here we present a highly accurate and informative tooth wear assessment method, which is also more convenient than the already available laboratory methods. It allows the measurement and visualization of occlusal tooth wear in three dimensions of space, on patients that received a bonded wire retainer during the assessment period. To our knowledge, this is the first study that addresses this issue. The suggested method requires the existence of two serial dental models to assess wear progress over time. In the era of digitization, this is not considered a limitation, since it is expected that soon an intraoral patient scan will be an integral part of basic dental diagnostic records. Providing that the suggested superimposition method registers sufficiently serial surface models similar to those tested here, it can be used for any relevant purpose, including occlusal material wear testing.

The present method offers the opportunity for detailed assessment of changes over time, in corresponding surfaces, without the need for placing any landmarks, which might be a time-consuming and error prone process [23,24]. Apart from the clinically relevant applications, following the proper superimposition of serial 3D tooth models, which enables the accurate detection of the worn tooth part during a specific time period, this method can be combined with various other types of 3D shape analysis, such as those used for ecometrics in dental ecology [25], including dental topography methods [24]. The method works on a μm scale that is defined by its accuracy, as well as by the resolution of the applied scanning systems. For example, based on scanner resolution of the intraoral, as well as the current dental lab scanners [11], microwear analysis might not be possible, though it might be quite useful for testing certain hypotheses [26].

In a previous study we developed a similar method [10] applicable on teeth that did not undergo significant alterations in any crown surface, apart

from the occlusal. Epidemiologic studies indicate that in modern humans, tooth wear, especially of the clinical crown, mainly concerns the occlusal part of the teeth due to the direct contacts with the antagonists [12,13]. Thus, the simulation model that was previously developed and applied here, represented adequately the most common clinical occurrence. However, certain patients may receive a fixed retainer at their buccal or more often at their lingual surfaces. This usually consists of a continuous wire bonded with composite resin at the middle of the respective tooth surfaces. This type of retainer is common in patients that received orthodontic treatment, but also in severe periodontally compromised patients, or in patients that required tooth stabilization following dental trauma [14,16,17]. Thus, we suspected that our previously suggested method might not perform similarly when a fixed retainer has been bonded to the test teeth during the assessed period. Indeed, after testing various possibilities for the latter case, we concluded that the complete crown with reduced estimated overlap of meshes to 20%, namely the CC(C) technique, provided the most accurate outcomes. The previous study, on intact teeth in non-occlusal surfaces, suggested an estimated overlap of meshes of 30% for optimal outcomes [10].

The present method offers a median accuracy of 0.002 mm³, with the worst individual measurement showing a difference of 0.178 mm³ from the gold standard measurement. The gold standard measurement always showed a precision higher than 0.020 mm³. The scanner plus the superimposition error for single teeth measurements, using the suggested technique, was always smaller than 0.035 mm³. Thus, even in the unfavorable scenario of extensive changes in non-occlusal surfaces, this method performs quite satisfactorily. A freeware and easy to use software (WearCompare, School of Dentistry, University of Leeds, Leeds, UK) [27] providing tooth wear measurements, following serial tooth surface model superimpositions, showed high performance when identical (duplicated) surfaces were used as superimposition references. However, when the original position of the duplicated models was altered, the software showed errors in volumetric assessment as high as 1 mm³. Furthermore, when actual patient data were considered, it showed considerable and statistically significant differences on volumetric assessments from Geomagic Control software (3D Systems,

Darmstadt, Germany), averaging 0.59 mm³ [27]. This software uses the buccal and lingual surfaces as superimposition references to assess occlusal tooth wear. We also tested this approach both in a previous [10] and in the current study and it did not provide superior outcomes to that of the suggested techniques, which use the whole crown as superimposition reference. Furthermore, the performance of WearCompare software in presence of considerable changes in the used superimposition reference areas remains to be tested.

The current settings might also be applicable to patients that show extensive tooth wear on buccal or lingual surfaces [12,15]. In such cases, apart from the occlusal surface, another surface is highly altered over time, such as with the placement of a retainer. Following the superimposition of serial tooth models, the operator can generate color coded distance maps and confirm the applicability of the suggested technique, if the detected changes are comparable to those simulated here. For example, in cases of erosion, changes might be present on the entire tooth surface and, thus, the suggested technique might not be applicable. Finally, if the teeth are not subjected to any change between two time points, the present technique still performs a complete registration of the two surface models (Supplementary Materials Figure S2). However, this will be a rare occasion, since in living humans, minimal changes in form or in spatial relations are always expected over time. Even if there is no morphological change, two serial intraoral scans will not provide identical models [11].

In actual patients, the gingival margin area, and thus the corresponding clinical crown structures, might also change over time. However, with the present method this is not a limitation, since in case of large differences in the gingival part of the crown, the operator can select the shortest clinical crown as the superimposition reference. Then, by selecting the “exclude overhangs” option, which is included in the suggested default settings, the software ignores the part of crown that does not exist in both models. The performance of this function has been extensively applied and tested in previous studies, on various types of surface models and has always provided solid outcomes [10,11,18,28–30].

The present study simulated tooth wear amounts of approximately 0.5, 1, and 2 mm to represent variations of clinically significant loss of tooth crown parts, in terms of dental appearance. As evident in an analogous study [10], the high performance of the technique presented here was not considerably affected by tooth wear amount. Smaller amounts of occlusal tooth wear might be present in actual patients, but were not simulated here. We considered the tested range more relevant, since the ICP algorithm would perform equally well, if not better, in cases of smaller surface changes (Supplementary Materials Figures S1b, S2, and S3) [11,18,28]. Providing adequate superimposition of serial tooth models under the tested circumstances, the accuracy of the suggested method is defined by its difference from the tooth wear value obtained using the gold standard method. The amount of tooth wear that can be safely detected by the method is determined by the specified accuracy level. However, a potential improvement of the accuracy level in cases of minimal tooth wear remains to be verified by future research.

The high accuracy laboratory scanner used here to generate the surface models, has comparable accuracy to the current high end intraoral scanners, considering relatively small structures, such as single tooth crowns [11,18,31]. In the present study, we selected this scanner to eliminate the scanner error effect on the gold standard measurement, which requires a larger superimposition reference area. This measurement is feasible only with the present experimental design, where the structures adjacent to a worn tooth are intact. The true wear amount is measured through the use of these intact structures as superimposition reference. This measurement is then compared to the measurement obtained using the single tooth crown as superimposition reference. Only the latter option is feasible in actual clinical conditions, where no structure adjacent to single teeth can be considered morphologically stable over time. This is the main reason why gold standard measurements (true values) cannot be available when using actual clinical data.

So far, most methods used to measure tooth wear are based on qualitative assessments with limited precision or on complex laboratory quantitative approaches that require expertise and special equipment to be applied [7]. The presented method requires 3D tooth surface models that can

nowadays be easily obtained through intraoral scanners [11]. These models can then be processed using software applications that are widely available under reasonable costs [32]. Thus, following the necessary short-term training, these methods can be potentially incorporated in a regular dental practice environment, enhancing the diagnostic ability of occlusal tooth wear, especially in cases that this is considered critical. Apart from this major advantage, the performance of this method is also comparable to, if not higher than most available methods [7]. So far, a direct comparison with other methods is not possible, since no other study has performed quantitative tooth wear assessment in teeth that underwent significant changes in surfaces other than the one tested. Among others, a significant strength of the present in vitro study is that it allowed the comparison of different techniques with a gold standard technique, which provided the true measurement. Thus, apart from reproducibility, the study tested the trueness of the measurements, which is usually a missing part from previous reports [7]. Furthermore, the present method is superior to methods that perform 2D measurements, such as the vertical loss of tooth structure, since it offers much higher amount of 3D information. In addition to the quantification of tooth volume loss, this 3D superimposition technique enables the visualization of a color coded distance map that allows a thorough quantitative and qualitative assessment of tooth wear in the 3D space. Thus, following the proper application of the suggested technique, patterns of tooth wear or any spatial differences in the tooth surfaces, can be easily identified and quantified according to the needs of each individual test.

Our research group has worked extensively in testing surface-based 3D superimposition in the craniofacial area, showing promising results in many different applications [10,11,18,28–30,33]. In the aforementioned studies, the performance of the used software and the specific algorithm has been thoroughly tested and shown highly reproducible results. Thus, the high reproducibility of the present techniques was an expected finding. Furthermore, the technique of choice consistently provided values very close to the true amount of tooth wear. The individual differences of the selected CC(C) technique from the true value were almost always smaller than 0.1 mm³. This accuracy level is comparable to that achieved on teeth that underwent changes

only at their occlusal surfaces [10]. However, the current approach consists a clinically applicable technique in a more challenging scenario, where the used tooth surfaces have been considerably changed over time.

