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TECHNICAL NOTE

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Quantification of dental macrowear using 3D occlusal surface topographic measurements in deciduous and permanent molars of children

Marlon Bas[1,2] | Lukas Waltenberger[2] | Christoph Kurzmann[3] | Patrick Heimel[4,5,6] | Katharina Rebay-Salisbury[2] | Fabian Kanz[1]

[1]Unit of Forensic Anthropology, Medical University of Vienna, Centre for Forensic Medicine, Vienna, Austria
[2]Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria
[3]Spezialambulanz Digitale Zahnheilkunde (Special Clinic for Digital Dentistry), Medical University of Vienna, University Clinic of Dentistry, Vienna, Austria
[4]Karl Donath Laboratory for Hard tissue and Biomaterial Research, Medical University of Vienna, University Clinic of Dentistry, Vienna, Austria
[5]Ludwig Boltzmann Institute for Experimental and Clinical Traumatology, Vienna, Austria
[6]Austrian Cluster for Tissue Regeneration, Vienna, Austria

Correspondence
Marlon Bas, Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria.
Email: marlon.bas@oeaw.ac.at

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Abstract

Objectives: Childhood paleodietary reconstruction via dental macrowear analysis is limited in part by available methods to measure dental macrowear. We describe a method to quantify dental macrowear progression (in both deciduous and permanent molars) using a handheld intraoral scanner and two 3D occlusal topographic measurements. We assess the agreement of our macrowear proxies with an established qualitative wear scoring system and their relationship to age.

Material and methods: We scanned 92 well-preserved dentitions of immature individuals from the medieval cemetery of St. Pölten in Lower Austria using an intraoral scanner. Two measurements were made on the resulting mesh files—the relative flat surface area in % of the occlusal surface (RFSA%) and the mesial interior slope angle. We estimated the technical error of measurement (TEM). Comparisons were made with the macrowear scoring system—tooth wear index.

Results: We found that TEM for both measurements was between 1 and 3%, except the interobserver TEM of RFSA% which was above 5%. Both quantitative measurements generally agree with the established qualitative scores and correlate with age; however, RFSA% does not reliably indicate the progression of macrowear for teeth after dentine exposure occurs.

Discussion: The proposed 3D topographic measurements can be made reliably, and within a certain range of wear provide good quantitative proxies of the progression of dental macrowear. Such measurements constitute a promising approach for improving dental macrowear analysis in contexts such as childhood paleodietary reconstruction, which benefit from additional precision in wear rate estimation and present less dentine exposure.

KEYWORDS
dental wear, intraoral scanner, nonadult, occlusal topography, paleodietary reconstruction

1 | INTRODUCTION

During childhood, the human stomatognathic system (teeth, jaws, and associated soft tissues) experiences continuous changes in anatomy and function (Hillson, 1996). However, not all changes are the result of ontogenetic developmental processes; environmental processes such as dental wear also act upon the dentition during the first years of life. The accumulation of wear at the macroscopic scale (dental macrowear) is of interest for the bioanthropological analysis of human remains, both as a means for age estimation and paleodietary reconstruction (Rose & Ungar, 1998; Watson & Schmidt, 2020). Paleodietary reconstruction via dental macrowear analysis is based on the observation that the rate and distribution of macrowear can vary between individuals with different diets and environments (McKee & Molnar, 1988; Molnar, 1971; E. C. Scott, 1979a, 1979b). It has been suggested in studies of microscopic dental wear, that differences in weaning strategies, exposure to abrasives, and the physical properties of available foods during childhood influence the process of dental wear (Hernando et al., 2020; Mahoney et al., 2016; R. M. Scott & Halcrow, 2017). However, due to the limitations of available dental macrowear analysis methods (Rose & Ungar, 1998; Watson & Schmidt, 2020), there are few studies of macroscopic dental wear variation between children (Mays, 2016; R. M. Scott & Halcrow, 2017). Most macrowear analysis methods were developed for adults and are not well suited to capture small amounts of wear, especially wear that occurs before dentine exposure. To address these issues, this article describes and evaluates the use of an intraoral scanner and occlusal topographic measurements as an alternative or complementary method to estimate the amount of wear that has occurred in both deciduous and permanent molars.

Presently, most research into human dental wear is conducted using scoring systems that assign a qualitative ordinal score to each tooth based on a variety of indicators of the progression of dental macrowear. These indicators include the presence of wear facets, the rounding of cusps, and the exposure of dentine on the occlusal surface (Molnar, 1971; Rose & Ungar, 1998; E. C. Scott, 1979a, 1979b). A widely used example is the tooth wear index (TWI) proposed by B. G. Smith and Knight (1984). Several paleodietary studies have successfully employed these qualitative ordinal scores to approximate wear rates, calculated mostly in adults, to detect broad differences between the wear rates of forager, agrarian, and industrialized populations (D'Incau et al., 2012; Rose & Ungar, 1998). However, these methods are limited in precision, and describe the progression of wear through ordinal variables (Rose & Ungar, 1998). An alternative is therefore to attempt to quantify the degree of dental macrowear, by measuring crown height (Walker et al., 1991) for large amounts of wear (Rose & Ungar, 1998), or by quantifying the relative amount of dentine exposure on the occlusal surface measured on photos (Clement & Freyne, 2012; Deter, 2009; Lunt, 1978). However, in our sample of children, half the deciduous molars and almost all the permanent molars do not present any dentine exposure. Current available methods are therefore not well suited to quantifying the degree of dental macrowear during the first years of childhood; we therefore propose a new method based on changes to occlusal topography as enamel is removed. Estimating the amount of enamel removed is difficult, the measurement must systematically follow changes in the tooth as it wears down, whilst simultaneously presenting limited sensitivity to phenotypic variation between individuals prior to wear. Out of many possible measurements of occlusal topography, we propose two new measurements described in this article, the relative flat surface area in percent of the occlusal surface (RFSA%) and the mesial interior slope angle (MISA) (Figure 1.). As well as being quantitative and non-dentine based, the proposed dental macrowear measurements have two additional advantages. Firstly, they can be made within minutes on a lightweight digital 3D surface model (a few megabytes) produced using an accessible handheld scanner, and free open source software. Secondly, they may contribute to dental microwear analysis, as they describe features of the occlusal surface that likely relate to dental microwear formation and measurement (Bas et al., 2020).

