DENTAL MATERIALS XXX (2019) XXX–XXX

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Investigation into the validity of WearCompare, a purpose-built software to quantify erosive tooth wear progression

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Tooth wear
Tooth erosion
Diagnostic imaging
Dental technology

ABSTRACT

Objectives. The use of surface matching software with intraoral scanners is developing rapidly which increases the need for accessible, accurate and validated measurement software. This investigation compared the current gold-standard Geomagic Control software to a purpose-built software "WearCompare".

Methods. Artificially created occlusal defects of a known size were created on 10 natural molar teeth scanned with a structured-light model-scanner (Rexcan DS2, Europac 3D, Crewe). The volume change, maximum profilometric loss and mean profilometric loss were obtained from both Geomagic Control (3D Systems, Darmstadt, Germany) and WearCompare (leedsdigitaldentistry.com). Duplicated datasets were randomly repositioned and re-alignment performed. The effect of the re-alignment was calculated by analysing differences between the known defect size and defect size after re-alignment using the same measurement metrics. Lastly, clinical wear measurements were compared on natural molar surfaces ($n = 60$) over 6 months using study models collected from a previous longitudinal trial. Data analysis was performed in SPSS v25 (paired t-tests, Pearson correlations, $p < 0.05$).

Results. Measurement correlation between the softwares was greater than 0.97 ($p < 0.001$) for all measurement metrics. The volume change error (SD) after alignment was -0.67 mm^3(1.14) for Geomagic and -0.06 mm^3(0.93) for WearCompare ($p = 0.140$ and $r = 0.065$, $p = 0.86$). Measurement errors were observed after alignment in both softwares and no statistical differences were observed between softwares. The volume change on the clinical dataset over 6 months was +0.29 mm^3(3.97) in Geomagic and -0.30 mm^3(1.82) for WearCompare ($p = 0.19$ and $r = 0.61$, $p < 0.001$). The mean profile gain was 42.86 μm(40.19) for Geomagic and 32.17 μm(23.72) for WearCompare ($p = 0.048$). Correlations between the softwares were greater than 0.6 for all measurement metrics except for mean profile gain.

Significance. WearCompare is a comparable tool to Geomagic for quantifying erosive tooth wear. WearCompare reported statistically less profile gain indicating less error but further research is needed to reduce the human errors in both softwares.

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https://doi.org/10.1016/j.dental.2019.07.023

1. Introduction

The use of surface matching software to quantify tooth wear progression is developing rapidly with potential to revolutionise the diagnosis and management of erosive tooth wear. To date, in vivo tooth wear measurement has relied upon visual qualitative assessment of casts of accurate analogue impressions of teeth taken at consecutive appointments [1,2]. Quantitative methods have utilized accurate impressions which are subsequently cast in dental stone [3], epoxy resin [4] or electro-conductive coatings [5] and then scanned, using laboratory based profilometers, and the digital maps aligned using commercial surface matching software or purpose built in-house software [6,7] to calculate differences between them [3,8–11]. This methodology has meant these techniques have been limited to university settings due to the specialised equipment needed for digitising and analyzing the complex tooth surfaces. The rapid and increasing improvement in the trueness and precision of intraoral and model scanners makes it unlikely that digitization of surfaces will be a limitation in the future. This makes the need for an accessible, accurate and validated software to superimpose scans and quantify intraoral changes more pertinent to facilitate accurate diagnosis in primary care.

