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Comprehensive analysis of laserscanner validity used for measurement of wear

Shu-Min Hsu[1] | Fan Ren[2] | Nader Abdulhameed[1] | Mijin Kim[1] | Dan Neal[3] | Josephine Esquivel-Upshaw[1] 🔘

[1]Department of Restorative Dental Sciences, University of Florida College of Dentistry, Gainesville, Florida

[2]Department of Chemical Engineering, University of Florida College of Engineering, Gainesville, Florida

[3]Department of Neurosurgery, University of Florida College of Medicine, Gainesville, Florida

Correspondence
Josephine F. Esquivel-Upshaw, University of Florida College of Dentistry, Gainesville, FL.
Email: jesquivel@dental.ufl.edu

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Summary

Objectives: The aims of this study were to test the hypotheses that (a) a laserscanner used for measuring maximum depth and volume loss will yield the same results as a surface profilometer; (b) the surface roughness will affect the maximum depth and volume loss measured with the laserscanner; (c) analytical results using the laserscanner from multiple operators have no more than 10% inter-rater difference and; (d) replicating samples using either stone or impression material is an accurate method for measuring wear using the laserscanner.

Materials and Methods: The volume and maximum depth of indentations from fine, medium and rough burs on glass-ceramic disks were measured using two devices, a surface profilometer (Dektak II, Veeco) and a 3D Laserscanner (LAS-20, SD Mechatronik). Replicates of the indentations made from polyvinysiloxane impression material and gypsum were also measured.

Results: Comparison of profilometer and laserscanner readings using ceramic disks demonstrated a mean error of 13.61% for depth and 25.32% for volume. Replication errors were minimal (2.6% for impression, 2.5% for stone). Surface profilometer data for volume measurements revealed a difference of 6.1% for impression and 6.5% for stone compared with ceramics. However, when measurements for replicates were compared between laserscanner and surface profilometer, depth had a mean error of 74% for impression and 51% for stone. Volume differences of 78% for impression and 44% for stone were recorded.

Conclusion: This work demonstrated that the laserscanner was a convenient device for measuring wear but there is a need to validate the accuracy of the measurements.

KEYWORDS
dental ceramics, erosion testing, profilometry, wear testing

1 | INTRODUCTION

In the last two decades, the wear of opposing enamel against new dental materials has become a major criterion in the assessment of these new materials. Wear can be caused by mechanical, chemical or biological factors, either in combination or separately.[1] The ideal dental material is one that will wear the same rate as natural enamel, will not cause undue harm to the surrounding tissues or

accelerate the wear of the opposing enamel. Various assessment techniques and devices have been used to evaluate the wear of dental hard tissue and dental restorative surfaces in vitro and in vivo.[2-14] However, since wear is caused by a combination of factors which are difficult to simulate in vitro, most of these tests are not representative of the wear that occurs intra-orally. The International Standards Organization measures in vitro wear of a dental material and the opposing enamel using a pin on disk method.[15] This method does not simulate masticatory movements since there is only a rotation mechanism involved. There are several wear machines which attempt to simulate masticatory movements by incorporating vertical and horizontal slide options.[16] Actual quantification of wear can be performed directly on the samples through the use of laserscanners or profilometers.[10-12,17] However, none of these correlate well with wear observed clinically since the masticatory system is complex. Measurement of in vivo wear involves creating a replica (either in gypsum or acrylic) of the teeth before and after wear occurs. A divet or a landmark is used to allow identification of the area of interest for wear measurement. Laserscanners or micro computerised tomography scanners using superimposition software[14] or surface profilometers [13,18] are then used to quantify wear.

Surface profilometry has been used for quantitative wear evaluation and can be either contact, which uses a stylus,[2,4,8,17] or non-contact profilometry, which uses a laser beam or white light as sources.[2,3,6,9-11] The contact stylus is usually a metal or diamond ranging from 2-20 μm in diameter loaded with a few millinewtons while contacting the surface.[4] The scan produced can provide a map of the surface topography. While this method is considered precise for depth profilometry, the process is time consuming.[5,8]

With the advent of digital dentistry, laserscanners were developed for scanning and comparing worn surfaces.[3,9-11,13] A digital image can be produced by the movement of the worn object under the projection of a laser line. The reflection of the cross-section profile of the worn area is then detected by sensors. The whole image consists of "point clouds," and each point represents x, y, z coordinates on the worn surface. Each profile can then be combined and transformed into a 3D worn image by an analysing or comparison software.[19,20]

The application of the laser beam produces higher resolution images. However, the laser beam can produce overshot reflections, otherwise known as the edge effect, in sharp edges or at the bottom of grooves, which cause artefacts and measurement errors.[21,22] Laser beam measurements are also affected by wet and glassy surface reflections. In some instances, replicates, such as stone or polyvinylsiloxane impression materials, are used to minimise surface reflections of samples that are to be measured by laserscanners.

