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The impact of surface dimensions on the accuracy of an intraoral scanner

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ABSTRACT

Objectives: Intra-oral scanners are being used to measure small changes to the surface form. This study aimed to identify the limits of detection of an intra-oral scanner (IOS) on depth and width of surface form.
Methods: We performed investigations on artificial teeth with increasing width and depth of discrete surface features captured by an intra-oral scanner at baseline and compared the data to a gold-standard white-light profilometer (WLP). 81 surface features with widths varying between 150 - 1300 μm and depths 5 - 360 μm were scanned five times using the WLP ($n = 405$) and IOS ($n = 405$) and analysed using a validated registration and subtraction algorithm. Both scan outputs used reference and an iterative closest point (ICP) registration to the Z-axis to analyse change and control variation of data. 2D maximum step height depth (μm) and 2D width (μm) of the surface features were calculated.
Results: The depth measurement error of the IOS had a negative linear association to width (Pearson correlation = - 0.87 (95 % CI - 0.90, - 0.82 $p < 0.001$ and $r^2 = 0.76$). The error of depth measurement was 100 % at 250 μm, 20 % at 750 μm and 0 % at 1200 μm. Overall, the IOS overestimated surface feature width by 155.5 μm and underestimated surface feature depth by -20.2 μm.
Conclusion: The accuracy of the IOS to capture surface features improved above 750 μm in width and was close to 100 % accuracy at 1200 μm. Caution is needed if an IOS is used to measure surface features below 1200 μm in width.

1. Introduction

An intra-oral scanner (IOS) is a hand-held surface imaging device designed for CAD/CAM dentistry. Whilst enhancing efficiency and patient experience [1], data on the resolution and accuracy particularly at <10 μm is conflicting [1–3]. In vitro, trueness of scanners can range between 25 and 72 μm and precision between 10 and 60 μm, depending on the scanner [4]. In vivo study methodology is more complex, and patient/operator factors may add to any errors [5].

Little attention has been paid to the impact of small changes to surface form, on the accuracy of an intra-oral scanner to capture data. Intra-oral scanners commonly rely upon a combination of deflectometry and focus variation to detect changes to surface form [6]. Deflectometry is a pattern of structured light projected onto a surface, imaged digitally and the distortion allows surface form to be reconstructed. Focus variation detects distances from the origin. When an image of a black and white structured pattern is in sharp focus, the contrast is optimum and there is sharp transition between adjacent pixels and the surface is at the focal distance from the imaging system. The resolution of the projected pattern and the imaging system that captures it determine the scale of the smallest surface features that can be detected [7]. This occurs several hundred times a second to build a map of the surface and to account for when the surface is not in focus. Practically, the accuracy of this map is determined by the number of pixels and the area of the surface measured at the focal distance [8].

The resolution, or pixel intensity data of an IOS is dependent on the hardware specification of the optics from the image sensor and this is proprietary information and not published by the manufacturer [9]. It is