In diagnostic accuracy studies, it is of utmost importance to assess differences between techniques or repeated measurements in each individual case and not only between group means [34]. In the latter, positive and negative differences between diverse cases can be eliminated providing the misleading impression of similar outcomes. However, it is important to have accurate measurements in each individual case, since, for example, this information might affect treatment decisions. Indeed, in the present study the mean values of all techniques were very close to each other and to the true value. However, when results of individual cases were considered, the superiority of the selected CC(C) technique became evident.

A limitation of the present study could be that only anterior teeth were thoroughly tested. This approach was followed because these teeth usually require a fixed retainer [14,16,17]. Furthermore, we also included canines in our tests, which are more round-formed teeth. Along with the present results, previous results have also shown that tooth type does not considerably affect the outcomes [10]. Thus, we expect that this technique will be also applicable on posterior teeth (Supplementary Materials Figure S3). Another limitation could be that intra-operator error was only assessed for the gold standard and the technique of choice. This was considered adequate since the two techniques showed satisfactory agreement and both provided excellent reproducibility outcomes. Furthermore, as described above, thorough error evaluation of similar techniques has been published previously and always provided favorable outcomes [10].

Conclusions

The present report suggests a 3D superimposition technique to assess occlusal tooth wear in anterior teeth that received a bonded wire retainer during the assessment period. Following the superimposition of serial tooth crown models, loss of tooth structure can be visualized and quantified in all dimensions of space. The technique is highly accurate, informative, and relatively easy to use, and thus, it will facilitate associated research, but it can

also be easily incorporated in a clinical environment. Further work is required to verify the performance of the technique on posterior teeth and regarding smaller increments of tooth wear.

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Conflicts of Interest

D. Halazonetis owns stock in dHAL Software, the company that markets Viewbox 4. Authors N. Gkantidis, K. Dritsas, Y. Ren, and C. Katsaros declare no competing interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Supplementary Material

Figure S1. Box plots showing in the Y-axis the difference of the technique of choice (complete crown (CC), setting C) from the gold standard technique in tooth wear measurements (a) by tooth type and (b) by amount of tooth wear. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value (trueness). Outliers are shown as black circles with a step of $1.5 \times \text{IQR}$ (interquartile range). Zero value indicates perfect agreement with the gold standard (horizontal dashed line). The vertical length of each plot indicates precision.

Figure S2. Superimposition of identical surface models of a maxillary incisor (left) and a mandibular canine (right). (a) Original tooth (yellow) and duplicate (red). (b) Superimposed tooth crowns using the complete crown technique and setting C (20% estimated overlap) shown from the buccal aspect. (c) Color coded distance maps of the superimposed crowns, shown from the buccal (above) and the palatal (below) side.

Figure S3. Tooth wear measurement in a mandibular molar with limited loss of tooth structure. (a) Tooth before (light yellow) and after (light red) tooth wear simulation. (b) Manually approximated tooth crowns. (c) Superimposed tooth crowns using the complete crown technique and setting C (20% estimated overlap). (d) Color coded distance map of the superimposed crowns. (e) Level (grey) used to simultaneously slice the two crowns. (f) Sliced tooth crowns. (g) Holes filled to create watertight models, and thus, calculate volumes. (h) Watertight models after slicing the same superimposed models using two slicing levels. (i) Tooth before (light yellow) and after (light purple) tooth wear plus retainer placement simulation and color coded distance map of the superimposed crowns using the complete crown technique and setting C (20% estimated overlap). The wear amount measured with one slicing level (a–g) was $0.021 \mu\text{m}^3$. The wear amount measured with two slicing levels (h) was $0.020 \mu\text{m}^3$. The wear amount measured following the retainer placement (i) was $0.020 \mu\text{m}^3$. The wear amount measured with the gold standard technique and two slicing levels was $0.020 \mu\text{m}^3$.

Chapter 5

Longitudinal 3D study of anterior tooth wear from adolescence to adulthood in modern humans

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Abstract

In modern humans, tooth wear can easily be observed as a loss of tooth substance, but its precise measurement is problematic. The aim of this longitudinal cohort study was to determine the precise amount of occlusal tooth wear in the anterior permanent dentition from adolescence to adulthood. Corresponding tooth crowns from serial 3D digital dental models of 72 individuals were best fit-approximated by applying novel, highly accurate 3D superimposition methods. The superimposed crowns were simultaneously sliced on intact structures, and the differences in the volumes of the subsequent occlusal parts were calculated. Over a thirteen-year period, there was an average loss of anterior occlusal surfaces of 1.58 mm³ per tooth. Tooth surface loss in at least one tooth was higher than 1 mm³ in 93.1% of the human subjects. Tooth wear severity differed by sex and tooth type, with males showing higher values versus females and upper canines versus other anterior teeth. The study revealed the endemic occurrence of occlusal anterior tooth wear, highlighting the need for monitoring of the condition in the population to identify high-risk patients and enable timely interventions. The novel methods applied here on 3D digital models are recommended for this.

Simple Summary

Tooth wear is the loss of tooth substance during everyday functioning by means other than dental caries. It is expected at a certain level in every person, and it increases with age. In the last decades, due to the increased life expectancy and high patient demands, it has become an important problem modern dentistry has to face. However, the average amount of tooth wear among individuals remains controversial. The purpose of this clinical study was to precisely detect the extent of anterior tooth wear over a thirteen-year period, from adolescence to adulthood. The present study revealed the very high tooth wear occurrence in the population already at early adulthood and showed that wear monitoring at an individual level is important for dentists to enable the better understanding of the problem and allow timely targeted interventions for patients in need. These might be preventive, such as the prescription of mouth guards to limit grinding and the cessation of harmful habits that lead to tooth

wear, or interceptive, such as the restoration of the lost tooth substance to stop the progress of the condition and improve esthetics and function.

Introduction

In modern humans, tooth wear is a physiological process that progresses slowly over time [1–3]. However, loss of tooth matter may also be atypical for the patient's age due to pathological conditions associated with attrition, abrasion, and erosion processes [2,4]. These conditions may coexist and act synergistically in varying degrees in individual patients [5].

Occlusal tooth wear is a very common finding in the general population, with anterior teeth exhibiting greater wear [2,6–9]. The etiology of tooth wear is multifactorial. Males show more often and more severe tooth wear than females [1,2]. Dietary factors, including acidic foods, have also been shown to have a critical role [2,4,6,9,10]. Certain occlusal factors, such as overjet and anterior protected articulation, have been associated with the progression of occlusal wear [11]. Subjects with different malocclusions have demonstrated different tooth wear patterns [12,13]. Masticatory function has also been associated with tooth wear [14].

In regard to the effects of tooth wear on individuals, the severity of occlusal/incisal tooth wear was found to be associated with dentine hypersensitivity severity [10]. However, the most important patient concern regards esthetics, followed by sensitivity, whereas functional problems and pain are less prevalent [15]. A series of studies designated anterior tooth wear as esthetically unpleasant [16–18]. Furthermore, anterior tooth wear negatively affected the quality of life in elder nursing home patients [19].

Proper monitoring of tooth wear is crucial for successful management [20]. Erosion has been found to progress more in individuals with previous signs of erosion, emphasizing the importance of an early diagnosis [21]. However, dental patients might be unable to recognize tooth wear and seek treatment, even in severe cases [5]. Additionally, conventional methods applied by dental professionals have been found to show a limited capacity to follow wear progress over time [22,23]. Therefore, novel clinically applicable 3D approaches have been developed for this [24–27].

The precise amount of tooth wear occurring in the long term on a group of individuals has not yet been fully explored. Longitudinal, quantitative *in vivo* studies on medium- to long-term tooth wear occurrence are scarce [28,29].

Thus, the purpose of the present study was to assess the amount of occlusal anterior tooth wear evident from adolescent to adulthood over a long-term period. To fulfill this purpose, recently developed 3D superimposition methods [24,25,27] were applied on serial post-orthodontic treatment digital dental models.

Materials and Methods

This study was reported according to the guidelines provided in the STROBE statement [30].

Ethical Approval

This research protocol was approved by the Research Ethics Committee of the canton of Bern, Switzerland (Project-ID: 2019-00326). All participants signed an informed consent form approving the use of their data for research purposes.

Sample

The sample consisted of individuals that completed their orthodontic treatment in a private practice in Grenchen, Switzerland and were selected for a previous project that tested the performance of fixed orthodontic retainers [31]. Time point 1 (T1) was defined as the point when the participants finished their orthodontic treatment. Time point 2 (T2) was a recall appointment performed to obtain, among others, alginate impressions and intraoral photos. T1 records were taken between 2000 and 2006 and T2 records between 2015 and 2016. A consecutive sample selection was applied to include all patients that fulfilled the eligibility criteria and accepted to participate in the study. The original sample collection was performed using the following inclusion criteria: (1) treated with fixed orthodontic appliances, (2) treated by the same orthodontist, (3) maxillary and mandibular retainers bonded at the anterior teeth immediately after active orthodontic treatment, (4) no orthodontic retreatment, (5) White patients, and (6) non-syndromic individuals. The following additional inclusion criteria were applied in the present study: (1) age at debonding between 12 and 24 years, (2) debonding 9–16 years prior to T2, (3) T1 and T2 casts of good quality in the anterior region of the dental arch, and (4) intact natural teeth without incisal or whole crown reconstructions.