With the increased dependence on these new measuring devices, there is a need to validate their accuracy. The objectives of this research study are to test the hypotheses: (a) that a laserscanner used for measuring maximum depth and volume loss will yield the same results as a surface profilometer; (b) that the surface roughness will affect the maximum depth and volume loss measured with

the laserscanner; (c) that analytical results using the laserscanner from multiple operators have no more than 10% inter-rater difference and; (d) that replicating samples using either stone or impression material is an accurate method for measuring wear using the laserscanner.

2 | MATERIALS AND METHODS

2.1 | Materials and instrumentation

A total of 36 indentations were created on six 12 mm × 2 mm commercially available heat-pressed ceramic disks (Zirpress, batch number K30420, Ivoclar Vivadent AG, Schaan, Liechtenstein), which were cut from ingots using a diamond saw (Buehler, etc). Both sides of each specimen were polished with 320, 400, 800, 1000 and 1200 grit abrasive papers (Ecomet 2500, Buehler Ltd., Lake Bluff, IL, USA). Three indentations were created on both sides of each disk by using either a fine, medium or rough grit bur (Brassler, USA) mounted on a drill press (PFG 100, Cendres & Metaux, Biel, Switzerland) at 10 000 rpm with a force of 30 N ± 10 N. The indentations were standardised by using the vertical ruler on the indenter and timing for 3 seconds from when the bur touches the surface of the disk. A new bur was used to make each indentation. Each disk received three indentations of the different grit burs on each side. Twelve indentations were made for each of the fine, medium and rough groups.

Replicas of each disk were made using light body polyvinyl impression material (Imprint 3, 3M ESPE) to provide a negative impression of the indentations. Stone models were poured using white stone (Fujirock, GC).

All specimens, including ceramic, stone and impression replicates, were measured for volume and depth, using the Dektak stylus profiler (Dektak II, Veeco). These measurements from the profilometer were compared between the ceramic samples and the replicates to determine the accuracy of the replication process. The ceramic measurements from the profilometer were then compared with laserscanner (LAS-20, SD Mechatronik) measurements from three operators. The same comparison was done for the stone and impression replicates.

2.2 | Analysis methods

The stylus profiler was used as the gold standard to measure volume (mm^3) and maximum depth (μm) for all indented surfaces. Two centre scans were made perpendicular to each other as shown in Figure 1A. A standard sample was used for calibration of the profilometer where a 0.005% difference was detected for a 1 mm range. The accuracy of depth measurement was calibrated to 50 nm. The profilometer is capable of producing 120 000 data points for each scan. For this experiment, the hills and valleys profile was chosen with a resolution of 0.417 μm and was equivalent to 3000-4600 data points for each cross-sectional scan. To measure the maximum depth, one depth scan was performed every 200 μm from one edge of the indentation to the other edge and two additional depth profile
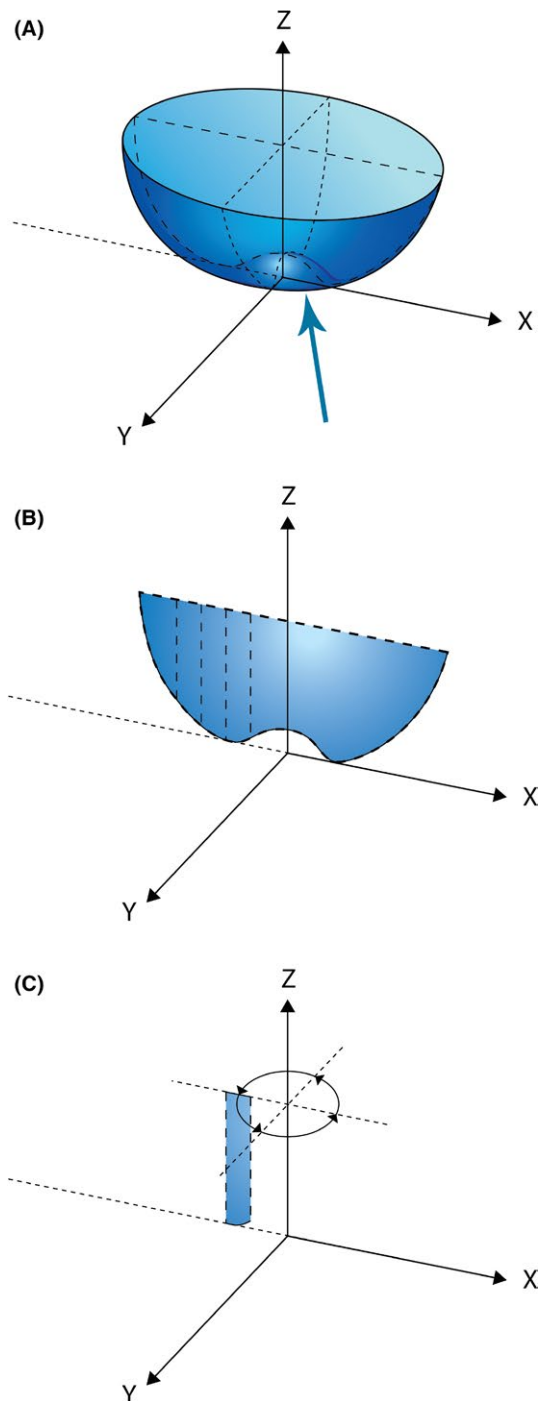
FIGURE 1 Schematic diagram of (A) two Dektak depth scans perpendicular to each other. Blue arrow showing irregularity with rough bur indentations; and (B, C) indentation volume determination by convolutional integration of the measured depth profiles