The objective of this technical note is to describe a new method for quantifying the progression of dental macrowear, using a well-preserved sample of medieval children. We first ascertain if the proposed measurements can be made reliably by measuring the technical error of measurement (TEM) (Harris & Smith, 2009; Perini et al., 2005; Stull et al., 2014). Then, to estimate accuracy, we compare our measurements with an established qualitative macrowear scoring system (as done by Deter to validate the use of the percentage of dentine exposure for dental wear quantification) (Deter, 2006, 2009) and examine the relationship between these measurements and the age of children in our sample. We finally discuss the suitability, potential application, and limitations of topographic dental macrowear proxies and their use in childhood palaeodietary reconstruction and similar contexts, as well as their expected advantages and drawbacks relative to established methods.

2 | MATERIALS AND METHODS

Our study was carried out on a sample of 92 subadult individuals from St. Pölten Domplatz, a medieval cemetery excavation in Lower Austria. The site was excavated recently between 2010 and 2019 as part of a rescue archaeology effort (Risy & Kanz, 2019). Most individuals in our sample (76 individuals—82.6%) were from a mass grave (Mass grave 6), containing about 200 individuals, a majority of whom were subadults, buried over a relatively short period. Additionally, 16 individuals (17.4%) from a cross-sectional sample of the cemetery were included in the study. All individuals were studied together. Although the specific diet and circumstances around the death of these children remain unknown, this sample was selected as it constitutes a large well-preserved sample with a high proportion of nonadult individuals.

We focused on one deciduous tooth position, the upper second deciduous molar (dm2), and one permanent tooth position, the first permanent molar (M1). We studied molars because they are known to accumulate wear with mastication, whereas anterior teeth may present wear from pacifiers made from an abrasive material (Mahoney

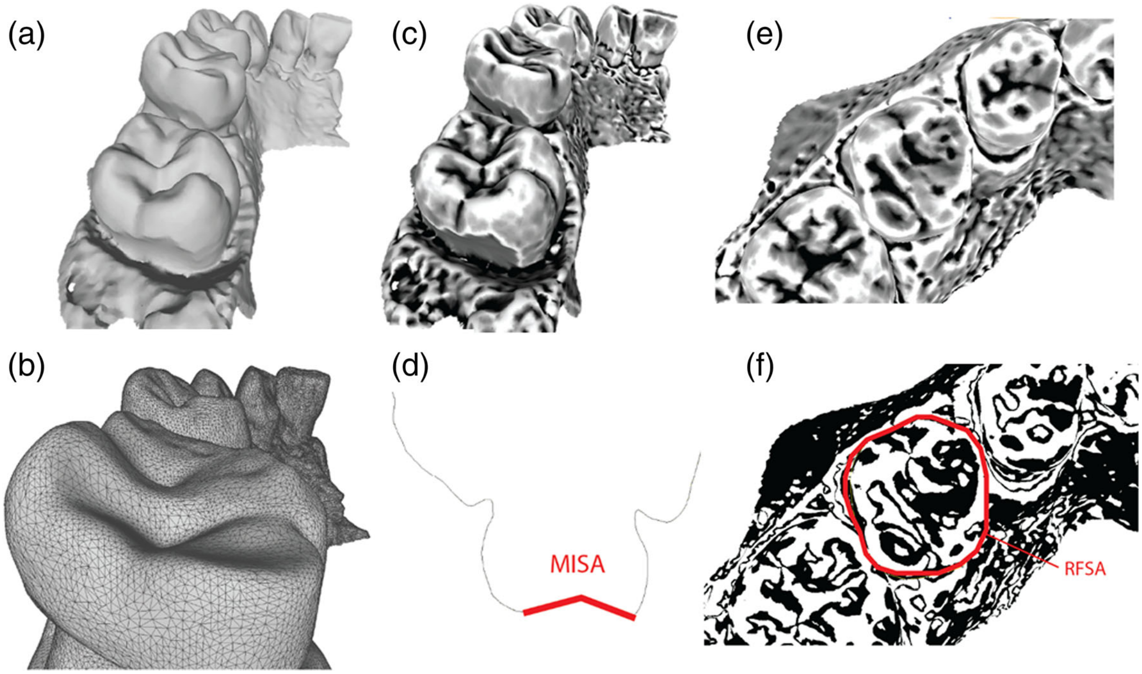

FIGURE 1 Measurement procedure. (a) Surface model produced by the intraoral scanner. (b) Visualization of the 3D triangular mesh. (c) Surface with the mean surface curvature quality map applied. (d) Measurement of mesial interior slope angle (MISA) (red) on extracted 2D profile running between the tips of the two mesial cusps. (e) Captured image of the occlusal surface. (f) Application of thresholds and measurement of the relative flat surface area in percent (RFSA%) using mean pixel value within region of interest (ROI) (red)

et al., 2016). We chose the upper molars because the enamel is thicker than in lower molars and therefore dentine exposure occurs later (Mahoney, 2013). Although the first deciduous molar (dm1) is also of interest for the study of childhood diet, we chose to develop the method initially on the second deciduous molar as fewer children in the sample present exposed dentine on this tooth, and we were interested in testing the potential of our method to quantify dental wear before dentine exposure.