The T1 and T2 dental stone models generated through alginate impressions were scanned using a 3D laboratory surface scanner (stripe light/LED illumination; full dental arch accuracy $<20\text{ }\mu\text{m}$; Laboratory scanner D104a, Cendres + Métaux SA, Biel/Bienne, Switzerland). This scanner resolves distances smaller than $5\text{ }\mu\text{m}$ between corresponding surfaces of repeated single jaw scans [24]. The subsequent maxillary and mandibular 3D surface models, consisting of approximately 600,000–900,000 triangles each, were exported as STL files. These files were used to measure anterior tooth wear, as described below.

Inadequate quality casts and broken or restored teeth were identified through the visual inspection of intraoral photos and 3D digital dental models. In case of doubt, the medical and dental histories of the patients were reviewed, the corresponding tooth pairs were superimposed, and color-coded distance maps were created for visualisation purposes. Afterwards, a joint decision was made by the first two authors (3 models).

From the 88 individuals included in the previous study [31], data from 72 individuals (54 females and 18 males) were used here. From the 16 excluded patients, 9 did not meet the age criteria, 2 the years from debonding, and 5 had poor-quality casts. Finally, tooth wear was measured on 690 individual teeth (Table 1). The median interval between the two time points was 12.8 years (interquartile range (IQR): 1.4). The median ages at the T1 and T2 points were 14.3 (IQR: 1.8) years and 27.4 (IQR: 2.2) years, respectively. All patients had acceptable occlusion at both time points, with the vast majority having positive overjet and overbites up to 4 mm and Angle Class I. The detailed occlusal characteristics of the sample are provided in Table 2.

Table 1. Teeth that comprised the tooth wear measurement sample.

Canines		Lateral Incisors		Central Incisors	
Upper	Lower	Upper	Lower	Upper	Lower
$n = 71$	$n = 65$	$n = 67$	$n = 61$	$n = 65$	$n = 56$
53F, 18M	50F, 15M	51F, 16M	47F, 14M	51F, 14M	41F, 15M
67R, 68L	60R, 63L	58R, 63L	55R, 51L	54R, 58L	49R, 45L

F: females, M: males, R: right, and L: left.

Table 2. Occlusal characteristics of the studied sample.

		T1	T2
Angle Class ¹	Class I	70	61
	Class II	2 (unilateral)	11 (9 unilateral, 2 bilateral)
Overjet ²	Normal	72	70
	Increased	0	2
Overbite ³	Normal	65	58
	Reduced *	7	14

¹ Class I: Molar relationship less than ¼ cusp deviation from Class I (in cases of asymmetrical extractions, premolar and canine occlusion was also considered). ² Normal: 1–4 mm and Increased: >4 mm, and ³ Normal: 1–4 mm and Reduced: <1 mm. * Only one patient at T2 had a negative overbite. In all other cases, the overbite was between 0 and 1 mm. T1: time point at end of orthodontic treatment. T2: time point on average 13 years after T1.

Tooth Wear Assessment Workflow

Tooth wear was measured by applying previously developed and validated 3D superimposition techniques [24,25,27] on corresponding individual anterior tooth crowns of the T1 and T2 models. All processing was performed using Viewbox 4 software (version 4.1.0.8 BETA, dHAL Software, Kifissia, Greece). The tooth crowns of the six anterior maxillary and mandibular teeth were selected on the T2 dental models. Each T2 individual tooth crown was superimposed on the corresponding T1 tooth crown using the complete T2 clinical crown as a superimposition reference under the following software settings: 20% estimated overlap of meshes, matching point to plane, exact nearest-neighbor search, 100% point sampling, exclude overhangs, and 50 iterations. The superimposition aimed at the best fit approximation of the two models achieved through the implementation of an iterative closest point algorithm (ICP) [32]. Before applying the final setting, the T1 and T2 crowns were manually approximated using a 100% estimated overlap of the meshes to facilitate the registration process.

The superimposed T1 and T2 crown models were simultaneously sliced using one or more planes. The subsequent occlusal crown parts were transformed into watertight models through a hole-filling process. For each T1–T2 crown pair, the T1 occlusal part volume was subtracted from the T2 volume, providing the tooth wear measurement in mm³. The superimposition and

measurement workflow are shown in Figure 1 (a-d) and were validated previously [24,25,27].

Figure 1. Tooth wear measurement process. **(a)** Corresponding T1 (light yellow) and T2 (light purple) central incisor tooth crowns. **(b)** Best-fit superimposition of the T1 and T2 tooth crowns. **(c)** Buccal and palatal aspects of the color-coded distance map of the superimposed T1 and T2 crowns. **(d)** Corresponding T1 and T2 occlusal crown parts, created following the simultaneous slicing of the superimposed T1 and T2 crowns. The subtraction of these volumes provided the tooth wear measurements used in this study. T1: time point at end of orthodontic treatment. T2: time point on average 13 years after T1.

Method Error

The whole superimposition and measurement process was repeated by the same examiner (K.D.) at least two weeks after the first measurement to assess method error. Twenty-four randomly selected teeth, representing each tooth type twice, were remeasured.

Statistical Analysis

Statistical analysis was performed in IBM SPSS statistics for Windows (Version 26.0. IBM Corp: Armonk, NY, USA). Data normality was tested using the Kolmogorov–Smirnov and Shapiro–Wilk tests and through the visualization of data distribution graphs. There were no significant deviations from normality, and thus, parametric statistics were applied.

Descriptive statistics were performed to present the variables of interest using exact measures and graphical representations.

Differences between the sides of the mouth (right left) were tested separately for each tooth type and jaw using paired *t*-tests. Based on the outcomes of these tests, the average values of the right and left sides were calculated for each tooth type.

Differences in the amount of tooth wear (dependent variable) among tooth types (fixed factor, 6 levels: upper canine, upper lateral incisor, upper central incisor, lower canine, lower lateral incisor, and lower central incisor) and between sexes (fixed factor, 2 levels: male and female) were tested using an analysis of covariance (ANCOVA; general linear model, full factorial). The patient and the duration of the assessment period were set as covariates to account for the matching and clustering effects and correct for the duration of the assessment period, respectively. Age at T1 was not included in the model, based on exploratory tests through bivariate correlations with the different tooth types (Supplementary Table S1). Following significant results, parameter estimates were calculated, and pairwise comparisons were performed.

The association of tooth wear between the different tooth types was investigated through bivariate Spearman's correlations.

The amount of error was assessed through the absolute differences between repeated measurements. The testing of systematic errors and assessments of individual measurements were performed through the Bland–Altman method.

The level of significance was set at an alpha level of 0.05. A Bonferroni correction was applied when multiple pairwise comparisons were performed for similar outcomes. The unit of analysis was each tooth crown.

Results

Method Error

There were no systematic differences between repeated measurements ($n = 24$; 95% Limits of Agreement: $-0.13, 0.25 \text{ mm}^3$). The average of the differences between repeated measurements was 0.06 mm^3 on an average tooth wear of $1.68 \pm 1.61 \text{ mm}^3$. The average of the absolute differences between repeated measurements was 0.09 mm^3 , with a standard error of 0.014 mm^3 . The

maximum difference detected was 0.24 mm³. Thus, the amount of error was considered negligible. The relevant Bland–Altman plot is shown in Figure 2.

Figure 2. Bland–Altman plot showing the intraoperator reproducibility of the tooth wear assessment in mm³. The axes lengths represent the true range of the measured tooth wear values. The continuous horizontal line shows the mean (0.06 mm³) and the dashed lines the 95% Limits of Agreement (−0.13, 0.25 mm³). M1: first set of measurements. M2: repeated measurements.

Tooth Wear Differences between Contralateral Sides

There were no significant differences between contralateral teeth of the same type (Supplementary Table S2). Thus, the wear amounts of each tooth type per side were averaged for further analysis.

Tooth Wear among Tooth Types and between Sexes

The average occlusal wear over the assessment period was 1.58 mm³ per anterior tooth. If we consider a cutoff value of 1 mm³ as of clinical importance, 50.4% of the tested teeth (348 out of 691) showed higher wear amount. Furthermore, 67 out of the 72 tested individuals (93.1%) had at least one anterior tooth with occlusal wear higher than 1 mm³.