scans perpendicularly across the centre of the indentation. The maximum value of the scanned depth was identified as the depth of the indentation. The volume of the indentation was obtained by adding up small portions of volume, which is mainly the product of each area of the scanned cross-sectional depth profile multiplied by the distance of 200 μm and the volume at both sides of the edges. However, because of the trenches and irregularities on the bottom

(Figure 1A) of the indentation that are present in the rough indentations, the calculation of adding up small portions of the volume every 200 μm may be inaccurate. Therefore, we also determined the volume by revolutional integration of the scanned profile crossing the centre of the indentation. The centre of the indentation was defined as half the distance between two edge points. The volume was computed by calculating the area at every 100 μm interval from the centre of the indentation and multiplied by 2πr (Figure 1B,C). Ideally, the indentation can be assumed to be a symmetrical object resulting from the spherical diamond bur spinning. However, we also examined the rough indentations by 360/180/90 degree in the event that they are not perfectly symmetrical as illustrated in Figure 1A,B. The difference of volumes estimated by two perpendicular scan depth profiles was less than 0.2%-6%, indicating that the assumption of the indentation being symmetrical is reasonable.

Volume loss (mm^3) and maximum depth (μm) of the indentations were measured using the laserscanner. Laserscans with an x-y resolution of 80 μm were chosen according to the manufacturer's recommendation. The scanning time for each indentation was about five minutes. Both sides of the disks were scanned once. The same scanned data were analysed by three different operators using a metrology software (Geomagic Control 2014, Geomagic USA), which is typically used for analysing point clouds, surfaces and 3D object data as well as performing volume comparison for clinical tooth wear. Scanning was attempted with higher resolutions of up to 5 μm, but the scanned data displayed excessive noise and spikes. These made area definition difficult for the operators. The software has a function for removing noises and spikes but the images became distorted. Therefore, higher resolution scanning was not applied to this study. The volume of the indentations was determined by placing a reference plane parallel to the top of the scanned flat-surface. The fill volume command was used to measure the volume confined between the reference plane and the scanned indentation surface below, and was defined as the volume of the indentation. The maximum height of the filled indentation was assigned as the depth of the indentation.

2.3 | Statistical analysis

The data were analysed using the R statistical software package (V.3.2.4) to assess agreement between two methods of measurement for ceramic disks and the stone and impression replicates. Additionally, the differences in measurements were assessed against their means. The distribution of the differences was assessed for normalcy to ensure that using a 95% confidence interval to quantify the extent of agreement is valid.

3 | RESULTS

3.1 | Maximum depth and volume loss analysis for ceramic samples

Since the scan resolutions in terms of measured depth and x-y stage movement of the surface profilometer are two orders higher than

those of the laserscanner, use of the volume of indentation and the maximal depth measured with the profilometer to calibrate these two values obtained with the laserscanner is reasonable. The diameters of the indentations ranged from 1.3 to 2.0 mm and were obtained by reading x and y coordinates from either the profilometer or the metrology software.

