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Geometrics of tooth wear

Lifong Zou[a,*], George Cherukara[a], Pengwei Hao[b], Kevin Seymour[a], DYD Samarawickrama[a]

[a] Centre for Adult Oral Health, Institute of Dentistry, Barts & The London, Queen Mary's School of Medicine & Dentistry, London, UK
[b] Department of Computer Science, Queen Mary University of London, UK

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ABSTRACT

Wear measurement implies the need for comparative measurements based on a reference frame. In this study, part of a tooth surface (common area) is proposed to be a reference frame for the comparative measurement. A registration procedure applies an iterative closest point algorithm for the least square best fit of the two surfaces on this common area. When the common area matches the best fit condition, the difference at the remaining part of the tooth surface represents changes between the two surfaces; in this case signifying tooth wear.

The minimum requirements to verify tooth wear results are a three quadrant spherical surface of a molar tooth to be common area, and the fit of the common area needs to be less than 10 μm, to achieve the sensitivity of wear measurement up to the 100 μm level on the occlusal tooth surface. Incise apparatus was used for the digitisation of the tooth surface. Cloud, a 3-D image analysis software package was utilised for visualisation, registration and image analysis. A mathematical scrutiny was applied to validate the findings in theory. The proposed methodology is proven to be adequate to quantify tooth wear.

1. Introduction

Managing the consequences of tooth wear has become an ever-increasing challenge for the dental profession as an increasingly aging population are retaining their teeth for longer. Thus, an accurate quantification of the wear is vital, as it will enable the researcher to measure and predict its characteristics [1], helping the clinician in the monitoring of tooth wear [2,3], and consequently assist in its clinical management [4].

Up until now, various methods have been developed to quantify tooth wear, the most popular of which are either modifications of the Tooth Wear Index [5] or the Tooth Wear Index itself [6,7]. Such clinically based measurement systems have drawbacks in that eye estimation can be operator dependent and unable to provide graphical information. In parallel with the Tooth Wear Index method, a three-dimensional graphics based surface measurement systems have been developed. These systems use external devices to be the reference: Bartlett and co-workers [8,9] used square or circular shaped discs, and more recently Schlueter et al. [10] have used star shaped discs to be the reference frame. A star disc can provide a structure on which to fix the orientation of a surface. However, these external devices may or may not remain in place during the periods of the tooth wear measurement due to the subjects' eating habits and their oral environment. Furthermore, they are invasive to the tooth surface.

In this study, we propose a 3-D co-ordinate surface measurement methodology to quantify tooth wear. This methodology must satisfy the following criteria: (1) non-invasive; (2) sensitive to surface loss at the 100 μm level and (3) user friendly to both clinicians and patients. More importantly, we have considered the merit of using a mathematical surface registration process to quantify the corresponding differences at the areas of interest, and the minimum requirements of the common surface for the registration, that will directly affect the quality of the wear measurement.

2. Material and methods

2.1. The measurement object (samples)

A molar tooth provides five large surfaces and a variety of geometrical features. Therefore, three plastic molar teeth were randomly selected: a lower left six (LL6 – first molar), an upper left six (UL6 – first molar) and a lower left seven (LL7 – second molar).

2.2. The digitisation instrument—3D dental scanner

A newly developed and purpose built dental 3-D surface scanner – Incise (Fig. 1) was used for the surface digitisation. Incise is designed on the novel mechanism of Triact. It gives a high dynamic performance, and low forces with small scanning deflections. It also

* Corresponding author. Tel.: +44 20 7882 8624; fax: +44 20 7377 7064.
E-mail address: l.zou@qmul.ac.uk (L. Zou).

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Fig. 1. Incise dental scanner (Renishaw, UK), (Courtesy of Renishaw PLC).

has a high-resolution optical scale for an accurate position feedback, and a high-speed controller. The specifications of Incise are listed as follows: measuring envelope: 90 mm diameter × 45 mm height; encoder resolution: sub micrometer; probe force: 0.5 N/mm; and uncertainty: 20 μm according to ISO 10360 part 4.

2.3. Measurement strategy

Samples are made of plastic; the surface is hard and smooth. Therefore, a 1 mm diameter ruby tipped probe was used for scan. The scan interval was 0.1 mm, and scan speed was 600 mm/min.

2.4. Image analysis and registration

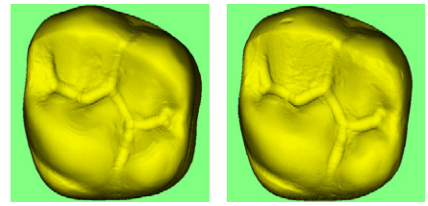
A 3-D image analysis software package – Cloud (UCL, UK) was used for data analysis. Comparative measurements between images are based on mathematical least square fit at common area in the registration procedure. The common area was identified by an operator.