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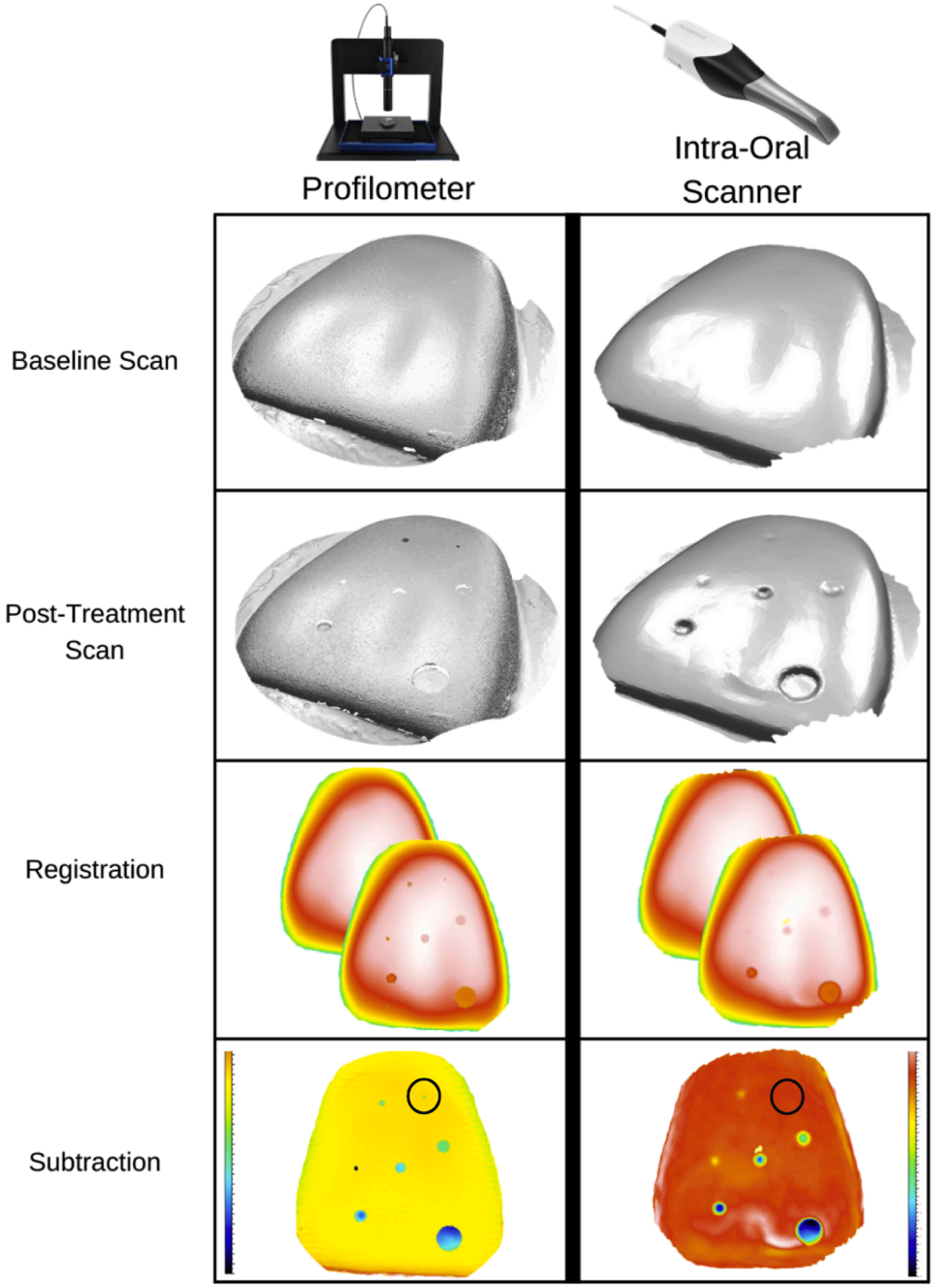

Fig. 1. An example overview of the workflow to obtain and analyse IOS and profilometer scans. Baseline scans were obtained using both and post-treatment scans were obtained after surface features., Baseline and post-treatment scans were registered (aligned) in the Z axis and subtraction resulted in the residual surface between both scans facilitating measurements. A small surface feature in the top right corner of the WLP scan (within the black circular marker) of the typodont cannot be visualised on the IOS scan. Colour: Red/ yellow are baseline, green shows a depression, and blue shows a greater depression.

illustrative to consider that the size of an intra-oral scanner head is around 25 × 25 mm and this directly impacts on resolution (Fig. 1). For example, a sensor on a scanner can produce data bandwidth with an array of 500 × 500 pixels sampled at 10 kHz. This suggests a single pixel detects in the range of 50 × 50 μm and gives a useful illustration of the limits of resolution. Increasing the number of pixels improves data capture and accuracy [5,10]. If there are insufficient pixels over an area, stitching can over-interpolate errors and smooth the data [8].