The indentation volumes measured with the laserscanner were generally smaller with variations ranging from 4% to 80% as compared with the indentation volumes determined by the surface profilometer. In addition, there were discrepancies of 18% to 31% in indentation volume estimation depending on the operators. A scatter plot of volume values determined by both methods is shown in Figure 2A, where the profilometer values are higher than the laserscanner measurements for almost all cases.

The difference of depth values between the surface profilometer and laserscanner was from 0.5 up to 40% and ranged from 12% to 14% error depending on the operator. The smooth burs actually produced the same depths as the rough burs. Depth measurements were made from the top of the reference plane to the deepest point.
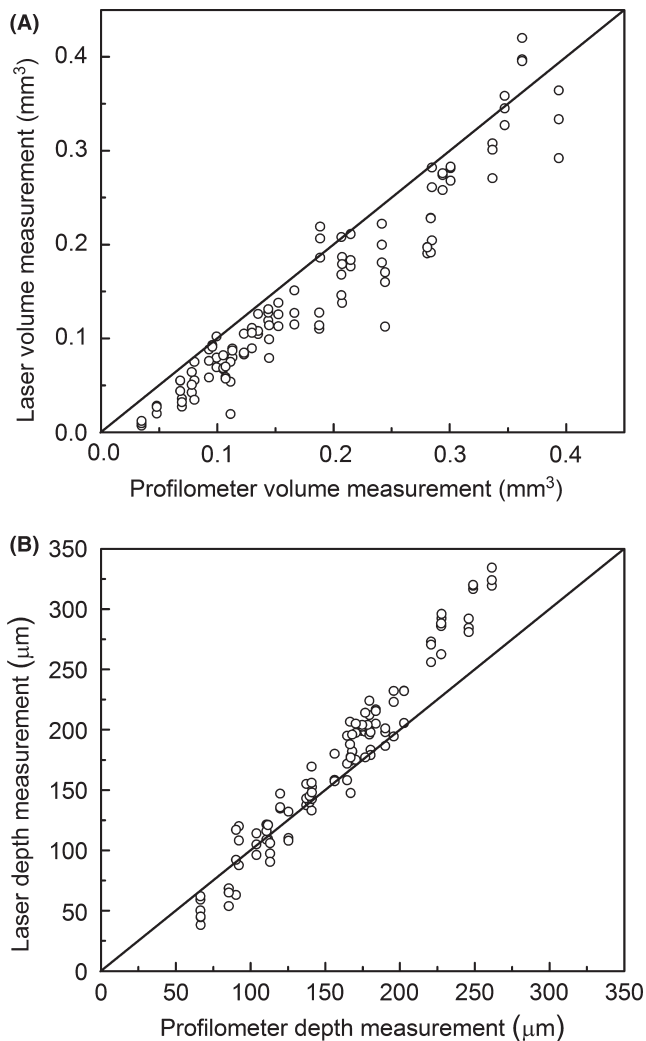
Figure 2B shows the scatter plot between depth measurements for profilometer and laserscanner which shows that the methods are in better agreement as compared with volume measurement. For a random indentation, the laserscanner volume reading can be expected to be 0.03 units (Figure 3A) lower than the profilometer reading, and there is evidence to suggest systematic bias between the methods (the confidence interval is lopsided in the negative direction). For depths >150 μm, the laserscanner tends to produce higher measurements. However, for depths <100 μm, dektak produced higher values. For a random depth value, expect the laserscanner depth to be 16.5 units (Figure 3B) higher than the profilometer reading. However, when data are stratified by depth, the methods may be comparable only for shallow and medium depths. For large depths, laserscanner produces higher readings than the surface profilometer.