The accurate superimposition of two scans and measurement of differences is a problem not limited to dental applications. To date, two 3D pointclouds are typically registered using either clusters of data points (features) or by aligning each individual data point, independent of the overall match in shapes. An iterative closest point alignment has been the approach taken by the majority of previous researchers in this area and the known disadvantages of these have been noted [12,13]. However, point registration algorithms are forced to align surfaces in a way that is not biologically informed, which can lead to severe local distortions. Engineering research suggests that a feature-based superimposition produces more accurate results and is less susceptible to outliers [14]. In addition to the technique used to register the two scans, the accuracy of alignment can be impacted by the areas chosen to align the scans with. A global best fit alignment approach is quick to perform and has been widely used [15,16]. However, this can lead to errors particularly in cases whereby a specific area of interest is anticipated to have changed more than others [17]. For example, in the case of molar occlusal tooth wear, global alignment will act to minimise all inter-surface distances between sequential scans. This has the effect of pulling the worn tooth in an occlusal direction, giving an erroneous underestimate of the amount of tooth wear and in some cases, reporting tooth gain. More accurate measurements can be achieved through selective surface alignment where the operator uses clinical judgement to select reference areas to align with and change is only measured on the surface of interest [17]. Despite the operator influenced error of the system, these principles and other feature-based surface matching algorithms, have been utilised for advanced free-form surface registration on MRI scans [18,19] and other applications [20].

Different methods for analysing differences between surfaces have included maximum surface height loss [11,21], average profile height loss [3,4], volume change [4,8,22] and percentage of surface area affected by wear [5]. Different methods of data extraction may be influenced to differing degrees by the method of alignment [13]. No one methodology has been used consistently and different methods have not been compared to date

The aim of this paper was to investigate the validity of a purpose-built surface matching freeware designed for dental applications. WearCompare (https://leedsdigitaldentistry.com/wearcompare.html) is based upon the use of advanced feature-based registration techniques and selective surface alignment. This software was compared to the current gold-standard, widely used Geomagic Control engineering software (3D Systems, Darmstadt, Germany). Our null hypothesis is that there is no difference and strong correlation between measurements taken with both systems.

2. Materials and methods

All electronic data used for this study were obtained from a previous longitudinal clinical trial measuring wear on teeth on 60 patients over a 6 month period (O'Toole et al. 2018, REC Ref: 14/EM/1171, clinical trials.gov registration ID: NCT02493803 [10]). Silicone impressions of teeth taken at baseline and 6 months later were poured in type 4 dental stone and the occlusal surfaces of the lower molars scanned using a triangulation laser profilometer (Xyris 2000 TL. TaiCaan, Southampton, UK) and data recorded every 50 μm, scanning from left to right in a raster pattern, at medium precision mode (scanning speed of 2.81 mm/s) [3]. This laser is accurate to 1.3 μm and repeatable to 1.6 μm. The coefficient of variation on volume measurements is <5% [23].

2.1. *Comparison using existing alignment*

Initially, ten random baseline scans of the occlusal surfaces of the lower first molars were chosen and a defect of 300 μm in depth was subtracted using Meshlab [24] in accordance with previously published protocols [17]. This created two scans in perfect alignment but with a quantifiable defect size. The differences between the scans were quantified using the gold standard Geomagic Control (3D Systems, Darmstadt, Germany) and with "WearCompare" (https://leedsdigitaldentistry.com/wearcompare.html). These differences were; volume change (overall volumetric change in mm^3), mean profile loss (average surface loss measured in microns), maximum point loss (the maximum point of loss recorded over the occlusal surface in microns), mean profile gain (average surface gain measured in microns) and maximum point gain (the maximum point of gain recorded over the occlusal surface in microns).

2.2. *Comparison using re-alignment*

The same scans were duplicated and then randomly repositioned undergoing a random rotation about an axis varying 0–360°, and a displacement along X, Y and Z between −10 and +10 mm. Re-alignment with the baseline scan was then performed using a selective surface technique in both Geomagic