Age estimations are based on Ubelaker, 1978, as this method is commonly employed and does not require observation of root development. Dental wear is of course expected to increase with age; however, the exact age at which eruption occurs can vary from individual to individual (Ubelaker, 1978), there remains therefore a degree of uncertainty about the time during which each tooth has been in use.

Dental wear was qualitatively scored during the selection of the dentitions using an adapted version of the TWI (B. G. Smith & Knight, 1984), as described in Table 1.

TABLE 1 Qualitative macrowear scoring system adapted from the TWI (B. G. Smith & Knight, 1984)

Score	Description
0	No observable changes to the occlusal surface
1	Some observable changes to the occlusal surface (facets, rounding of the cusps) but no dentine exposure
2	Small islands of dentine exposure
3	Confluent islands of dentine exposure making up at least one-third (approximately) of the occlusal surface

Abbreviation: TWI, tooth wear index.

A Planmeca Emerald intraoral scanner and Planmeca Romexis 5.3.2.13 acquisition software was used to make a 3D model of the right or left upper dental quadrant for each individual. The scanner's precision has been estimated at 55.3 μm with an accuracy below 100 μm (Michelinakis et al., 2019). Many 3D dental imaging methods use higher resolution scanners; however, the accuracy was considered sufficient to capture the macroscopic features targeted in this study. The scanner is free moving and handheld and is designed to make a 3D model of a living patient's dentition, it builds this model in real time using a video feed. In skeletal remains, teeth are relatively loose in the alveolar socket and so vibrations (caused by nearby movement or contact with the supporting surface) can make the teeth move very slightly relative to one another during the scan. Any such movements will confuse the scanner and lead to aberrations in the 3D model. Therefore, before the scan, the dentition was placed in sand to absorb any vibrations. Provided the occlusal surfaces were exposed to the scanner, the orientation of the dentition during the scan was not important as occlusal surfaces were treated individually and could later be rotated within the coordinate system. This same approach was therefore suitable for dentitions (at all stages of development), fragmented dentitions, and isolated teeth, provided they were correctly held in place by the sand. By moving the scanner in a scan pattern, according to the manufacturer's instructions, a model of the surface was built in around 1–3 min. Although only the maxillary teeth of children were used in this study, the scanner is suitable for both maxillary and mandibular dentitions and the dentitions of both children and adults; the scanning process remains the same. This 3D data was then exported as a .stl triangular mesh file in which points of the data across the surface of the tooth are connected to form triangles that approximate the shape of the dentition surface. Once the mesh files were extracted, they were post-processed using Mesh Lab v2016.12 (Corsini et al., 2012) (Figure 1.). The occlusal surface was aligned in the coordinate system, and the local mean surface curvature was calculated and mapped onto the model based on the angle between adjacent triangles (Figure 2.). The specific steps used in Mesh Lab are described in the supplementary materials.

For each individual, we placed a virtual camera within Mesh Lab to obtain two pictures, one of the 2D height profile running through the tips of both cusps called "profile" (Figure 1(f)), and one picture of the mean curvature map of the occlusal surface called "surface" (Figure 1(g)). Converting the 3D data into 2D facilitates analysis with ImageJ and allows for an analysis procedure that is analogous with 2D methods measuring the % of dentine exposure (Deter, 2009) which do not require to segment out the occlusal basin or individual wear facets manually.

The angle of the interior slope of the mesial cusp was measured in ImageJ (FIJI) on the "profile" picture by setting an angle between the tip of the mesiobuccal cusp, the lowest point between the two cusps, and the mesiolingual cusp. This angle is representative of the general slope of the cusps and increases as the tooth wears, we refer to this angle in degrees as MISA. The "surface" picture was run through a FIJI—ImageJ macro that set the image to 8bit and applied greyscale thresholding selecting pixels with a value between 60 and 190 (a range that included all pixels of visually identified "wear facets" in multiple individuals). These surfaces with a gray value between 60 and 190 were considered "flat." Concave and convex surfaces became white. Using a custom macro in FIJI, we then manually outlined the occlusal surface as region of interest (ROI) and saved it to the ROI manager. We then estimated the proportion of the surface that was flat using the mean between white and black pixels. The RFSA is the mean pixel value of the ROI. Theoretically, a perfectly flat occlusal surface (100% flat) would be completely black and the mean pixel value would be 255, and a surface with no flat surfaces (0% flat) would be perfectly white and the mean pixel value would be 0. We calculated the RFSA% in percent using the following formula:

$$\text{RFSA\%} = \frac{\text{RFSA}}{255} \times 100$$

A mean pixel value of 127.5 within the ROI (so RFSA = 127.5), for example, corresponds to an occlusal surface which is 50% flat (RFSA % = 50%), as half the pixels within the ROI—that is, the occlusal surface—are classified as belonging to a flat surface (based on the chosen threshold).

Total measurement time from scan to final measurements was about 10–20 min per individual depending on the dentition and the experience of the observer.

We estimated the TEM (Harris & Smith, 2009; Stull et al., 2014) to express the error margins for these new measurements. We compared measurements from 30 individuals with an equal representation of TWI wear scores (5 teeth each). Author M. B. made two series of measurements for comparison to estimate the intraobserver error rate, author L. W. measured the same series of individuals and his measurements were compared to one of the series of M. B. to calculate the interobserver error rate. Two measurements were removed from the calculation as both observers had not selected the same tooth, so 28 individuals were used in the final calculation. The following formula was employed to calculate the absolute TEM.

$$\text{TEM} = \sqrt{\frac{\sum D^2}{2N}}$$

D is the difference between two measurements for the same observer (for the intraobserver error rate) and the difference between two measurements from two different observers (for the interobserver error rate), and N is the number of individuals compared. A relative TEM can then be calculated that considers the average measurement value and is therefore a percentage of error that can be compared between measurements. To calculate the relative TEM we divided the absolute TEM by the average of all measurements and multiplied it by 100.