For the analysis of inter-rater differences in the laserscanner, the mean per cent difference was calculated for Operator A vs Operator B; Operator A vs Operator C; and Operator B vs Operator C. The overall percentage for mean volume difference was 13%, which is significantly higher than 10% ($P = 0.037$) and are high across all roughness groups. The overall percentage for mean depth difference
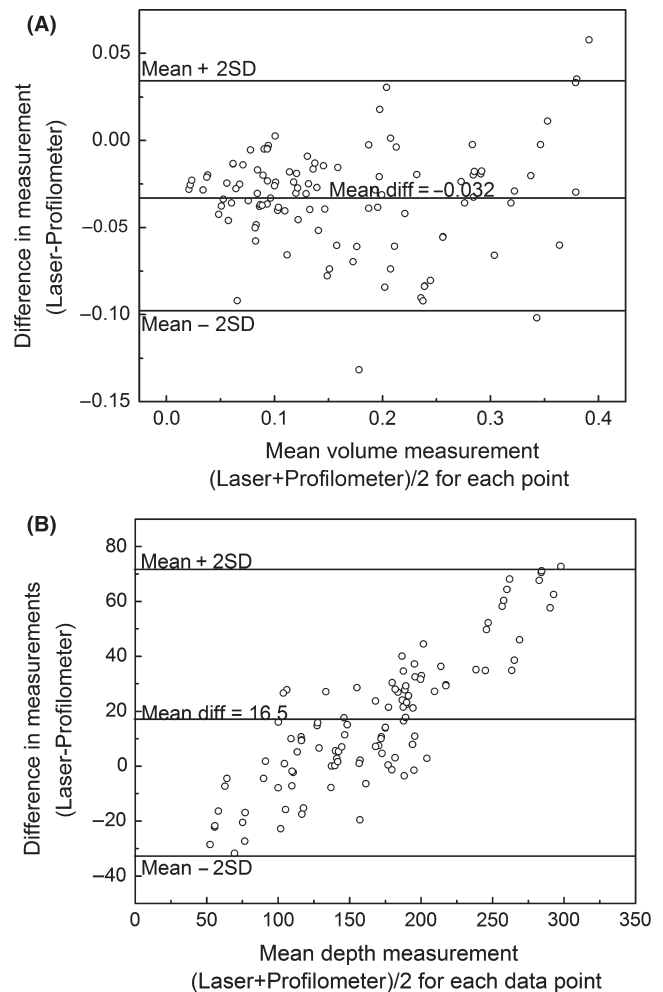

FIGURE 2 Scatter plots for (A) volume and (B) depth mean measurements with diagonal line indicating perfect agreement between the two measuring devices

FIGURE 3 Scatter plots for (A) volume and (B) depth differences in measurements against the mean for each data point

was 7.5%, which is not significantly higher but is actually significantly less than 10% (P = 0.002).

For the effect of surface roughness (fine, medium, rough) on the measurement of the laserscanner, ANOVA results show that roughness is significantly associated with the volume (P = 0.005). Pairwise comparisons show that "rough" measurements are significantly higher than "smooth" (P = 0.004). "Medium" measurements are significantly higher than "smooth" (P = 0.006), but rough and medium are not significantly different (P = 0.886). ANOVA results show that depth measurement is also not significantly associated with roughness (overall P = 0.762).

3.2 | Maximum depth and volume loss analysis for stone replicates

The mean error for depth measurements between the ceramic and the replicates using dektak is 2.6% for impression and 2.5% for stone, indicating that the replication process produced minimal errors. Using the same technique for volume measurements revealed a difference of 6.1% for impression and 6.5% for stone.

The laserscanner reads consistently higher than profilometer for depth measurements. The mean difference is 81.9 units, SD = 57.6 (95% CI = [−32.2, 196] but the effect differs systematically with the magnitude of the depth being measured (that is, the larger the depth, the greater the difference between the two methods). The mean percentage difference is 49.0%, SD = 28.6 (95% CI = [–7.7%, 106%]) (Figure 4A).

(A) Difference in percentage error for depth

(B) Difference in percentage error for volume

FIGURE 4 Comparison of differences in percentage error for (A) depth and (B) volume between the three materials

The laserscanner reads consistently higher than the profilometer for volume measurements. The mean difference is 0.077 units, SD = 0.052 (95% CI = [−0.25, 0.180]), but the effect differs systematically with the magnitude of the volume being measured (that is, the larger the volume, the greater the difference between the two methods). The mean percentage difference = 43.7%, SD = 17.4% (95% CI = [9.2%, 78.2%]) (Figure 4B).

3.3 | Maximum depth and volume loss analysis for impression replicates

Similar to the stone replicas, laserscanner reads consistently higher than the profilometer for depth measurements for impression samples. The mean difference is 118.4 units, SD = 63.0 (95% CI = [−6.5, 243]), but the effect differs systematically with the magnitude of the depth being measured (the larger the depth, the greater the difference between the two methods). The mean percentage difference = 73.6%, SD = 34.8% (95% CI = [4.6%, 143%]) (Figure 4A).

For volume, laserscanner reads consistently higher than profilometer measurements. The mean difference is 0.121 units, SD = 0.068 (95% CI = [−0.013, 0.255]), but the effect differs systematically with the magnitude of the volume being measured (the larger the volume, the greater the difference between the two methods). The mean percentage difference is 77.5%, SD = 27.8% (95% CI = [21.8%, 133%]) (Figure 4B).