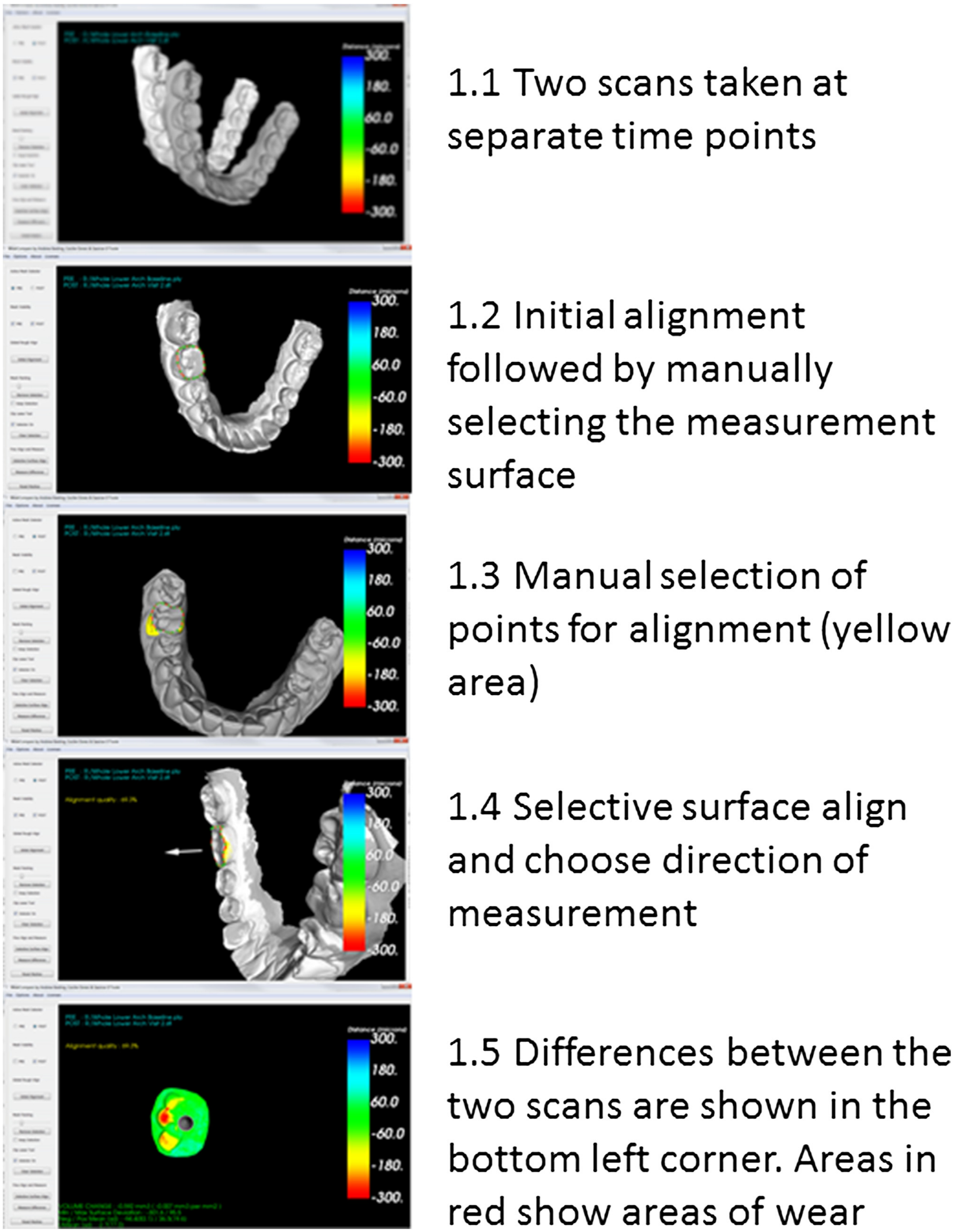

Fig. 1 – Workflow of alignment and measurement with WearCompare.

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Control and WearCompare. Selective surface alignment in Geomagic was performed according to previously published protocols [17] whereby the displaced file was duplicated and area with the defect was removed from the scan and the remaining sections used for alignment. For selective surface alignment in WearCompare, an initial alignment was performed, the defect and reference areas were highlighted and the same measurements taken (Fig. 1).

2.3. Aligning and measuring a clinical data set

Lastly, clinical wear using the baseline and after 6 months ($n = 30$ patients and 60 molars) compare between Geomagic and WearCompare [6]. The scan from each molar ($n = 60$) was aligned using the same selective surface alignment technique as described above in Geomagic and WearCompare and the differences compared.