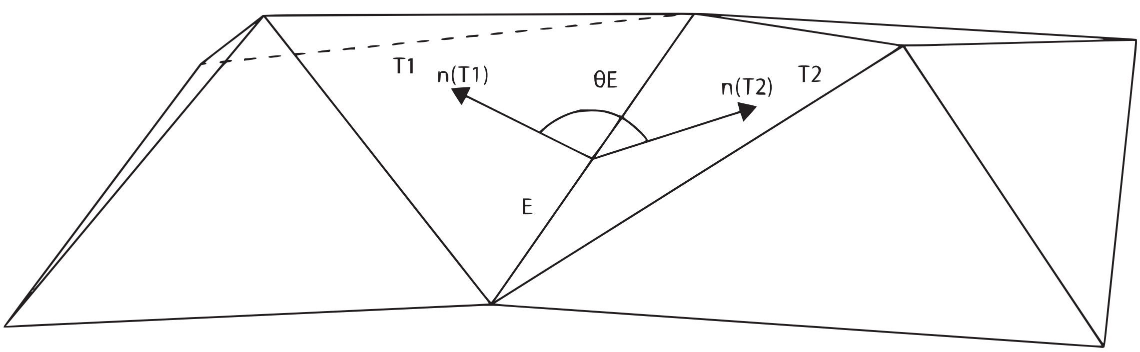

FIGURE 2 Angle θE between two adjacent triangles T1 and T2 for edge E, for every edge E an angle is calculated. Angles in the local area are used by MeshLab to calculate "mean curvature" values that are converted into greyscale values that color each triangle surface

Statistical tests were carried out in SPSS v26 (IBM SPSS Statistics for Windows) and R 4.0.3 (R Core Team, 2020). A Kendall's correlation test (carried out in R) was used to describe the strength of the relationship between the qualitative TWI based macrowear score (ordinal variable) and our quantitative RFSA% and MISA measurements. This is a test of the monotony of the relationship between these variables (i.e., if they do increase or decrease together). The relationship between continuous variables, age and the RFSA% and MISA measurements, was described with Spearman's correlation (monotony of relationship) and Pearson's correlation (linearity of relationship) (tests carried out in R). Groups were compared in SPSS using nonparametric statistics to avoid assumptions of distribution. A Kruskal–Wallis test was used to test the difference in RFSA% and MISA measurement distribution across all groups. SPSS performed an associated series of post hoc tests to identify which specific group pairs differ significantly (applying Bonferroni's correction to results).

The distribution of the qualitative TWI score for each group was represented using a bar chart showing the number of individuals with each score for each group. Distributions for the quantitative RFSA% and MISA measurements for each TWI score were represented using standard boxplots. A scatterplot was used to visualize the relationship between two continuous variables, age and the RFSA% and MISA measurements. All graphs were produced in R using the following packages ggplot2, ggpubr, and gridExtra.

3 | RESULTS

3.1 | Intraobserver and interobserver TEM

Results of the TEM evaluation are summarized in Table 2.

For each TWI score, the mean, SD, and relative SD (RSD in %) were calculated, for both molar types (dm2 and M1) and measurements (RFSA% and MISA) (Table 3.). When compared with the RSD, the TEM accounts for less than half of the variation between measurements for a given TWI macrowear score.

3.2 | Comparison with an established method (TWI)

Kendall's test for nonparametric correlation between the quantitative measurements (RFSA%/MISA) and the ordinal macrowear score (based on TWI) found a highly significant ($p < 0.000$) moderate to strong relationship for both variables (RFSA% and MISA) in both deciduous molars (RFSA%: 0.616 strong/MISA: 0.709 strong) and permanent molars (RFSA%: 0.459 moderate/MISA: 0.563 strong). The nonparametric Kruskal–Wallis test rejected the null hypothesis ($p < 0.000$) that distributions across wear scores are not significantly different, for both variables (RFSA% and MISA) and in both deciduous and permanent molars. After the Kruskal–Wallis test, a post hoc pairwise comparison of macrowear scores was made for both quantitative variables and in both types of teeth, significance values were adjusted by the Bonferroni correction (Table 4.). The distribution of quantitative measurements for each qualitative wear score are summarized in Figure 3.

3.3 | Relationship with age

The number of individuals for each age group and the proportion of each qualitative macrowear score (TWI) are summarized in the bar chart Figure 4. Dental wear increases with age, with dentine exposure occurring on the deciduous molars between the age of 3 and 6 years old and becoming very prevalent after the age of six. For the permanent molars, dentine exposure occurs only occasionally in the older children (three children out of 23 above the age of 9 years old). Correlations between age and dental wear measurements are described in

TABLE 2 TEM estimates for RFSA% and (MISA) (absolute and relative)

	Absolute TEM RFSA%	Relative TEM RFSA% (%)	Absolute TEM MISA	Relative TEM MISA (%)
Intraobserver error	1.6	2.7	2.3	1.9
Interobserver error	2.4	5.2	3.0	2.4

Abbreviations: MISA, mesial interior slope angle; RFSA%, relative flat surface area in percent; TEM, technical error of measurement.

TABLE 3 Mean, SD, and RSD in % for quantitative RFSA% and MISA measurements for each TWI macrowear score

	RFSA% dm2			RFSA% M1			MISA dm2			MISA M1		
	Mean	SD	RSD (%)	Mean	SD	RSD (%)	Mean	SD	RSD (%)	Mean	SD	RSD (%)
Score 0	37.6	4.4	11.7	40.3	3.7	9.2	100.1	8.1	8.1	105.6	8.6	8.1
Score 1	43.3	4.8	11.1	48.4	7.1	14.7	117.4	12.3	10.5	127.4	15.7	12.3
Score 2	51.4	5.6	10.9	49.5	4.0	8.1	150.4	15.7	10.4	140.5	12.2	8.7
Score 3	53.2	4.5	8.4				160.3	17.3				

Abbreviations: MISA, mesial interior slope angle; RFSA%, relative flat surface area in percent; RSD, relative SD; TWI, tooth wear index.