4 | DISCUSSION

The results indicate that ceramic volumes recorded for the laserscanner were generally smaller than those obtained for the surface profilometer. To confirm the cause for the variability, three disks were selected at random for smooth, medium and rough groups. The diameter of each indentation was measured using a calibrated microscope at 100x magnification (Keyence VH 1000x, Keyence USA). The same diameters were measured using the surface profiler and the laserscanner. Comparison analysis confirmed that the x- and y-scanned distances were around 21% shorter for the laserscanner compared with only 0.022% error for the profilometer. This discrepancy accounted for the majority of the deviations of the measured indentation volume measured by the laserscanner. The rationale for this discrepancy in measurement values is that the laserscanner is subject to the "edge effect" mentioned earlier. This is the result of reflected laser beams splitting into different angles from the edge of the indentation and creating measurement artefacts. In this case, a ridge or bump along the edge of the indentation (Figure 5A) is produced. To compensate for this artefact, the operators had to decide on a reference plane to base volume calculations and depth calculations from, essentially removing the "bump" from the edge of the indentation (Figure 5B). The 13% difference in indentation volumes between operators (which is the difference between 18% and 31% mentioned in the results section) was because of different positions of the reference plane chosen by different operators. The impact
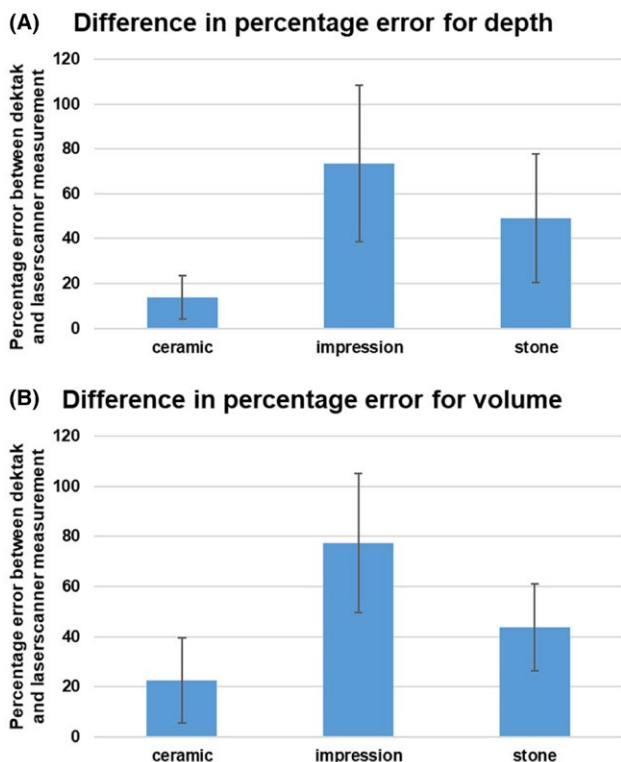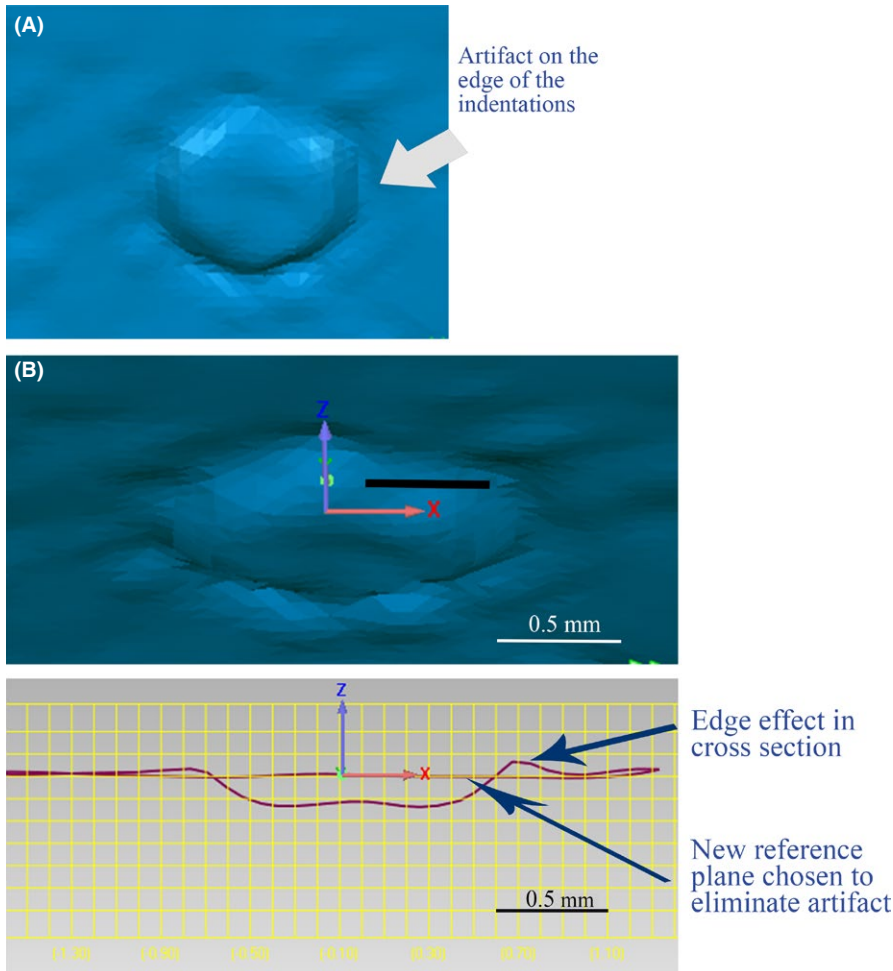
FIGURE 5 Actual scans from the laserscanner showing (A) the edge effect; (B) the arbitrary reference plane chosen to remove the artefact