The term surface feature is a recognised metrological term to describe a change in surface form for example, a hole [11]. Current evidence is lacking on the limitations of an intraoral scanner's accuracy to measure small surface features and to assess how width of an area influences the accuracy of depth measurements. The primary aim of this study was to determine the accurately of an intra-oral scanner to measure surface features with depth 5 - 360 μm and width 150 – 1300 μm. The null hypothesis was that the width is not affected by depth.

2. Materials and methods

Surface features were created on the vestibular surface of six maxillary right central incisor typodont tooth (11 AG3 Frasaco GmbH, Germany) and two CAD/CAM composite resin block (Tetric CAD Ivoclar Vivadent, Liechtenstein, HT A1/ C14, Ref: 692,167, LOT: 2053F1, Mg: 2022–06–28, Exp: 2025–06–28). The plastic teeth and blocks were

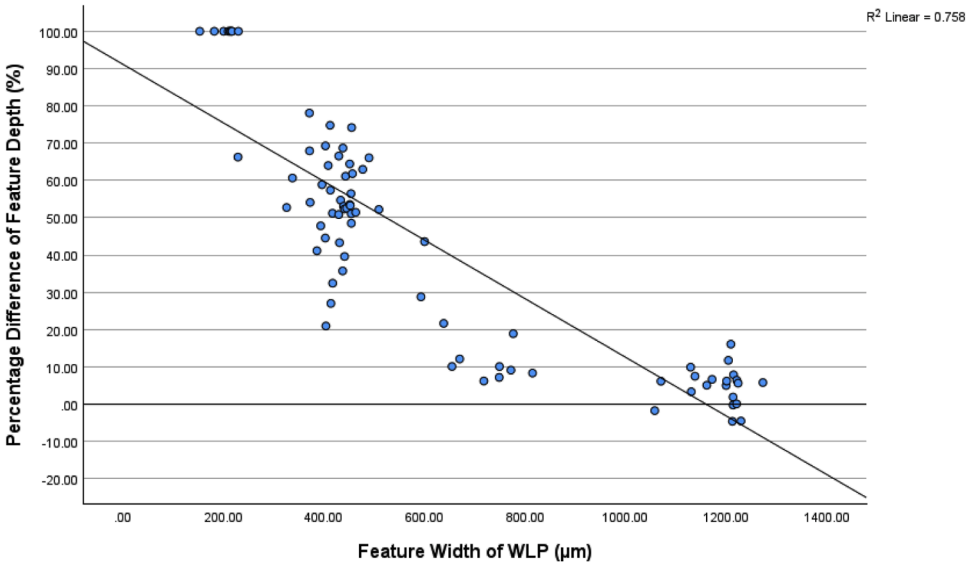

Fig. 2. Scatterplot showing the relationship between the percentage difference in surface feature depth (%) between WLP and IOS and the corresponding width (µm) measured by the gold-standard WLP. The percentage difference between the two methods decreases as width increases, crossing the 0 % line at approximately 1200 µm. Measurement error falls below 20 % at around 800 µm.

mounted onto a custom-made 3D-printed acrylic block (RGD720, General Purpose Transparent, Stratasys, USA) using composite resin (3M Filtek Restorative Composite, USA).

2.1. Scanning protocol

Baseline scanning and follow up scans were performed using a confocal white-light chromatic profilometer (WLP) (Taicaan XYris 2020 HL System TaiCaan Technologies, UK) with a chromatic aberration sensor operating at up to 10 kHz sampling frequency. The precision motion tables provided positional repeatability of better than 50 nm laterally [12]. The optical sensor of the profilometer projected a 12 µm spot of light onto the source and was able to resolve surface features to 6 µm in diameter with axial (vertical) resolution of 9 nm. The intra-oral scanner (Primescan® Dentsply Sirona, Germany) uses structured patterned light technology and the principles of confocal microscopy, along with a pixel sensor to register a surface. The light distortion is dependent on the surface metrology of the surface to be scanned, which is registered by a light detector [13]. Scans were based on previously published protocols [14].