TABLE 4 Kruskal–Wallis post hoc comparisons of RFSA% and MISA distributions between individuals grouped by TWI macrowear score

	RFSA%—dm2			MISA—dm2		
TWI score	Test statistic	SE	Adj. sig	Test statistic	SE	Adj. sig
0–1	−16.4	6.5	0.070	−18.0	6.5	**0.034**
0–2	−39.2	7.0	**0.000**	−43.5	7.0	**0.000**
0–3	−43.6	10.5	**0.000**	−48.3	10.5	**0.000**
1–2	−22.8	5.8	**0.000**	−25.6	5.8	**0.000**
1–3	−27.3	9.7	**0.029**	−30.4	9.7	**0.010**
2–3	−4.5	10.0	1.000	−4.8	10.0	1.000
	RFSA%—M1			MISA—M1		
TWI score	Test statistic	SE	Adj. sig	Test statistic	SE	Adj. sig
0–1	−19.6	4.7	**0.000**	−22.5	4.7	**0.000**
0–2	−26.0	10.5	**0.038**	−34.9	10.5	**0.003**
1–2	−6.4	10.2	1.000	−12.4	10.2	0.670

Abbreviations: MISA, mesial interior slope angle; RFSA%, relative flat surface area in percent; RSD, relative SD; TWI, tooth wear index.
Note: Bold values are significant (i.e. the p-value falls below the 0.05 significance threshold).

Table 5. The Spearman's ρ suggest a strong correlation (monotonous positive relationship—they increase together) for both measurements (RFSA% and MISA) and tooth positions (Udm2 and UM1) ($\rho \geq 0.7$). Pearson's correlation coefficients suggest a moderately strong or strong correlation for both measurements (RFSA% and MISA) and tooth positions (Udm2 and UM1) (coefficient ≥ 0.6), in particular the MISA of dm2 with a correlation of 0.81 (Figure 5(b)) (linear positive relationship—they increase together with a linear relationship), RFSA% and MISA macrowear measurements are strongly and positively correlated with age (Figure 5 and Table 5).

4 | DISCUSSION

4.1 | Measurement reliability

The intraobserver TEM for both measurements (RFSA and MISA) is comparable to many existing anthropometric methods (Perini et al., 2005).

The interobserver TEM is only slightly higher than the intraobserver error for MISA, but noticeably higher for RFSA%. This is surprising as we expected RFSA% to be less subjective than MISA as the latter requires a manual alignment step. Discrepancies in the amount of buccal and lingual surface apparent alongside the occlusal surface in the top-down view are likely driving this RFSA% error rate, we suggest the occlusal surface should be aligned such as the XY axes plane strictly bisects both the lingual and buccal cusp tips and the point of origin placed roughly in the center of the occlusal surface, before the virtual camera is set in a top-down view along the Z-axis, this step will likely reduce RFSA% interobserver TEM in the future.

Comparison with the RSD indicate the measurements detect variations in dental wear between individuals which are not detected using the qualitative TWI score even when taking into account the associated TEM, meaning they are more precise.

Considering these results, we conclude that the intraobserver TEM is acceptable for both RFSA% and MISA. The interobserver error rate is acceptable for MISA but should be improved for RFSA%.

4.2 | Measurement accuracy

Results suggest that RFSA% and MISA measurements are measuring the same changes in dental morphology as assessed visually by the TWI macrowear scoring system. The RFSA% measurement may, however, lack sensitivity to early wear-related changes of the occlusal surface partly due to the use of a threshold that could filter out initial subtle wear. Additionally, RFSA% does not appear to increase reliably with the progression of dental wear after dentine exposure, likely because the islands of dentine create depressions in the flat wear facet surfaces that increase the surface curvature in that area. Wear facets increase in size until dentine exposure occurs but decrease after dentine exposure as the exposed area increases (which is why highly worn teeth are not included in microwear texture analysis studies) (Bas et al., 2020; Mahoney et al., 2016). The small number of teeth in our sample with a TWI score of 3 (dentine exposure over a third of the occlusal surface) also makes it difficult to evaluate statistically the relationship between the measurements and the scoring system when teeth are heavily worn.

As time is an important factor in dental wear (Rose & Ungar, 1998), another indicator of measurement accuracy is its relationship with age. RFSA% and MISA measurements increase with age. In second deciduous molars RFSA% appears to increase reliably with age before dentine exposure only, MISA increases with age through childhood regardless of dentine exposure. In permanent molars, wear