The ANCOVA identified a significant effect of tooth type and sex on the tooth wear amount (Table 3 and Figure 3). The parameter estimates indicating the effect of the tested factors on the tooth wear amount (dependent variable) are provided in Supplementary Table S3 and the estimated marginal means for

the factors sex and tooth type in Supplementary Table S4. Males showed, on average, 2.66 (95% CI: 2.38–2.95) mm³ occlusal tooth wear in the anterior dentition, whereas females showed 1.21 (95% CI: 1.05–1.37) mm³. The upper canine presented the highest tooth wear amount (average: 3.30; 95% CI: 2.93–3.67 mm³), followed by the upper central incisor (average: 2.27; 95% CI: 1.86–2.68 mm³) and the lower canine (average: 2.13; 95% CI: 1.73–2.52 mm³). On the contrary, the upper lateral incisor showed the least tooth wear amount (average: 0.90; 95% CI: 0.52–1.29 mm³). Although males displayed approximately 2.2 times more tooth wear than females, the pattern of wear severity per tooth type was similar for both sexes (Figure 3). Furthermore, there were moderate-to-strong correlations (average Spearman's ρ : 0.57; range: 0.39–0.81; $p < 0.005$) between the wear amounts detected on different tooth types of the same individual (Supplementary Table S5).

Table 3. Results of the ANCOVA testing the effect of tooth type and sex on the detected tooth wear amount after controlling for the patient and duration of assessment period.

Source	df	F	Sig.
Corrected Model	13	16.35	0.000
Intercept	1	0.08	0.782
Patient	1	3.45	0.064
Assessment period	1	11.37	0.001
Tooth type	5	20.76	0.000
Sex	1	74.57	0.000
Tooth type * Sex	5	2.77	0.018

R-Squared = 0.364 (Adjusted R-Squared = 0.342). df: degrees of freedom. F: F-value. Sig.: Significance shown as p-values.

Figure 3. Box plots showing tooth wear for each tooth type and sex. The upper limit of the black line represents the maximum value, the lower limit the minimum value, the box the interquartile range, and the horizontal black line the median value. Outliers are shown as black circles (°).

Three-dimensional occlusal wear patterns of representative cases of the average and the maximum amounts detected per tooth type, for the entire sample, are shown in Figure 4.

Figure 4. Three-dimensional superimpositions of serial tooth crowns and corresponding color-coded distance maps of representative cases showing the average and the maximum volumetric tooth wears detected per tooth type for the entire sample. From top to bottom: upper canine, upper lateral, upper central, lower canine, lower lateral, and lower central. T1: tooth crowns at end of orthodontic treatment. T2: the same tooth crowns as in T1, on average 13 years after T1.

Discussion

The common occurrence of anterior tooth wear, in combination with the high esthetic demands and the increasing life expectancy of modern individuals, designates tooth wear an important challenge for contemporary dentistry. However, so far, there is limited information on the extent of the problem in the population over a long-term period. The present study applied highly accurate 3D superimposition techniques on a group of 72 adolescents, followed over a thirteen-year period. The average occlusal wear per anterior permanent tooth

was 1.58 mm³. Approximately 50% of the tested teeth showed values higher than 1 mm³, whereas 93% of the tested individuals had at least one such tooth.

In the literature, we were able to identify only one study quantifying long-term tooth wear, and this was cross-sectional and used 2D radiographs. The average tooth wear of permanent incisors, between 10 and 70 years of age, was 1.01 mm in the maxilla and 1.46 mm in the mandible, measured as the tooth crown length reduction [33]. A longitudinal study identified a crown length reduction of approximately 100–200 µm on the maxillary incisors of 10 middle-aged patients with nocturnal bruxism over a 4-year period [28]. In a previous study by our group, we calculated that 0.5-, 1-, and 2-mm vertical tooth crown loss corresponds to approximately 1.5-, 3.4-, and 8.5-mm³ volumetric loss, respectively [25]. Another longitudinal study performed a qualitative assessment of anterior tooth wear in orthodontically treated patients over a 5-year retention period [3]. Finally, a 3-year longitudinal study on 29 adults referred to a dental center for tooth wear management reported an average volume loss of 0.93 mm³ for the occlusal surfaces of all teeth, excluding third molars. More specifically, the measured volume loss was 2.53 mm³ on molars and 0.83 mm³ on upper central incisors [29]. Thus, the present study is advantageous to the available longitudinal studies, since it investigated a larger sample, which was followed over a much longer period and tested through newly developed accurate 3D methods.

The present findings revealed the endemic occurrence of anterior tooth wear, highlighting the need for proper diagnosis, prevention, and management tools. The identification of prognostic factors is crucial to define high-risk individuals for severe tooth wear and facilitate timely management. In accordance with previous findings [1,2], males showed 2.2 times higher tooth wear amounts than females. Interestingly, the pattern of tooth wear severity per tooth type was similar for both sexes. Apart from sex, the fact that tooth wear amounts within a dentition were correlated indicates a general effect of the predisposing or causative factors on the anterior dentition. This is not surprising when considering that the known associated factors, including sex [1,2], diet [2,4,6,9,10], occlusion [11–13], and mastication pattern [14], are not expected to have effects solely limited to specific teeth.

However, the multifactorial etiology of tooth wear complicates the accurate identification of high-risk individuals prior to the development of the problem. Additionally, there is evidence supporting that tooth wear progresses faster within a certain time period in individuals with previous wear signs [21]. Probably, such individuals continue to occupy the predisposing and causative factors that led to tooth wear at the earlier stages. Additionally, the fact that wear between tooth types is correlated within a dentition indicates that, in individuals featuring the predisposing factors, a number of teeth are affected. Thus, the detection of tooth wear at the early stages and the proper monitoring of its progression over time is imperative, especially in high-risk patients, to prevent this condition prior to a stage where relatively complex treatments, with questionable medium-to-long-term prognoses, might be required [20].

Apart from the known prognostic factors, such as sex [1,2] or acidic food [4,6,9,10], early diagnosis at an individual level will define the need for a detailed assessment with regular follow-ups. Eventually, this will enable the early identification and elimination of potential causative factors in high-risk patients. The methodology applied here offers a risk-free, low-cost, convenient, and highly accurate tooth wear assessment at a micrometer scale, provided that serial 3D digital dental models are available [24,25,27]. The high incorporation of intraoral 3D scanners in daily dental practice facilitates this purpose [34,35]. Currently, various intraoral scanners are available on the market, enabling the easy acquisition of highly accurate dental models, especially when considering structures of limited extent, such as single teeth [24,25,27,35]. We strongly recommend the acquisition of an intraoral model for every patient that attends a dental practice at the early stages of permanent dentition. This can be used as a reference to accurately monitor the progress of morphological alterations in the oral structure, such as tooth wear [24,25,27], by superimposing them with future models of the same patient.

The present study offers unique 3D information on the amount of tooth wear that should be expected in a young population from adolescence to early adulthood. The use of orthodontically treated individuals minimized the potential confounding from occlusal factors that have been shown to be associated with tooth wear development [11–13]. On the other hand, it could

restrict the generalizability of the findings, though, in modern societies, it is quite common for patients with malocclusion to receive orthodontic treatment. Furthermore, a large-scale observational study on general practice patients did not identify any association between tooth wear and previous orthodontic treatments [1]. Non-White individuals were excluded from the study, since they represented a small percentage of the patients treated in the place of a sample collection. Thus, few patients with highly variable racial and cultural characteristics could have been included, potentially confounding the outcomes. In the present sample, the studied subjects had clinically acceptable occlusion and did not wear any removable appliances to retain their orthodontic treatment outcome, which might be another confounding factor. On the other hand, confounding deriving from dimensional instability of the digitized orthodontic stone models might be evident [7]. Large distortions, though, were excluded through the visual inspection of intraoral photos and primarily of distance maps of superimposed teeth.

Another limitation of the study is that the T1 data were retrospectively retrieved. Therefore, potential related factors, such as diet or masticatory function, were not assessed. Although specific risk factors on an individual level cannot be assessed, the tested sample can be considered representative of the tested population for reasons discussed earlier. Retrospective data collection might introduce selection and detection bias. Selection bias is not expected in this study, since the original sample was consecutively selected for another purpose—namely, to test the orthodontic retainer performance. To reduce the selection bias, all patients of the original sample who fulfilled the eligibility criteria were included. Detection bias was also not expected, since the applied methods were automated and standardized. Finally, the sample originated from a Central European population, and the outcomes need to be confirmed in other populations.

Conclusions

The present study revealed the very high occurrence of anterior tooth wear in a population over a thirteen-year period, from adolescence to adulthood. The anterior occlusal surfaces averaged a loss of 1.58 mm³ per tooth, with 93.1% of the tested individuals having at least one tooth worn more than 1 mm³. Tooth

type and sex were significant factors related to tooth wear development, with males and upper canines showing the highest tooth wear amounts. The study revealed the endemic occurrence of occlusal anterior tooth wear, highlighting the need for closer monitoring of the condition in the population. The novel powerful 3D imaging methods applied here can facilitate this purpose, enabling the better understanding of the problem and timely targeted interventions for patients in need.

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Conflicts of Interest

D.H. owns stock in dHAL Software, the company that markets Viewbox 4. In the present study, D.H. was not involved in data curation and formal analysis. N.G., K.D., M.G., D.H, Y.R., and C.K. declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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Supplementary material

Supplementary Table S1. Spearman's correlation of the initial patient's age (T1) and the duration of the assessment period with the tooth wear amount detected for the different tooth types.