of the reference plane position on the volume determination would be larger for indentations with smaller volumes (less than 0.1 mm^3), since the same volume difference resulting from the arbitrary reference plane position would have a larger per cent deviation for those indentations with smaller volumes. Additionally, the depth measurements were measured using filled indentations from the top surface to the deepest point. The difference was around 2% which was also affected by different operators deciding on the position of the reference plane.

The cross-section profiles of the same samples are superimposed for the laserscanner (red) and profilometer (blue) and shown in Figure 6A. The two profiles display similar trends with regards to the morphology of the indentation surface. However, the profile from the laserscanner does not depict the actual surface roughness seen on the indented surfaces. The grit sizes for the different burs used were 30 microns for fine, 100 microns for medium and 150 microns for rough. The differences in these grit sizes are highly evident in the profile from the surface profilometer; however, they are not as clear with the laserscanner profiles. This is the result of the highly accurate measurement for the surface profilometer which generated 3000-4600 data points per scan.

The laserscanner also underestimated or overestimated depth measurement depending on the depth of the indentation. The

underestimation can be explained through the edge effect mentioned previously. The overestimation resulted from the burs which produced asperities on the centre of the indentation (Figure 6B). The formation of a circular groove around the bottom of the indentation was due to the uneven surface and grit size of the burs. These irregularities served to deflect the laser beams, similar to the edge effect to give erroneous readings for depth measurement. This can also account for the discrepancy in volume measurement discussed earlier.

Some laserscanners and wear measurement techniques utilise the indirect method of scanning where an impression or stone replicate is made of the sample and this is what is utilised for scanning.[17] The measurements obtained from the replicates using the profilometer were compared with the ceramic measurements, and the mean error ranged from 2% for depth and 6% for volume. This indicates that the replication process does not introduce any major errors and probably accounts for the setting expansion for the stone (0.12%) and the linear dimensional change in the impression material (1.5%). While the scans for both the impression and the stone models appear to have minimised the edge effect or "noise" (Figure 7A-C), their laserscanner measurements show errors which far exceed those seen with the actual ceramic samples.

The laserscanner and profilometer measurements are not comparable for stone measurements since laserscanner reads about
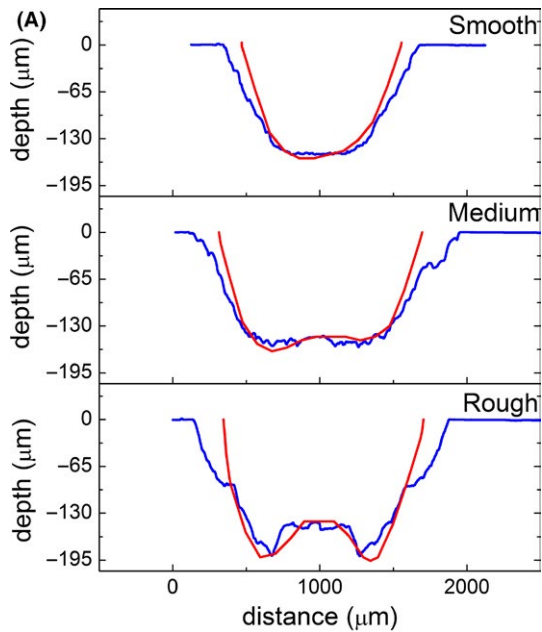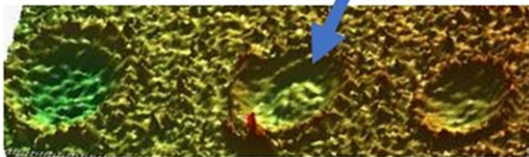
FIGURE 6 (A) Surface profiles of indentations obtained from laserscanner (red) and surface profilometer for smooth, medium and rough grit burs. Laserscanner readings do not demonstrate the level of detail as the profilometer images do. (B) Actual scan of ceramic surface showing asperities in the centre of the indentation (arrow)