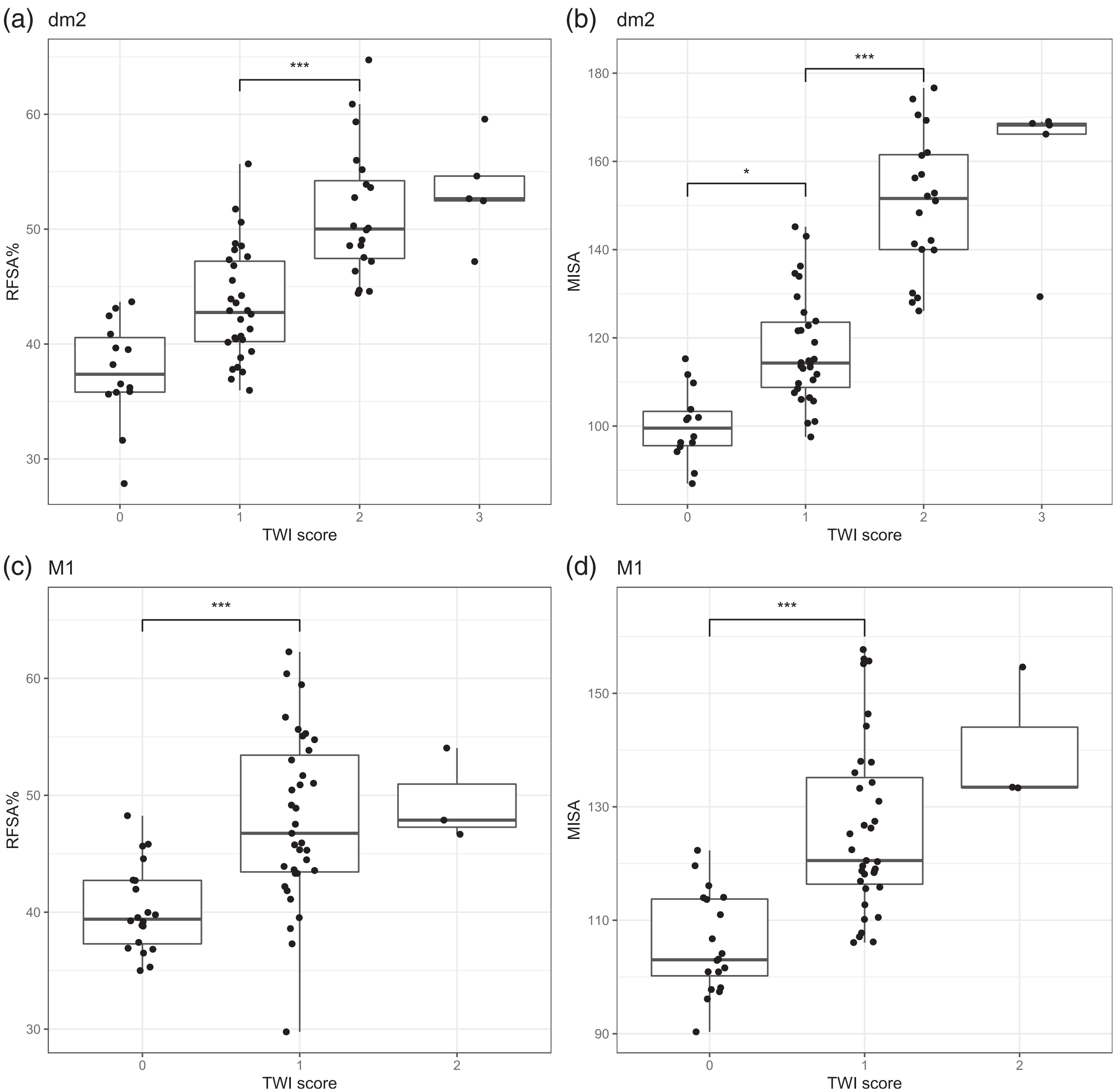

FIGURE 3 Boxplots of relative flat surface area in percent (RFSA%) and mesial interior slope angle (MISA) measurements for each macrowear score. (a) RFSA% measurements on the second deciduous molar (dm2). (b) MISA measurements on the second deciduous molar. (c) RFSA% measurements on the first permanent molar. (d) MISA measurements on the first permanent molar. Significant differences in the Kruskal–Wallis test between adjacent groups are noted with * for $p <= 0.05$, ** for $p <= 0.01$, and *** for $p <= 0.001$

occurs at a slower rate, both quantitative measurements increase over time; however, the relationship becomes less clear after 9 or 10 years of age. We suggest that this increase in measurement spread after the age of nine is likely indicative of a diversification of dental wear rates towards the end of childhood and during early adolescence in our target population, and not reflective of a change in the proxies' abilities to track dental wear progression in older children.

In sum, RFSA% and MISA present as suitable proxies for the progression of dental wear, with some notable limitations for RFSA% as it possibly does not capture initial wear and cannot reflect the progression of wear after dentine exposure.

4.3 | Comparison with existing methods

The proposed method provides several advantages over existing methods. Scans were produced using a handheld device (intraoral scanner) commonly used in a clinical setting, the device is easy to