		Upper canine	Upper lateral	Upper central	Lower canine	Lower lateral	Lower central
Age at T1	Spearman's ρ	-0.07	-0.12	0.01	-0.06	-0.07	0.20
	P-value	0.553	0.339	0.962	0.649	0.605	0.143
	N	71	67	65	65	61	56
Assessment period	Spearman's ρ	0.35	0.20	0.27	0.28	0.13	-0.06
	P-value	0.003*	0.113	0.029*	0.023*	0.318	0.678
	N	71	67	65	65	61	56

*Significant correlations with $p < 0.05$

Supplementary Table S2. Differences in tooth wear (mm³) measured for the different tooth types at the right and left sides of the mouth.

		N	Mean	SD	Mean $\pm$ SD Difference	95% Confidence Interval of the Difference		P-value*
						Lower	Upper	
Upper canine	right	64	2.77	2.51	0.42 $\pm$ 1.40	0.07	0.77	0.019
	left	64	2.35	2.29				
Upper lateral	right	54	0.78	0.97	0.06 $\pm$ 1.08	-0.24	0.35	0.695
	left	54	0.73	0.94				
Upper central	right	47	1.88	1.86	0.24 $\pm$ 1.52	-0.21	0.69	0.284
	left	47	1.64	1.45				
Lower canine	right	58	1.72	1.60	-0.10 $\pm$ 1.25	-0.42	0.23	0.562
	left	58	1.81	1.68				
Lower lateral	right	45	0.93	1.02	0.16 $\pm$ 0.59	-0.02	0.34	0.072
	left	45	0.77	0.69				
Lower central	right	38	1.48	1.36	-0.11 $\pm$ 0.90	-0.41	0.19	0.456
	left	38	1.59	1.49				

SD: Standard Deviation

*P = 0.01, Bonferroni correction applied

Supplementary Table S3. Parameter estimates indicating the effect of tested factors on tooth wear amount (dependent variable).

Parameter	B	95% Confidence Interval		Sig.
		Lower Bound	Upper Bound	
Intercept	-0.79	-2.51	0.92	0.364
Patient	-0.01	-0.01	0.00	0.064
Assessment period	0.19	0.08	0.30	0.001
Lower canine (ref.: upper lateral)	1.64	0.67	2.61	0.001
Lower lateral (ref.: upper lateral)	0.02	-0.97	1.00	0.972
Lower central (ref.: upper lateral)	1.28	0.32	2.25	0.009
Upper canine (ref.: upper lateral)	3.20	2.27	4.12	0.000
Upper central (ref.: upper lateral)	1.65	0.66	2.63	0.001
Female (ref.: male)	-0.93	-1.70	-0.15	0.019
Lower canine * Female (ref.: lower canine * male)	-0.83	-1.94	0.27	0.138
Lower lateral * Female (ref.: lower lateral * male)	0.20	-0.93	1.32	0.733
Lower central * Female (ref.: lower central * male)	-0.36	-1.48	0.76	0.526
Upper canine * Female (ref.: upper canine * male)	-1.61	-2.67	-0.54	0.003
Upper central * Female (ref.: upper central * male)	-0.56	-1.68	0.56	0.328

ref.: reference

Supplementary Table S4. Estimated marginal means for the factors sex and tooth type. The F tests the effect of these factors based on the linearly independent pairwise comparisons among the estimated marginal means.

	Mean	Std. Error	95% Confidence Interval		F	P - value
			Lower Bound	Upper Bound		
Tooth type						
Lower canine	2.13	0.20	1.73	2.52	20.76	0.000
Lower lateral	1.02	0.21	0.61	1.43		
Lower central	2.01	0.21	1.60	2.41		
Upper canine	3.30	0.19	2.93	3.67		
Upper lateral	0.90	0.20	0.52	1.29		
Upper central	2.27	0.21	1.86	2.68		
Sex						
F	1.21	0.08	1.05	1.37	74.57	0.000
M	2.66	0.15	2.38	2.95		

Supplementary Table S5. Spearman's correlations of tooth wear amount between the different tooth types.

		Upper canine	Upper lateral	Upper central	Lower canine	Lower lateral	Lower central
Upper canine	Spearman's ρ		0.70	0.57	0.81	0.51	0.49
	P-value		0.000*	0.000*	0.000*	0.000*	0.000*
	N		67	65	64	60	56
Upper lateral	Spearman's ρ	0.70		0.58	0.61	0.48	0.39
	P-value	0.000*		0.000*	0.000*	0.000*	0.004*
	N	67		63	61	58	54
Upper central	Spearman's ρ	0.57	0.58		0.55	0.66	0.53
	P-value	0.000*	0.000*		0.000*	0.000*	0.000*
	N	65	63		60	57	53
Lower canine	Spearman's ρ	0.81	0.61	0.55		0.62	0.48
	P-value	0.000*	0.000*	0.000*		0.000*	0.000*
	N	64	61	60		61	56
Lower lateral	Spearman's ρ	0.51	0.48	0.66	0.62		0.61
	P-value	0.000*	0.000*	0.000*	0.000*		0.000*
	N	60	58	57	61		53
Lower central	Spearman's ρ	0.49	0.39	0.53	0.48	0.61	
	P-value	0.000*	0.004*	0.000*	0.000*	0.000*	
	N	56	54	53	56	53	

*Significant correlations with $p < 0.05$

Chapter 6

General discussion

Tooth wear impact

Tooth wear comprises a challenge that contemporary dental professionals have to face in a daily basis. This is primarily because of the following three reasons that underline the importance of the specific condition. Firstly, tooth wear is observed in all living humans, and the vast majority of them have at least one tooth that is considerably affected, already at the early stages of adult life (Gkantidis et al. 2021a). Secondly, tooth wear is a condition which progresses over time, and thus the more a dentition is functioning within an individual, the higher the tooth wear amount will occur. In recent years, the life expectancy of modern humans has increased considerably, leading to the necessity for functioning of the permanent dentition for more than seventy years on average. Lastly, in contemporary societies the patient demands have also increased, seeking functionality combined with a pleasant esthetic appearance (Lussi and Carvalho 2014).

Dentistry responded to this shift incorporating Oral Health Related Quality of Life (OHRQoL) measures in clinical research and practice (Sischo and Broder 2011). These subjective measures reflect “people’s comfort when eating, sleeping and engaging in social interaction; their self-esteem; and their satisfaction with respect to their oral health” (DHHS, 2000). Anyone’s life can be affected by alterations of oral health in any of the components stated above (Sischo and Broder 2011). Tooth wear has been shown to affect both functional and esthetic components impacting quality of life (Wazani et al. 2012; Al-Allaq et al. 2018). Dentine hypersensitivity, pain, difficulty in eating and chewing and tooth or restoration fractures are among the functional problems that have been related to tooth wear (Wazani et al. 2012; Olley et al. 2015). However, esthetic concerns are the main reason leading patients to seek treatment (Wazani et al. 2012; Betrine Ribeiro et al. 2017; Machado et al. 2013; Sobral et al. 2019). This is not surprising, since the face is the most influencing factor in human interactions (Little et al 2011; Kanavakis et al. 2021) and the smile a major component that dominates perception in interpersonal communication (Horn et al. 2021). This also explains why dissatisfaction with smile has been identified as the major reason for adults to seek orthodontic treatment (Pabari et al. 2011).

Tooth wear assessment methods

Despite the very high prevalence of tooth wear in the population and its impact on patient's quality of life, which demonstrate the importance of the condition, the currently available diagnostic tools present severe limitations. Due to these limitations, data on the extent of the problem in the population, especially over a long-term period are limited (Gkantidis et al. 2021a) and accurate individual patient monitoring over time is difficult (Gkantidis et al. 2020a; Gkantidis et al. 2020b; Gkantidis et al. 2021b). Thus, the present thesis aimed to develop accurate and clinically applicable 3D tooth wear assessment methods for a range of possible clinical occurrences and apply these methods to determine the anterior occlusal tooth wear that should be expected from adolescent to adulthood in a modern human population, following the completion of orthodontic treatment.

So far, the most widely used methods for tooth wear assessment are qualitative, based on indices, such as the Basic Erosive Wear Examination (BEWE) (Bartlett et al. 2008), the New Tooth Wear Index (NTWI) (Hooper et al. 2004), or the Smith and Knight index (Smith and Knight 1984). These methods have been widely applied for clinical and research purposes because they are simple, easy to use, and they are not time-consuming. However, their main shortcoming is the subjectivity that results in reduced precision and reproducibility (Al-Omiri et al. 2013; Wulfman et al. 2018).