2.5. Reproducibility of the measurement

This was to investigate the reproducibility of the measurement, which includes the uncertainties of the digitisation procedure, registration process and calculation of the surface difference. A complete digitisation and analysis process was applied three times to the same tooth (LL7) of which results are presented in Section 3.1.

2.6. Minimum common area analysis of the measurement

The image of tooth UL6 was used to investigate the effectiveness of the selection of common area in the registration procedure.



Figs. 8 and 9. (8) Baseline image; (9) Image after an alteration.

Clinical experience indicates that lingual, mesial and distal surfaces are often worn at a slower rate compared to the occlusal surface. Therefore, one, two, three, four and more than four quadrants of the surface of a molar tooth were selected for the registration procedure, see Section 3.2 for these results.

2.7. Tooth wear measurement

Three images of three teeth LL6, UL6 and LL7 were digitised as a baseline. Unknown to the operator, a clinician made an alteration to one of the teeth, to simulate tooth wear. Further scans were then carried out on the three teeth. The wear was measured using the minimum common area methodology, and the results are reported in Section 3.3.

3. Results

3.1. Investigation of the reproducibility

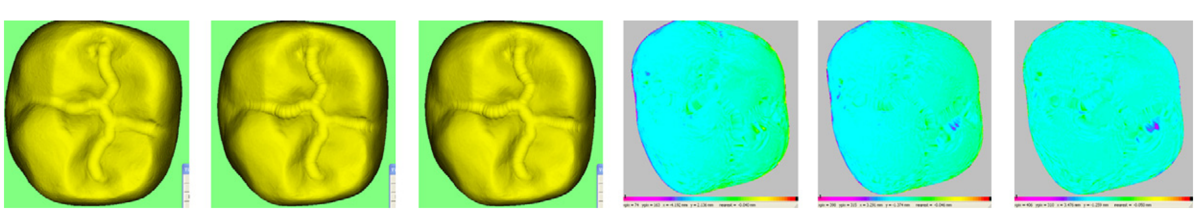
Three digitisation images are shown in Figs. 2–4, respectively. Their comparative images Figs. 5–7 are displayed in a subtraction manner, the differences in depth between the surfaces are presented by different colours, a legend is attached to each superposed image. Sea blue colour represents zero difference. Green-yellow colour represent a +10 to +20 μm difference indicated in a few small isolated areas and dark blue and purple colours representing −40 to −50 μm difference at only two very small patches in Figs. 6 and 7.

3.2. Investigation of the minimum common area for registration procedure

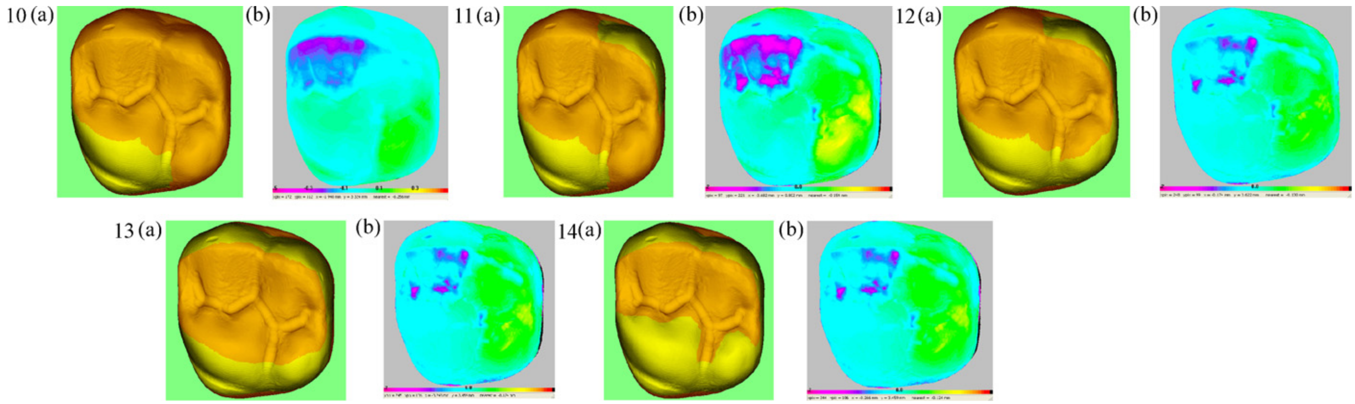
The registration procedure involves two parts: the selection of the common area; and to find and calculate the difference between the two images. The molar upper left 6 (UL6) is used for minimum common area analysis. Figs. 8 and 9 are two images showing scans from the baseline and after an alteration, respectively.