The WLP was operated at room temperature and used a raster pattern for each X, Y data point acquired in 10 µm intervals within a 10 mm x 10 mm grid at 1000 Hz scan rate. All scanning was performed by a single operator. The intraoral scanner was calibrated before each session following the manufacturer's instructions and samples were scanned until data saturation with previous studies reporting data captured every 60 - 120 µm [15]. A baseline scan was repeated 5 times. No RMS errors were detected >1 µm.

2.2. Surface feature creation

The plastic teeth and composite blocks were mounted on an electrodynamic wear simulator (Bose Enturatec, 3200 Series III, TA Instruments, USA) and a speed-increasing electric micromotor handpiece (Z95L NSK, Japan) with a micro-bur used at 50,000 rpm (rpm) and perpendicularly aligned to the surface. The drill depth was set by the operator to cut 5 – 360 µm and widths 150 – 1300 µm. The tooth and composite block were cleaned with ethanol to remove debris, placed in an ultra-sonic bath for three minutes and blasted with high-pressure air to remove remaining water droplets. They were stored dry in a sealed clean container to prevent contamination and scans repeated using WLP and IOS as described above. Each surface features was scanned five times by the IOS and profilometer to reduce variation.

2.3. Data analysis

The WLP produced data orientated to exact X, Y and Z axes in cartesian space [16]. The profilometer scans were used to orientate the IOS scans to the Z axis (Geomagic Control 9, Geomagic Inc., North Carolina, USA) [17]. The WLP scan was fixed as a reference and an iterative closest point (ICP) registration used for each IOS scan to ensure measurements were consistent in the Z-direction [18]. Datasets were subtracted to reduce ICP error [17]. The midpoint profile and the mean (SD) 2D depth and width parameters (µm) were extracted according to ISO 5426–1 [19]. Analysis was repeated five times and the mean value calculated.

Baseline repeatability, reproducibility for the operator and an initial pilot study was then performed. Repeat analysis on the same scan was repeated ten times for each of the profilometer and the intraoral scanner. The reproducibility was assessed by repeating the scanning and analysis of the same surface feature ten times for each of the profilometer and the intraoral scanner.

2.4. Pilot study and sample size calculation

For sample size calculation an initial pilot study was performed ($n = 9$). For this, depths were created 60 – 300 µm and widths 750 – 1275 µm and each surface was scanned by the WLP and intra-oral scanner and analysed. The correlation between 2D Step height obtained from both scan types was $r^2 = 0.0983$. Using G*Power version 3.1.9.7 (Department of Psychology, Heinrich-Heine-Universität Düsseldorf, Germany), 80 % power and 5 % alpha, the sample size required was a minimum of 67 surface features. This was increased to 81 to capture a wider range of widths and depths [20]. When a surface feature was not captured by the IOS, an error was reported at 100 %.

2.5. Statistics

The percentage difference in depth was calculated for IOS vs. WLP measurements and plotted against the gold standard width measurement (µm). A linear trendline and R^2 value were computed using statistical software SPSS (IBM Corp. 2023. IBM SPSS Statistics for