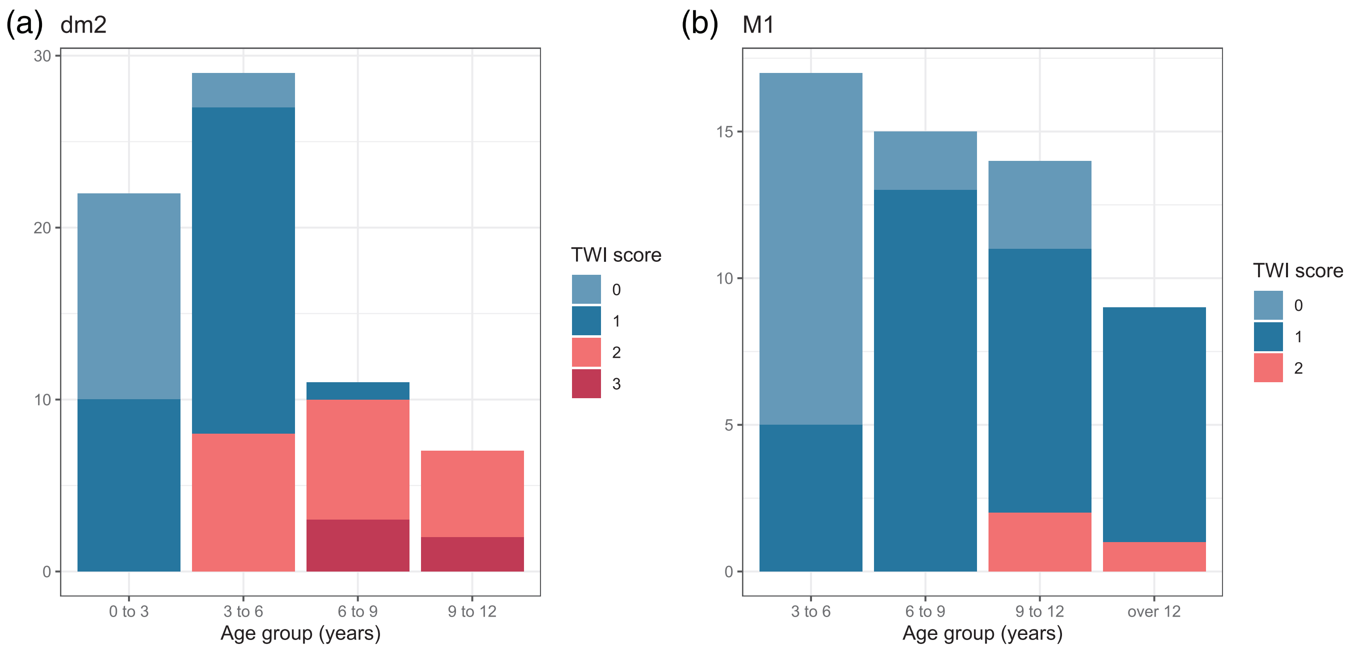

FIGURE 4 Bar chart with the individual count and the proportion of macrowear scores for each age group. (a) Tooth wear index (TWI) scores of the second deciduous molars (dm2). (b) (TWI scores of the first permanent molars (M1)

TABLE 5 Correlation of macrowear RFSA% and MISA measurements with age (mean age estimate based on Ubelaker (1978))

		Spearman ρ	Spearman *p*-value	Pearson correlation	Pearson *p*-value	Pearson 95% CI
RFSA%	dm2	0.73	**4.32E-13**	0.68	**8.29E-11**	0.53–0.79
	M1	0.70	**2.83E-10**	0.65	**1.03E-08**	0.48–0.78
MISA	dm2	0.81	**2.20E-16**	0.81	**2.20E-16**	0.71–0.88
	M1	0.76	**1.88E-12**	0.74	**1.05E-11**	0.60–0.83

Abbreviations: MISA, mesial interior slope angle; RFSA%, relative flat surface area in percent.
Note: Bold values are significant (i.e. the p-value falls below the 0.05 significance threshold).

operate and can be transported. Subsequent data collection can be done using free open source software that can be operated without the need for a powerful computer. Like measurements of dentine exposure (Clement & Freyne, 2012; Deter, 2006, 2009) the measurements are made on digital files of a few megabytes that can easily be shared online. However, unlike methods based on dentine exposure, by describing the occlusal surface the proposed measurements may additionally contribute to microwear texture analysis by providing useful information about the context in which microwear has formed (Bas et al., 2020; Mahoney et al., 2016).

Like crown height (Walker et al., 1991) and dentine exposure, RFSA% and MISA reduce dental wear to a single variable, the degree. Methods can also focus on the pattern in which wear forms, such as in Molnar, 1971 where the shape and orientation of the occlusal surface are described (Molnar, 1971), the orientation was later quantified by B. H. Smith (1984). These descriptions of the occlusal surface aim to further contribute to paleodietary reconstruction as dental macrowear patterns are known to differ between hunter-gatherers and agrarian populations (Rose & Ungar, 1998; B. H. Smith, 1984; Watson & Schmidt, 2020). Quantitative methods describing wear patterns such as OFA (occlusal fingerprint analysis) (Kullmer et al., 2009), are especially suited to study the biomechanics of both deciduous and permanent teeth (Fiorenza et al., 2020; Fung et al., 2021); however, such studies are more time consuming are require more specialized equipment. The measurements proposed in this study could likely be adapted to describe dental macrowear patterns, by, for example, dividing the occlusal surface into quadrants or measuring multiple intercusp slope angles and calculating ratios between them, however, it is uncertain how useful such an approach would be given the success of existing methods for describing dental macrowear patterns.

Occlusal topographic measurements are suited to measuring changes in the occlusal surface before dentine exposure, this is important as for about half the children in our sample dentine exposure has not yet occurred on deciduous teeth. However, if the proposed RFSA % measurement is limited in sensitivity to initial wear as well as heavy wear, this is likely due to the application of a threshold that filters out the first changes to cusp morphology. By removing the threshold, an alternative system based directly on the mean curvature calculations from a surface scan might yield better results. MISA provides a proxy for the progression of occlusal molar wear during the first years of life, that can be measured reliably and within a few minutes.