Five different common areas are selected as shown in Figs. 10(a), 11(a) 12(a), 13(a) and 14(a). The golden yellow represents the tooth surface, and bright yellow colour in each figure is selected common area. Based on the selections, the difference in depth along the surface normal at each position over the entire tooth surface is displayed in a colour-coded image next to each selection in Figs. 10(b), 11(b) 12(b), 13(b) and 14(b).

The results in Table 1 clearly demonstrate that using a larger common area leads to a better quality in the registration proce-



Figs. 2–7. (2) LL7-1; (3) LL7-2; (4) LL7-3; (5) LL7-1 and -2; (6) LL7-1 and -3; (7) LL7-2 and -3.



Figs. 10–14. (10a) Single quadrant of the side tooth surface is selected in yellow and (10b) registration image; (11a) Two quadrants of the side tooth surface are selected in yellow and (11b) registration image; (12a) Three quadrants of the side tooth surface are selected in yellow and (12b) registration image; (13a) Four quadrants of the side tooth surface are selected in yellow and (13b) registration image; (14a) Four plus quadrants of the tooth surface are selected in yellow and (14b) registration image.

dure. However, this tendency can be saturated to a value. In this case, the superposition procedure is not getting any better when the common area is larger than 4 quadrants. Therefore, 4 quadrants would give the saturation value, or if a 6-μm error is acceptable, then three quadrants would give a better saturation value. This can be supported by a mathematical equation, and it is discussed in Section 4.2.

3.3. Tooth wear measurements

Images of three plastic teeth LL6, UL6 and LL7 are in Figs. 15–17 and re-scan images are shown in Figs. 18–20 after the alteration. Based on the minimum common area method, three quadrants of the side areas were used for the registration procedure, which were the buccal, lingual and mesial sides of the molar tooth. The superposed images of the three pairs are in Figs. 21–23.

The differences of 61 and 33 μm in Figs. 21 and 23 in respect to LL6 and LL7 cannot be considered as tooth wear, as these values are marginally close to the reproducibility of the measurement. However, in Fig. 22, the result indicates that the UL6 has been manipulated by the clinician as the simulation of tooth wear. Take a count of the reproducibility, the quantity of wear is within a range of 80–180 μm in depth, and the wear pattern and locations are exhibited by the blue and purple colours in Fig. 22.

4. Discussion

4.1. Repeatability

The sign of the results in Figs. 5–7, is dependent upon the order of the subtraction; therefore, it is of little significance. These results indicate a small uncertainty of 10–20 μm between the first and second images (Fig. 5), but when they are compared with the third image (Figs. 6 and 7); they both have a larger uncertainty up to 40–50 μm. It is most likely a random error occurring during the third scanning process, as the scanning room has no temperature, air or anti-vibration control, and this has happened in only one of the three scans. If the sample size is enlarged to 8 or 10 μm in any future study, a more definite repeatability can be determined.

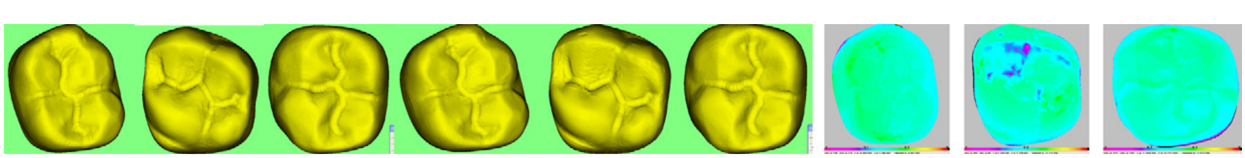
4.2. The saturation value in relation to the selection of minimum common area

In Table 1, the results clearly show that a larger common area provides a better surface registration. However, clinically there is a limitation in the area of availability, due to the wear pattern and relationship to the neighbouring teeth. Therefore, a requirement of minimum common area is raised. Further more, if the minimum common area has not been satisfied, with a degree of compromise, or level of uncertainty accepted in relation to the selection of this common area it would not provide a valuable guide line for tooth wear measurement in practice.

This problem can be simplified as to find the relations between the number of the randomly selected vertices and the maximum error between the surface of the selected vertices and the original surface. The maximum error of all triple neighbour vertices exists at the centre of the triangle of the three vertices and in the surface region of the maximum curvature of the surface. With the fact that curvature on a sphere is the same everywhere, we further simplify the problem as to find the error between a sphere and an inscribed triangular mesh. The error is defined as the distance between the centre of the triangle and the sphere. If we can find the relations between the minimum radius of a sphere, the number of inscribed vertices and the error, then the error can be estimated easily.