To overcome these limitations, quantitative techniques have been also applied in the past, but mainly for research purposes, due to their high complexity that requires expertise and special equipment. A further drawback of these techniques, including digital profilometry and 3D surface matching, was that their performance was solely assessed through reproducibility testing, since no true reference, required for accuracy testing, was available in most existing studies (Ahmed et al. 2017; Wulfman et al. 2018). Additionally, certain studies testing these methods compared only differences between corresponding measurements in terms of group means. This is inadequate when testing diagnostic methods, which should be able to work properly in each individual case (Bland and Altman 1995). Finally, these methods required the use of intraoral impressions and stone model construction, adding potential

sources of error in the process. Despite the methodological issues of certain existing studies, there are such techniques that show high accuracy, at a range of 15 to 20 μm , in terms of vertical loss of crown height. Thus, the high complexity of these methods, which increases the costs, resources and time required to be applied, is the main reason hindering their widespread use.

Advancements through the present work

The work presented in the current thesis attempts to provide the clinician and researcher with useful, risk-free 3D diagnostic tools of high accuracy, which are at the same time easily applicable, with limited training and reasonable costs.

A search for previous attempts in the same direction, resulted in a freeware, user-friendly software named WearCompare that was developed by the University of Leeds (<https://leedsdigitaldentistry.com/wearcompare.html>; accessed on 25.07.2021) (O'Toole et al 2019). Similar to our methodology, this group suggested the 3D superimposition of serial tooth surface models for occlusal tooth wear assessment. The suggested method was reported to provide optimal outcomes when duplicated surface models were superimposed, but not when the original position of the duplicates were altered or on actual patient data (O'Toole et al 2019), where the superimposed surfaces are almost never identical. A recent study testing the agreement of this method to a qualitative one (BEWE index) reported limited sensitivity and specificity (Marro et al. 2020), although qualitative approaches do not allow for an accurate wear quantification (Al-Omiri et al. 2013; Perry et al. 2000; Wetselaar et al. 2016).

On the contrary, we performed thorough testing of our methods on various clinical scenarios that might occur in an individual and compared the outcomes to the true reference value, obtained following superimposition of serial models on intact structures (Gkantidis et al. 2020a; Gkantidis et al. 2020b; Gkantidis et al. 2021b; Henninger et al. 2019; Winkler and Gkantidis 2020). At first, we developed a 3D method to assess occlusal tooth wear on teeth that were intact in all surfaces, apart from the occlusal (Gkantidis et al. 2020a). Then, we tested various similar approaches in cases of limited changes in non-occlusal surfaces, such as those induced by dental caries, fillings, tooth wear, or other factors (Bartlett et al. 2013; Gkantidis et al. 2010; Iliadi et al. 2015) and concluded that the previously developed approach (Gkantidis et al. 2020a)

provided the best outcomes also in such cases (Gkantidis et al. 2020b). Finally, we simulated the placement of an orthodontic wire retainer on lingual tooth surfaces to test the scenario of extensive changes on non-occlusal surfaces, additionally to occlusal wear. Such wires are quite often placed in orthodontic patients at the completion of their treatment, for long-term retention of the outcome (Iliadi et al. 2015). Thus, it is expected to be quite common for an orthodontic patient to have a dental model without and a future model with an orthodontic retainer that need to be superimposed to assess tooth wear. It became evident that in the latter case certain modifications are required to provide optimal assessments (Gkantidis et al. 2021b). The above circumstances cover a wide range of clinical occurrences, in terms of possible changes of the models to be superimposed, which represent the vast majority of occlusal tooth wear assessment cases.

The perfect registration achieved following superimposition of serial models on intact structures provided the true measurement. The in vitro methodology applied here allowed for this, since in actual patient data no structure can be considered intact between two different time points. Even consecutive intraoral scans will insert an amount of error attributed to the acquisition method itself (Henninger et al. 2019; Winkler and Gkantidis 2020). Thus, with the present methodology, the true values obtained with the reference technique were compared to those of clinically applicable methods, allowing the identification of easily applicable methods that provide highly accurate outcomes.

Utilization of the study findings

With the methodology suggested on this thesis, following proper registration of two or more serial tooth models, outcomes can be visualized through color-coded distance maps and accurately quantified as needed (e.g. vertical loss at any surface point, mean vertical loss of a selected surface area, or volume loss). The application of the presented methods prerequisites the existence of serial 3D digital dental models (Gkantidis et al. 2020a; Gkantidis et al. 2020b; Gkantidis et al. 2021b), specific 3D analysis software and short training. Providing that detailed tooth wear assessment in one tooth requires approximately 2–3 min, in large-scale studies or in a busy practice where time

restrictions might apply, the use of index teeth can be a viable solution (O'Toole et al. 2020).

Considering the high level of information obtained by the application of the suggested methods and the very high incidence of tooth wear in the population (Schierz et al. 2014; Awad et al. 2019; Marro et al. 2020; Gkantidis et al. 2021a), we suggest that a dental model, if possible generated through an intraoral scan, is acquired from every patient that attends a dental practice, at the early stages of permanent dentition. This model can provide the reference to be superimposed and compared with future models of the same individual, enabling the accurate monitoring of morphological changes in the oral tissues, such as regarding tooth wear (Gkantidis et al. 2020; Gkantidis et al. 2020b; Gkantidis et al. 2021b). Similarly, an intraoral dental model can also be obtained after the placement of a restoration that requires monitoring. Depending on the risks and the specific characteristics of each case, the treating dentist should define the time span between consecutive diagnostic scans on an individual basis. Scanned stone models created following conventional impressions might also serve this purpose. However, stone models require additional costs and physical storage and they can be subjected to dimensional changes over time (Ahmed et al. 2016).

The fast incorporation of intraoral scanners in everyday practice makes this possible at no extra cost and with minimal training (Stucki and Gkantidis 2020; Winkler and Gkantidis 2020). The current high-end scanners available in the market offer adequate accuracy, especially when considering small structures, such as single teeth, which are used here for tooth wear assessment (Gkantidis et al. 2020a; Gkantidis et al. 2020b; Gkantidis et al. 2021b; Winkler and Gkantidis 2020; Winkler and Gkantidis 2021).

Application of the developed methods on actual clinical data

At the final part of this thesis, the newly developed methods were applied on a longitudinal sample to identify patterns of occlusal tooth wear in the anterior dentition of modern humans from adolescent to adulthood (Gkantidis et al. 2021a). In the literature, the information regarding the precise tooth wear amount that should be expected in a population over a medium- to long-term period is scarce. There is one long-term cross-sectional study on 2D

radiographs (Ray et al. 2015), a small longitudinal study on 10 middle-aged patients with nocturnal bruxism followed over a 4-year period (Korkut et al. 2020) and a 3-year longitudinal study on 29 adults referred for tooth wear management (O'Toole et al. 2020). The study presented on this thesis offers unique information based on a robust sample of 72 orthodontically treated individuals that are representative of the general population and were followed over an average period of 13 years. This period extends from the early years of full establishment of the permanent dentition to maturation in adulthood. The anterior tooth wear occurrence was widespread in the population with 93% of the tested individuals having at least one tooth with wear higher than 1 mm³ over the assessment period. The average wear per anterior tooth was 1.58 mm³, with approximately 50% of the tested teeth showing values higher than 1 mm³ (Gkantidis et al. 2021a).

Implications of the study findings

By precisely identifying the significant extent of the problem, the present findings highlight the need for early diagnosis and development of effective prevention and management tools. Tooth wear management is complex. Thus, early diagnosis, especially of high risk cases is crucial to identify individuals that should be subjected to timely targeted preventive or interceptive measures. These measures are relatively simple and cease the advancement of the problem to a degree that would require complex management with questionable long-term outcomes (Loomans and Opdam 2018). For example, a preventive intervention could be the prescription of mouth guards to limit grinding or the cessation of harmful habits, such as acidic food, which lead to tooth wear. An interceptive intervention would be to restore the lost tooth substance, and thus, stop the progress of the condition and improve esthetics and function. Apart from the known general prognostic factors, such as sex (Cunha-Cruz et al. 2010; Schierz et al. 2014; Gkantidis et al. 2021a) or acidic food (Kitasako et al. 2015; Liu et al. 2014; Awad et al. 2019; Olley et al. 2015), early diagnosis at an individual level will define the need for close monitoring with regular follow-ups and also enable the early identification and elimination of potential causative factors in high-risk patients. Within a dentition, there was an association between the tooth wear extent on individual teeth, indicating a

general effect of the predisposing or causative factors (Gkantidis et al. 2021a). This is in accordance with recent findings suggesting the use of index teeth, namely the upper central incisors, for tooth wear detection, instead of screening all teeth in a dentition (O'Toole et al. 2020). This enables the precise clinical screening of dental patients, as well as the implementation of the current methods in large scale studies, using reasonable resources.