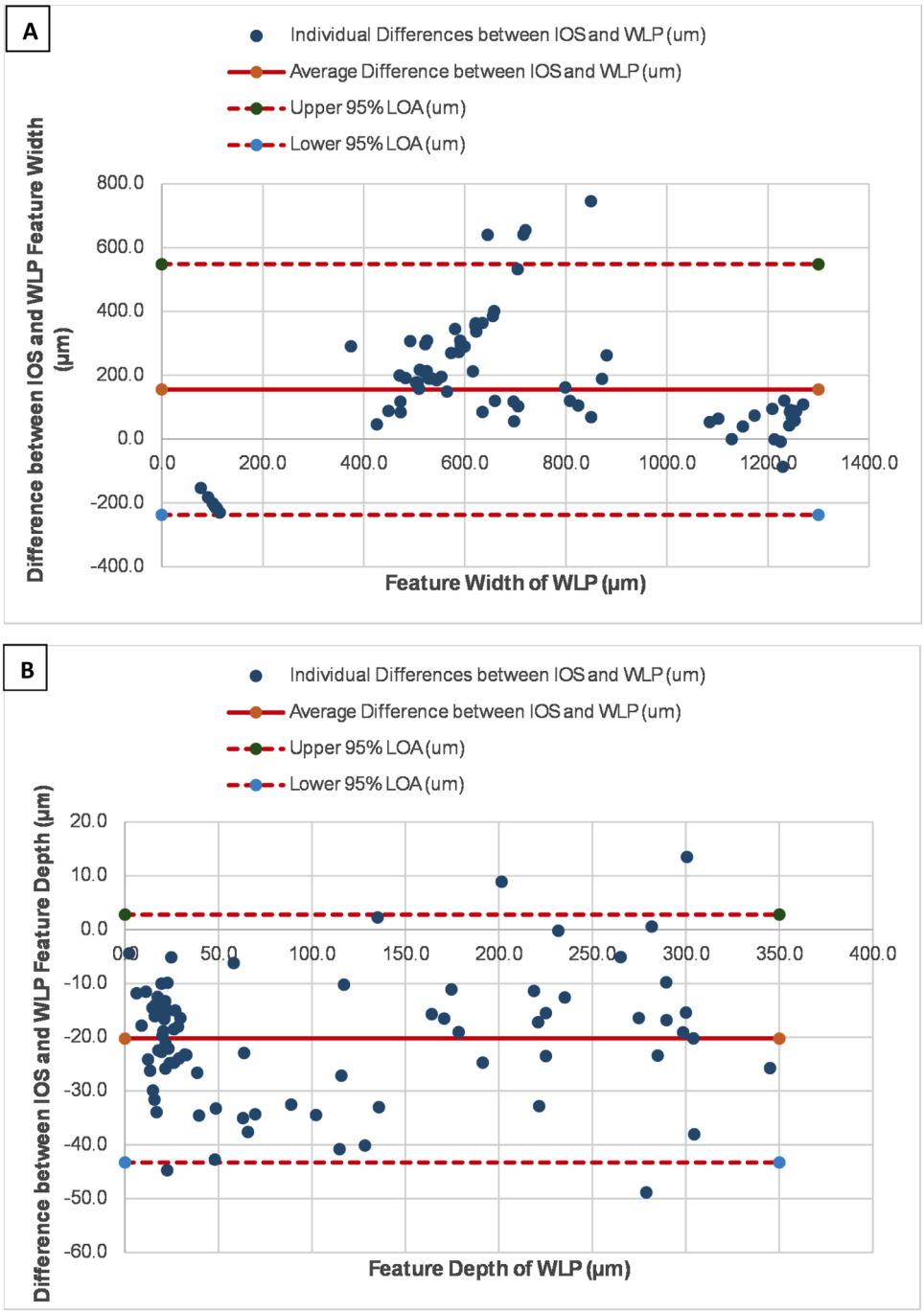

Fig. 3. Bland-Altman graphs showing the individual differences (µm) between the IOS and WLP at width 4A (above), and depth 3B (below) detection plotted by depth (µm) of WLP with upper and lower limits of agreement (dashed lines) and average difference (solid line).

Windows, Version 29.0.2.0 Armonk, NY: IBM Corp) to plot the coefficient of determination of width and depth measurements by the intra-oral scanner. Two-tailed Pearson Correlation determined the p - value of the correlation and the 95 % confidence intervals. Data were also analysed using descriptive statistics to compare the IOS to the WLP for depth and width [21]. Bland-Altman plots were constructed to further illustrate the limits of agreement between the IOS and WLP scanners.