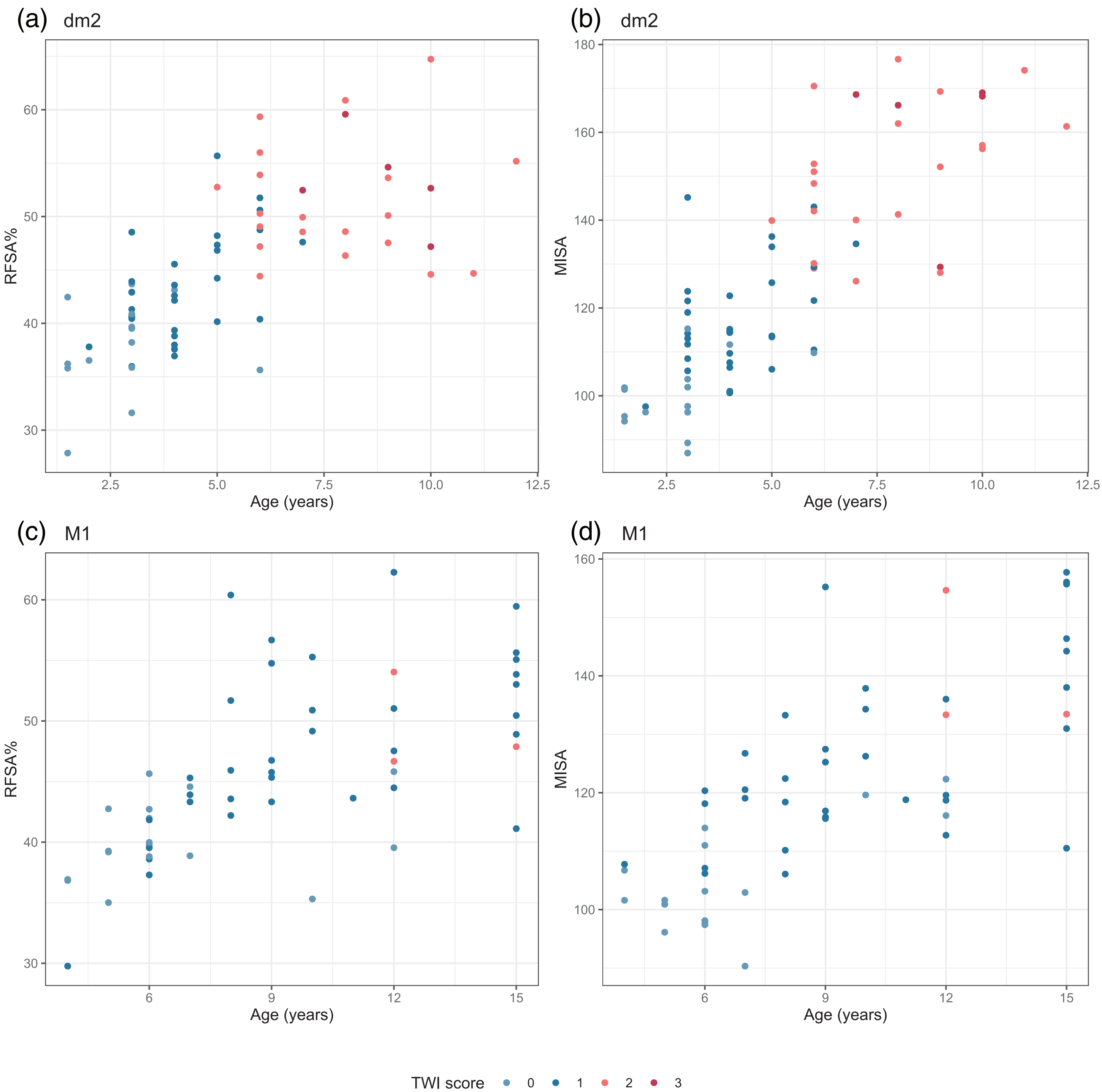

FIGURE 5 Scatterplot of relative flat surface area in percent (RFSA%) and mesial interior slope angle (MISA) measurements by age (mean age estimate based on Ubelaker (1978)). (a) RFSA% measurements on the second deciduous molar (dm2). (b) MISA measurements on the second deciduous molar. (c) RFSA% measurements on the first permanent molar. (d) MISA measurements on the first permanent molar. Point is colored based on the associated tooth wear index (TWI) macrowear score

Taking about 10–20 min per tooth from scan to measurement, the combined RFSA% and MISA data collection takes longer than qualitative dental wear methods, and perhaps a little longer than dentine exposure measurements. These methods, however, measure different aspects of the progression of dental wear and are not equivalent.

Although only upper molars from children were tested in this study, the method likely works the same for lower molars, and could be applied for adults as well, in contexts where such an approach would be advantageous. However, we anticipate that in most cases, the use of qualitative ordinal scales or measurements of dentine exposure may remain preferable.

5 | CONCLUSION

In this article, we show that using a portable intraoral scanner and occlusal topographic measurements it is possible to quantify molar macrowear progression. Measurement of the MISA can be made with a reasonably low technical error of measurement (TEM) and is comparable to an established qualitative dental macrowear scoring system (TWI). The RFSA measurement (RFSA%) was generally less successful and likely cannot measure increases in dental macrowear after dentine exposure. However, within a defined range of wear, both measurements are representative of the amount of dental wear that has occurred. As both measurements relate to the removal of enamel and not dentine exposure, they are particularly suitable for the study of children, as many teeth do not yet show exposed dentine. Although gathering data with this method takes a little longer than existing methods, and requires an intraoral scanner or equivalent to make the 3D surface scans, such an approach remains nondestructive and relatively economic, and so would be worthwhile in contexts where existing methods are not well suited. We conclude that occlusal topographic measurements of dental macrowear made on 3D scans constitute a promising approach to expand palaeodietary reconstruction to address questions of subtle intrapopulation macrowear variation such as those that might result from differences in weaning and childhood diet.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

AUTHOR CONTRIBUTIONS

Marlon Bas: Conceptualization, methodology, software, formal analysis, writing - original draft, visualization. **Lukas Waltenberger**: Validation, writing - review and editing. **Christoph Kurzmann**: Methodology, resources, writing - review and editing. **Patrick Heimel**: Software, resources, writing - review and editing. **Katharina Rebay-Salisbury**: Conceptualization, funding acquisition, project administration, writing - review and editing. **Fabian Kanz**: Conceptualization, methodology, resources, supervision, writing - review and editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Marlon Bas https://orcid.org/0000-0001-7236-2404
Lukas Waltenberger https://orcid.org/0000-0002-9670-6117
Christoph Kurzmann https://orcid.org/0000-0002-1483-0393
Katharina Rebay-Salisbury https://orcid.org/0000-0003-0126-8693

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