Table 1
The superposition results

Common area	1 quadrant	2 quadrants	3 quadrants	4 quadrants	4+ quadrants
Maximum difference at mesial buccal cusp	0.256 mm	0.154 mm	0.130 mm	0.124 mm	0.124 mm



Figs. 15–23. (15) LL6; (16) UL6; (17) LL7; (18) TW1; (19) TW2; (20) TW3; (21) Max. 61 μm; (22) Max. 132 μm; (23) Max. 33 μm.

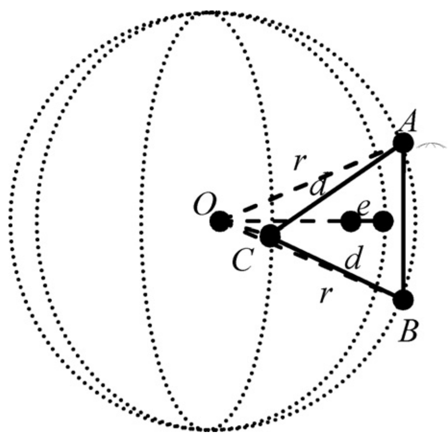


Fig. 24. Illustration of relationship of triangle (side length: d), sphere (radius: r) and error (e).

Suppose the radius of a sphere is r and the side length of inscribed equilateral triangles is d in Fig. 24, then we can find the error between the triangle and the sphere to be:

$$e = r - \sqrt{r^2 - \frac{1}{3}d^2} \quad (r \text{ is the radius of a sphere, } d \text{ is the side length of equilateral triangles}) \tag{1}$$

We have

$$r^2 = r^2 + d^2 - 2rd\cos\alpha \quad (\alpha \text{ is the angle of side triangle OAB}) \tag{2}$$

And

$$d^2 = (d\sin\alpha)^2 + (d\sin\alpha)^2 - 2(d\sin\alpha)(d\sin\alpha)\cos\theta \tag{3}$$

To solve the equations, we obtain:

$$\cos\theta = \frac{2r^2 - d^2}{4r^2 - d^2} \tag{4}$$

The area of the corresponding spherical triangle CAB is:

$$(3\theta - \pi)r^2$$

If all the triangles are of the same area, the number of the triangles is:

$$F = \frac{4\pi r^2}{(3\theta - \pi)r^2} = \frac{4\pi}{3\theta - \pi} \tag{5}$$

For a simple polyhedron, the number of faces F and the number of vertices V have $2V - F = 4$,

Thus, we have:

$$\theta = \frac{\pi}{3 - 6/V} \tag{6}$$

By using Eqs. (4), (6) and (1), we can find the error is:

$$e = r\left(1 - \frac{1}{\sqrt{3}}\cot\frac{\pi}{6 - 12/V}\right) \tag{7}$$

The error is monotonic decreasing with the number of vertices (Fig. 25), which means the bigger the common area has smaller error. When an acceptable error is selected, base on the radius (the shape of surface), n minimum area (vertices V) can be fixed.

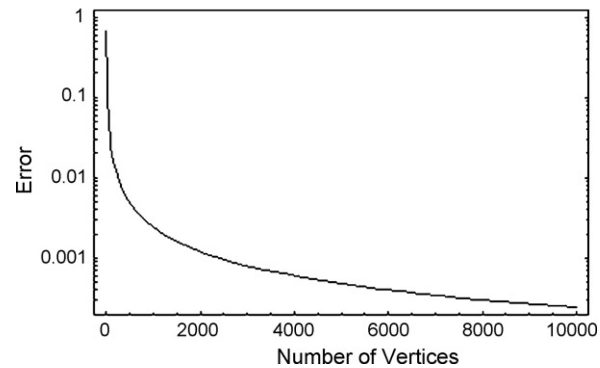


Fig. 25. The quality of fit (error) is monotonic decreasing while the number of vertices increases.

The vertices can be controlled by the sampling intervals in digitisation. However, a tooth surface is free-form. A radius of a tooth surface as such does not exist, but locally, a radius can be calculated. In this case radius at outside of each cusp of UL6 is 2.5 mm, with vertices of 25 square mm × 10 mm (coverage area of 5 mm width × 10 mm height of the cusps each side), then a predicted theoretical error is about 0.1 × 2.5 mm which equals 0.25 mm. This has an excellent correlation with the results presented in Fig. 10.

5. Conclusion

This proposed methodology is non-invasive, clinically user friendly and wear measurement sensitivity achieved at the 100 μm level, and it is rich in 3-D geometrical information.

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