3. Results

The repeatability of IOS scan analysis was a mean 0.82 µm (SD 0.24) and the reproducibility was mean 1.35 µm (SD 1.19). The error of depth measurement was 100 % when the surface feature width was 250 µm, 20 % when the width was 750 µm and 0 % when the width was 1200 µm. As the width increased, the error of the IOS depth detection decreased. A scatterplot demonstrating the relationship between the percentage difference of depth to width showed the error reduced from a maximum of 100 %, when the surface feature width was 150 µm to 0 % error when the surface feature width was 1200 µm (Fig. 2). The regression formula for the fitted trendline was $y = 91.15 - 0.08*x$. The Pearson correlation coefficient was - 0.87 (95 % CI: 0.895 to - 0.82, $p < 0.001$). The negative linear association between the width of a surface feature and the error of depth measurements was statistically significant. The coefficient of determination, R^2, was 0.76.

Fig. 3 shows the Bland-Altman analyses of the differences (µm) between the IOS and WLP for width and depth detection. These analyses

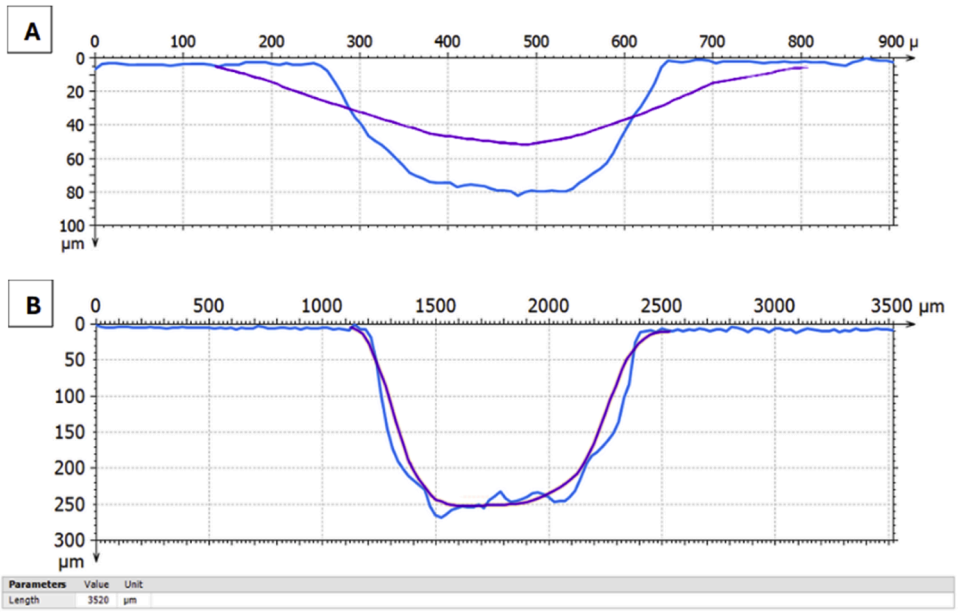

Fig. 4. (above): visual representation of a 399.3 µm wide surface feature scanned by both a profilometer and an IOS. 4B (below) visual representation of a 1215 µm wide surface feature scanned by both a profilometer and an IOS. The purple line represents a single line profile from an IOS scan, and the blue line represents a profile from the WLP scan.

revealed that the IOS overestimated surface width by 155.5 µm and underestimated depth by −20.2 µm. The 95 % limits of agreement of width detection were + 548.0 µm and - 237.0 µm respectively, and of depth detection was + 2.8 µm and - 43.3 µm, respectively.

Edge detection of the IOS was poor, as it consistently over interpolated data resulting in widening and narrowing of the surface feature. Fig. 4 demonstrates the 2D profile of a width 400 µm and 1200 µm. The IOS did not acquire sufficient pixel data on the sides or base to produce an accurate outline. For the narrow surface features, the IOS overestimated the width by 65 %. However, for a wider feature the IOS captured the edge, sides and base to produce a more accurate representation. Widths and depth measurements were not statistically different to the profilometer ($p > 0.05$). However, an overlay of the two patterns (Fig. 4B) demonstrates rounding of the edge, sides and base of the surface feature.