Future perspectives

Due to the reasons explained above, the patient is expected to largely benefit from the developed methods in terms of oral health status. The accurate diagnosis of tooth wear, even at very early stages, using relatively simple means is of utmost importance for our patients, since the multifactorial etiology of this condition impedes the accurate detection of high-risk individuals prior to the development of the problem. Furthermore, the implementation of the current methods in associated research, will provide high level of information at reasonable costs, enabling the generation of accurate data in large scale studies. This will facilitate the better understanding of the problem in terms of etiology, progress, prevention, management and effect on OHRQoL. For example, there are studies in the literature indicating a negative impact of orthodontics on tooth wear progression during active treatment. However, the issue remains debatable and an important factor contributing to this controversy is the lack of precision of the existing studies (Makrygiannakis et al. 2018).

Concluding remarks

Summarizing, in the present thesis we developed highly informative and accurate 3D occlusal tooth wear assessment methods that are can be incorporated in clinical settings and implemented in large-scale studies with reasonable costs, time, and human resource needs. We tested the robustness of these methods under various clinical scenarios and suggested certain modifications that cover a large spectrum of incidences that might be evident in real-life conditions. Finally, we applied these methods on a longitudinal sample of orthodontically treated patients, representative of the general population, to define the extent of the problem at the onset of functioning of the permanent dentition, over a long-term period. Based on the work presented on this thesis the following conclusions can be drawn:

1. Using currently developed methods and easily accessible software applications, as well as intraoral scanners, accurate 3D tooth wear assessment is possible with reasonable training, costs, and time requirements.
2. The methods need to be adapted according to the extent of surface changes of the superimposed tooth crowns.
3. The incidence of tooth wear that might be considered to require monitoring and potential intervention is very high in the population already in early adulthood.
4. Due the above considerations, the acquisition of an intraoral reference model at the early permanent dentition is suggested for every patient to facilitate tooth wear monitoring through superimposition with future models of the same individual.
5. Based on the endemic occurrence of the tooth wear, future research should elaborate further on the impact of tooth wear on patient's quality of life and aim on the development of efficient preventive measures and management protocols.

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Summary

In this Thesis, easily applicable, but highly accurate, three-dimensional tooth wear assessment methods were developed and applied in actual orthodontic patient data to detect long-term tooth wear occurrence from adolescence to adulthood. **Chapter 1** identifies the problem in terms of high prevalence in the population and limitations of the currently available methods, setting the background to support the study aims.

Tooth or material wear in a dentition is a common finding that requires timely diagnosis for management and prevention of further loss and associated esthetic or functional impairment. Various qualitative and quantitative methods have been suggested to measure tooth or material wear, but they present with limitations, such as imprecision, subjectivity, or high complexity. In **Chapter 2**, we introduce an efficient 3D superimposition method, developed to accurately measure occlusal tooth wear on 3D digital dental models. For this purpose, teeth on plaster casts were manually grinded on their occlusal surfaces to simulate various degrees of tooth wear. The casts were scanned using a surface scanner. Grinded tooth crowns (T1) were segmented and compared to the original crowns (T0) using five 3D surface superimposition techniques and a gold standard technique (GS). GS measurements were obtained by using intact adjacent structures as superimposition references. The technique of choice (complete crown with 30% estimated overlap of meshes) showed the best reproducibility (maximum difference < 0.050 mm³) and excellent agreement with the GS technique (median difference: 0.032 mm³). The suggested 3D superimposition method offers a highly efficient and accurate tool for tooth wear assessment, which could be applicable to clinical conditions.

The method described above was developed for teeth that underwent changes in their occlusal surfaces, but were otherwise intact. In **Chapter 3**, we present the development of an accurate and convenient 3D occlusal tooth wear assessment technique for cases where surfaces other than the occlusal undergo additional changes during the observation period. For this, various degrees of occlusal tooth wear were simulated in vitro on 18 molar and 18 premolar plaster teeth. Additionally, their buccal and lingual surfaces were gently grinded to induce superficial changes, and digital dental models were generated. The

grinded and the original tooth crowns were superimposed using six different 3D techniques (two reference areas with varying settings; gold standard: GS). Superimposition on intact structures provided the GS measurements. Tooth wear volume comprised the primary outcome measure. All techniques differed significantly to each other in their accuracy ($p < 0.001$). The technique of choice (CCD: complete crown with 30% estimated overlap of meshes) showed excellent agreement with the GS technique (median difference: 0.045, max: 0.219 mm³), no systematic error and sufficient reproducibility (max difference < 0.040 mm³). Tooth type, tooth alignment in the dental arches, and amount of tooth wear did not significantly affect the results of the CCD technique ($p > 0.01$). The suggested occlusal tooth wear assessment technique is straightforward and offers accurate outcomes when limited morphological changes occur on surfaces other than the occlusal.

Previous investigations, including those presented in Chapters 2 and 3, suggested different methods for tooth wear assessment, but no study has developed a three-dimensional (3D) superimposition technique applicable in cases where tooth surfaces, other than the occlusal, undergo extensive morphological changes. A common occurrence of such a condition regards orthodontic patients that regularly receive a wire retainer, bonded to the lingual aspects of the anterior teeth, to stabilize the orthodontic treatment result. Therefore, in **Chapter 4**, we manually grinded plaster incisors and canines to simulate incisal tooth wear of varying severity in teeth that received an orthodontic wire retainer, bonded on their lingual surfaces during the assessment period. The corresponding dental casts were scanned using a surface scanner. The modified tooth crowns were best-fit approximated to the original crowns using seven 3D superimposition techniques (two reference areas with varying settings) and the gold standard technique (GS: intact adjacent teeth and alveolar processes as superimposition reference), which provided the true value. Only a specific technique (complete crown with 20% estimated overlap of meshes), which is applicable in actual clinical data, showed perfect agreement with the GS technique in all cases (median difference: -0.002, max absolute difference: 0.178 mm³). The outcomes of the suggested and the GS technique were highly reproducible (max difference < 0.040 mm³). The presented technique offers low cost, convenient, accurate, and risk-free

tooth wear assessment and should be applied in cases of extensive changes in non-occlusal surfaces, instead of the technique presented in Chapters 2 and 3.

Tooth wear is expected at a certain level in every person, and it increases with age. In the last decades, due to the increased life expectancy and the high patient demands, it has become an important problem modern dentistry has to face. However, the average amount of tooth wear among individuals remains controversial. The methods developed and reported in Chapters 2-4 of this Thesis enable the precise measurement of occlusal tooth wear using convenient tools and techniques that was problematic so far. In **Chapter 5**, the newly developed methods were applied on a longitudinal cohort of orthodontically treated individuals to determine the precise amount of occlusal tooth wear in the anterior permanent dentition from adolescence to adulthood. This cohort was followed from the completion of active orthodontic treatment to an average period of 13 years. Corresponding tooth crowns from serial 3D digital dental models of 72 individuals were best fit-approximated by applying novel, highly accurate 3D superimposition methods. The superimposed crowns were simultaneously sliced on intact structures, and the differences in the volumes of the subsequent occlusal parts were calculated. Over a thirteen-year period, there was an average loss of anterior occlusal surfaces of 1.58 mm³ per tooth. Tooth surface loss in at least one tooth of a dentition was higher than 1 mm³ in 93.1% of the human subjects. Tooth wear severity differed by sex and tooth type, with males showing higher values versus females and upper canines higher values versus other anterior teeth. The study revealed the endemic occurrence of occlusal anterior tooth wear, highlighting the need for monitoring of the condition in the population to identify high-risk patients and enable timely interventions. The novel methods applied here on 3D digital models and presented in Chapters 2-4 are recommended for this.

In the general discussion in **Chapter 6**, the background knowledge on the subject is presented and discussed in relation to the results of the studies included in the present thesis, from a clinical perspective, demonstrating the contribution of our research findings in the field and suggesting future research opportunities.

Samenvatting

In dit onderzoek werden eenvoudig toepasbare, maar zeer nauwkeurige driedimensionale meetmethoden voor gebitsslijtage ontwikkeld en toegepast bij orthodontische behandelde patiënten om het optreden van gebitsslijtage over langere termijn – van adolescentie tot volwassenheid – te bepalen.

Hoofdstuk 1 geeft achtergrondinformatie en duiding aan het probleem gebitsslijtage in termen van prevalentie en beperkingen van de momenteel beschikbare meetmethoden, ter ondersteuning van de doelen van dit onderzoek.

Gebitsslijtage komt veelvuldig voor, waarbij een vroegtijdige diagnose en behandeling vereist is om verder weefselverlies en de daarmee samenhangende verminderde esthetiek of functie te beperken. Er zijn verschillende kwalitatieve en kwantitatieve methoden voorgesteld om gebitsslijtage te meten, maar deze hebben beperkingen, zoals onnauwkeurigheid, subjectiviteit of ze zijn erg complex. In **Hoofdstuk 2** wordt een efficiënte 3D-superponeermethode geïntroduceerd die ontwikkeld werd om occlusale gebitsslijtage nauwkeurig te meten op 3D digitale gebitsmodellen. Voor dit doel werd gebitsslijtage van verschillende ernst gesimuleerd door de occlusale vlakken van gebitselementen op gipsmodellen te beslijpen. De gipsmodellen werden met een oppervlaktescanner gescand. De beslepen kronen (T₁) werden gesegmenteerd, en met behulp van vijf 3D-superponeertechnieken en een gouden standaardtechniek (GS) vergeleken met de originele kronen (T₀). GS-metingen werden verkregen door intacte aangrenzende structuren als referenties te gebruiken voor het superponeren. De techniek van keuze (complete kroon met 30% overlap van mazen) vertoonde de beste reproduceerbaarheid (maximaal verschil <0,050 mm³) en een uitstekende overeenkomst met de GS-techniek (mediaan verschil: 0,032 mm³). De voorgestelde 3D-superponeermethode is een zeer efficiënt en nauwkeurig hulpmiddel voor het beoordelen van gebitsslijtage, dat toegepast kan worden in klinische situaties.