FIGURE 7 Actual scans of indentations for ceramic, stone and impression. Note the decreased "edge effect" for the stone replica (C). Impression (B) compared with the ceramic (A) (arrows)

50% higher for depth, with a standard deviation of 29%, and demonstrated values that are 44% higher for volume, with a standard deviation of 17%. Both measurements are also not comparable for impression replicates since the laserscanner reads about 74% higher for depth, with a standard deviation of 35%, and 78% higher for volume, with a standard deviation of 28%. While a correction factor can be applied to the laserscanner readings by reducing the values by their respective error percentages, these measurements on average would still be too high or too low based on the standard deviation.

While the replication error does not account for the error differences seen between the profilometer and the laserscanner readings for both depth and volume, another explanation could be the influence of material[23] and the wavelength of the laserscanner. The 3D laserscanner used for this study utilised a red laser beam which has a high wavelength. Higher wavelength beams have less resolution, more diffraction and have less writing density. Depending on the nature of the material, the laser can penetrate
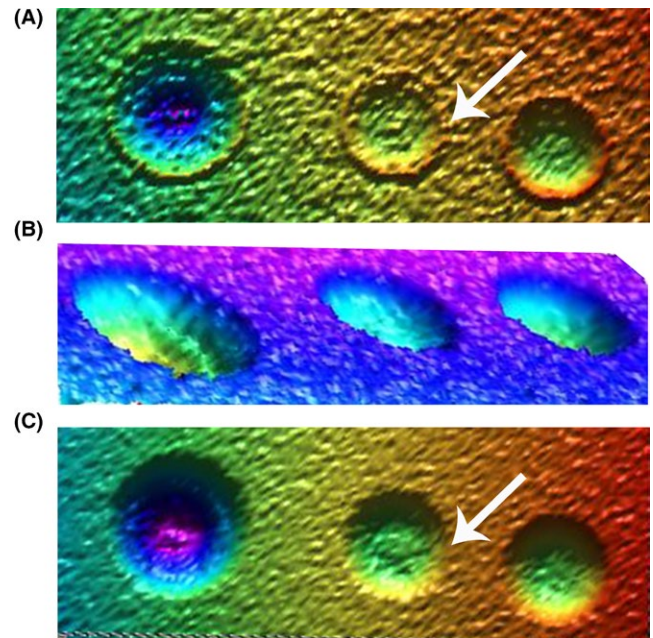
through the material to cause a diffusion on the surface. This results in loss of focus on the surface being measured and sends inaccurate readings back to the detector, which in turn leads to invalid measurements. There is a possibility that the stone, which is a porous material, allowed diffusion of the red laser beam on the surface to cause the large error deviations. The error for the impression material was probably caused by the glossy nature of the material which led to distortion of the red laser light. While there are settings on the scanner that account for the reflectance value (in this case, plastic glossy and plastic material settings) of the material being measured, there was still a lot of noise observed on the scans (Figure 7C). This noise or "speckling" is a result of distorted signals being sent back to the scanner detector which leads to inaccuracies in measurement. Despite the absence of the edge effect with the stone and impression replicates, these other factors could have contributed to the large differences in readings compared with the surface profilometer.

5 | CONCLUSION

The results of this study show that while the 3D laserscanner is a convenient tool for measuring volume loss and maximum depth to quantify wear, there were errors demonstrated compared with the measurements from the surface profilometer. An underestimation or overestimation of depth and volume was seen as a consequence of the edge effect, the nature of the material or the high wavelength of the laser beam. The laserscanner advantages such as expediency and user-friendliness were diminished specially when

accurate measurements are warranted. Replication of the samples did not alleviate the problems associated with measurement errors. Laserscanner measurements are also highly subjective to operator expertise. Therefore, more advances in scanning technology are needed to develop highly accurate devices which can compare with surface profilometers to produce valid and reliable measurements.

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CONFLICT OF INTEREST

There are no conflicts of interest associated with this research project.

ORCID

Josephine Esquivel-Upshaw https://orcid.org/0000-0003-3642-8087

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