4. Discussion

Intra-oral scanners are designed to capture images of preparations of teeth to construct crowns. They are not designed to measure small changes. Our work investigated the impact of width and depth using an intra-oral scanner. The IOS did not capture depth data when surface features were below 250 µm in width and is likely to be a limitation of the hardware. The stitching algorithm within the software of the IOS may disregard small changes as outliers and omit these features from the dataset. As the width increased, a greater number of datapoints were captured at the edge, sides and base of the IOS. Depth error started to reduce at 600 µm and was consistently below 20 % at 750 µm and at 1200 µm the minimum width was achieved for full reproducibility.

Qualitative and quantitative data suggest that the IOS is less accurate at edge detection for high precision measurements. This is likely to be a combination of a hardware and software issues. If there are insufficient data points at the edge, the fitting algorithm interpolates, and rounds off the edge. When the width of the surface feature was 400 - 600 µm the IOS tended to overestimate the width as much as 573 µm. As width increased it tended to underestimate. Depth measurements were more predictable, with consistent underestimation by 40 µm. Interestingly, provided there was sufficient width, the 2D step height was not statistically different between the IOS and the WLP. These findings may explain discrepancies in IOS accuracy as reported in the literature. For example, Witecy et al. [22] stated that the IOS detected a mean (± SD) tissue loss of 17.1 ± 4.7 µm and 10.1 ± 5.1 µm with no significant difference to a gold standard profilometry. However, their maximum depth was assessed in one dimension, without considering width or volume changes. A study using volume change to compare an IOS to profilometry for extensive non-carious cervical lesion progression, observed no differences between the IOS (TRIOS 4; 3Shape A/S, Copenhagen, Denmark) and an optical profilometer (Proscan 2000; Scantron, Taunton, UK) [23].

This study had several limitations. Width and depth features were made on free form surfaces from typodont acrylic teeth rather than natural enamel surfaces. The buccal surface was selected because it is relatively flat as was the composite block. This made the superimposition more accurate and allowed a more controlled environment. Human enamel would have some degree of light opacity and different depths of enamel may behave differently to reflected light depending on prism orientation [24]. The occlusal surface of a molar would also create a greater challenge for the software calculation of change. Saliva might impact light reflection and is likely to result in further accuracy changes for small surface features, but the underlying physics of the system will not change. The shape of the features used in this model were created using diamond dental burs resulting in regular and circular morphology and are likely to be an advantage to the IOS. It is possible that other intra-oral scanners may provide slightly different results, but the underlying principles of data capture and interpolation apply. It is likely in time that the software of many IOS will improve, but the detection accuracy of the IOS will be limited by the speed of the sensor and the measurement area of scan tip. A wider measurement area (larger optical sensor) could facilitate greater pixel return but this limits access in tight areas of the mouth.

Further work is needed to improve registration of 3D scans to facilitate detection between sequential scans. Outside of a highly controlled laboratory environment, changes in the reference surfaces and erroneous data points are likely to introduce registration errors which will increase overall error for wear detection. Whilst IOS scanners have similar technological principles of operation, testing multiple scanners was beyond the scope of this study. Further work is needed to understand the measurement limits of other models of IOS scanners.

Furthermore, the scanning and analysis was completed by only one operator, which is also a limitation of this study.

5. Conclusion

We discovered that the IOS used in this study has limitations in accurately measuring small changes. This probably reflects the pixel size and limitations in the optics of the hardware. For dimensions <1 mm in width the software combined with hardware smoothed the edges and caution needs to be used when claiming accuracy at that level. Wider features provided accurate depth measurement.

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CRediT authorship contribution statement

Sneha Chotaliya: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saoirse O'Toole:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization. **Rupert S Austin:** Writing – review & editing, Supervision, Software, Resources, Methodology, Funding acquisition, Formal analysis, Data curation. **Thomas Bull:** Writing – review & editing, Visualization, Validation, Investigation. **David Bartlett:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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