Bovenstaande methode werd ontwikkeld voor gebitselementen die veranderingen hebben ondergaan bij de occlusale vlakken, maar verder intact waren. In **Hoofdstuk 3** presenteren we de ontwikkeling van een nauwkeurige en doelmatige 3D-techniek ter beoordeling van casus waarbij tijdens de observatieperiode, naast occlusale gebitsslijtage, ook andere oppervlakken

veranderingen ondergaan. Hiertoe werden in vitro verschillende hoeveelheden occlusale gebitsslijtage gesimuleerd bij 18 molaren en 18 premolaren die waren vervaardigd uit gips. Bovendien werden hun buccale en linguale oppervlakken voorzichtig beslepen om oppervlakkige veranderingen teweeg te brengen. Hiervan werden digitale gebitsmodellen gegenereerd. De beslepen en de originele tandkronen werden gesuperponeerd met behulp van zes verschillende 3D-technieken (twee referentiegebieden met verschillende instellingen; gouden standaard: GS). Superponeren op intacte structuren leverde de GS-metingen op. Het volume van de gebitsslijtage vormde de primaire uitkomstmaat. Alle technieken verschilden significant van elkaar in hun nauwkeurigheid ($p < 0,001$). De techniek van keuze (CCD: complete kroon met 30% geschatte overlap van mazen) vertoonde een uitstekende overeenkomst met de GS-techniek (mediaan verschil: 0.045, max: 0.219 mm³), geen systematische fout en voldoende reproduceerbaarheid (max. verschil < 0.040 mm³). Type gebitselement, al dan niet opgelijnde tandbogen en de hoeveelheid gebitsslijtage hadden geen significante invloed op de resultaten van de CCD-techniek ($p > 0,01$). De voorgestelde occlusale gebitsslijtage-beoordelingstechniek is eenvoudig en biedt nauwkeurige metingen wanneer beperkte morfologische veranderingen optreden op andere oppervlakken dan de occlusale vlakken.

Eerdere onderzoeken, waaronder die gepresenteerd in hoofdstuk 2 en 3, hebben verschillende methoden voorgesteld voor het beoordelen van gebitsslijtage, maar geen enkele studie heeft een 3D-superponeertechniek ontwikkeld die toepasbaar is in casus waarin tandoppervlakken anders dan de occlusale vlakken, uitgebreide morfologische veranderingen ondergaan. Dit fenomeen wordt veelvuldig waargenomen bij orthodontisch behandelde patiënten waarbij een spalk wordt bevestigd op de linguale vlakken van de frontelementen, om het resultaat van de orthodontische behandeling te stabiliseren. Daarom werden in **Hoofdstuk 4** incisieven en cuspidaten op gipsmodellen beslepen om incisale gebitsslijtage van verschillende ernst te simuleren bij frontelementen waar een orthodontische spalk bevestigd was op de linguale vlakken. De gipsmodellen werden vervolgens gescand met een oppervlaktescanner. De beslepen en de originele kronen werden volgens de best-fit methode gesuperponeerd met behulp van zeven 3D-technieken (twee

referentiegebieden met verschillende instellingen) en de gouden standaardtechniek (GS: intacte buurelementen en de processus alveolaris als referentie voor het superponeren), die de juiste waarde opleverden. Alleen een specifieke techniek (volledige kroon met 20% geschatte overlap van mazen), die toepasbaar is bij echte klinische metingen, toonde in alle gevallen een perfecte overeenkomst met de GS-techniek (mediaan verschil: -0,002, max absoluut verschil: 0,178 mm³). De uitkomsten van de voorgestelde en de GS-techniek waren uitstekend reproduceerbaar (max verschil < 0,040 mm³). De voorgestelde techniek biedt een goedkope, eenvoudige, nauwkeurige en risicovrije beoordeling van gebitsslijtage en dient te worden toegepast in geval van uitgebreide veranderingen van niet-occlusale oppervlakken, in plaats van de techniek voorgesteld in hoofdstuk 2 en 3.

Een zekere vorm van gebitsslijtage kan bij ieder individu worden verwacht en neemt toe met de leeftijd. De afgelopen decennia is, door de toegenomen levensverwachting en de hoge eisen van de patiënt, gebitsslijtage geworden tot een belangrijk probleem, waarmee de huidige tandheelkundige professie wordt geconfronteerd. De gemiddelde hoeveelheid tandslijtage onder individuen blijft echter controversieel. De methoden die zijn ontwikkeld en beschreven in Hoofdstukken 2-4 van dit proefschrift maken het mogelijk occlusale gebitsslijtage met behulp van geschikte hulpmiddelen en technieken nauwkeurig te meten, hetgeen tot dusver moeilijk uitvoerbaar was. In **Hoofdstuk 5** werden de nieuw ontwikkelde methoden toegepast op een longitudinaal cohort van orthodontisch behandelde individuen om de exacte hoeveelheid occlusale gebitsslijtage bij de frontelementen vanaf de adolescentie tot de volwassenheid te bepalen. Het cohort werd vanaf de afronding van de actieve orthodontische behandeling, gedurende een gemiddelde periode van 13 jaar, gevolgd. Overeenkomstige kronen van seriële 3D digitale gebitsmodellen van 72 individuen werden met nieuwe, zeer nauwkeurige best-fit 3D-superponeermethoden beoordeeld. De gesuperponeerde kronen werden tegelijkertijd vergeleken met intacte structuren en de verschillen in de volumes van de occlusale vlakken werden berekend. Over een periode van dertien jaar was er een gemiddeld verlies van occlusale vlakken van 1,58 mm³ per frontelement. Bij 93,1% van de proefpersonen was het oppervlakverlies in ten minste één gebitselement meer dan 1 mm³. De ernst van de gebitsslijtage

verschilde per geslacht en type gebitselement, waarbij mannen hogere waarden vertoonden dan vrouwen en bovencuspидaten hogere waarden vertoonden dan overige frontelementen. De studie legde het endemisch voorkomen van occlusale slijtage van frontelementen bloot, wat de noodzaak van het monitoren van de aandoening benadrukt om risicopatiënten te identificeren en tijdig te interveniëren. De nieuwe methodes die hier op digitale 3D-modellen worden toegepast en in de hoofdstukken 2-4 worden gepresenteerd, worden hiervoor aanbevolen.

In de algemene discussie in **Hoofdstuk 6** wordt, vanuit een klinisch perspectief, de achtergrondkennis over het onderwerp gepresenteerd en ter discussie gesteld in relatie tot de resultaten van de studies die in dit proefschrift zijn opgenomen, waarmee de bijdrage van onze onderzoeksresultaten in het veld wordt aangetoond en voorstellen voor toekomstige onderzoeksmogelijkheden worden gedaan.

Curriculum Vitae

Nikolaos Gkantidis is since 2016 a full-time staff member at the Department of Orthodontics and Dentofacial Orthopedics, University of Bern, Switzerland. Besides his clinical and research work, he is involved in under- and post-graduate teaching, as well as in research supervision. From 2012 to 2016 he was a part-time staff member of the Department.

Nikolaos Gkantidis graduated in 2006 from the Dental School of the Aristotle University of Thessaloniki, Greece and followed afterwards a combined Master of Science and Orthodontic specialty program at the University of Athens, from where he graduated with honours in 2010. From 2010 to 2016 he run a private practice in Thessaloniki, specialised in multidisciplinary treatment of orthodontic patients.

His main research areas of interest include the development and utilisation of 3D imaging techniques in clinical research and practice, the perceived effects of various treatments on facial attractiveness, and the utilisation of geometric morphometric techniques for the investigation of hypotheses concerning facial shape and size. Currently, he is the Editor-in-Chief of the Topic “Diagnosis of Craniofacial Changes: Conventional Approaches and Novel Methodologies”, which involves five scientific journals (<https://www.mdpi.com/topics/diagnosis>) and he serves as the President of the Scientific Committee of the Annual Congress of the European Orthodontic Society in 2022, Limassol, Cyprus.

A list of Nikolaos Gkantidis publications in the scientific literature can be found online on:

<https://pubmed.ncbi.nlm.nih.gov/?term=gkantidis&sort=date&size=100>

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