3. Results

3.1. Comparison using existing alignment

Fig. 2 shows the average volume of the defect (SD) measured in Geomagic was 11.83 mm^3 (3.46) and 11.86 mm3 (3.61) in Wear Compare ($p = 0.771$) and were highly correlated (0.998, $p < 0.001$). There were high correlations of greater than 0.97 for all measurement metrics with no statistical differences between any measurement metric in Geomagic and WearCompare.

3.2. Comparison using re-alignment

The re-alignment showed the volume change error (SD) of −0.67 mm^3 (1.14) for Geomagic and −0.06 mm^3 (0.93) for WearCompare ($p = 0.140$ and $r = 0.065$, $p = 0.86$). Fig. 3 reports the measurement metrics for maximum point change errors and mean profile change errors. The average maximum point loss error was −15.63 μm (33.57) and −18.3 μm (14.08), respectively. Interestingly, the only measurement metric to be correlated between the two softwares was mean loss error ($r = 0.822$, $p = 0.004$).

3.3. Aligning and measuring a clinical dataset

The average volume change on 60 molar surfaces over 6 months measured by Geomagic was +0.29 mm^3 (SD = 3.97) and for WearCompare −0.30 mm^3 (SD = 1.82). ($p = 0.19$ and $r = 0.61$, $p < 0.001$). Fig. 4 reports the mean and maximum loss for Geomagic was 40.32 μm and 273.11 μm and the mean and maximum profilometric loss for WearCompare was 37.37 μm and 247.87 μm ($p > 0.05$). The maximum gain for Geomagic was 215.09 μm (SD 132.78) and WearCompare 184.39 μm (SD 126.06) and these were statistically different ($p = 0.015$) and values were correlated ($r = 0.623$, $p < 0.001$). The mean profile gain for Geomagic was 42.86 μm (SD 40.19) and for WearCompare 32.17 μm (SD 23.72 and was statistically different ($p = 0.048$) but moderately correlated ($r = 0.523$ $p < 0.001$) and Fig. 5.

4. Discussion

A very high correlation was observed between Geomagic and WearCompare when quantifying the same defect, indicating that measurements from either software are equally valid. However, the measurements were not strongly correlated after re-alignment, despite the fact that there were no statistical differences between the values observed. This indicates that there were differences in the alignment algorithm. Differences between the softwares were also observed in the clinical data and therefore the null hypothesis was rejected.

There are several reasons for differences between the softwares. Firstly, the underlying surface registration algorithm is different. WearCompare uses a feature based global registration [25] coupled with a custom iteratively refined version of the Iterative Closest Point algorithm [26]. This contrasts with Geomagic which uses a variation of an Iterative Closest Point algorithm alone to align corresponding points in the 3D dataset with greater potential to skew the data. This may explain why WearCompare reported significantly less positive deviation error or "gain" than Geomagic using the clinical dataset. Secondly, there is a difference in how the two softwares handle peripheral data. Ideally data located at the periphery of the scan needs to be removed to obtain two coincident scan sizes. In Geomagic, unless a plane is used to section through the 3D mesh, the accuracy of the periphery of the mesh is limited to the size of the triangle which is typically 50 microns but can go up to 100–200 microns [27]. WearCompare automatically sections through triangles. A third reason is differences between the handling of voids in scan. If a void is not filled by the operator, Geomagic will analyse this data as part of the scan. WearCompare automatically fills in voids following the curvature when taking measurements.

The most appropriate measurement metric to quantify tooth wear progression is unknown. Positive gain during alignment represents error in the process. Volumetric change gives an indication of the total surface change [17,28], taking into account negative and positive deviations. In our data, there were no statistical differences in volume change between the two softwares, although the error value was smaller for WearCompare. For the other parameters, mean profilometric loss was consistent between the two softwares and may be the best metric to use if consistency between the softwares is desired. However, this does mean that all positive data within the alignment is unaccounted for.

Although it does not affect the data, there were differences in the workflow. In Geomagic, using a reference surface alignment requires additional steps and while surface deviations were measured together alongside the colour map, volume calculation requires a separate procedure. In WearCompare all measurement metrics and colour maps are produced simultaneously, reducing the time taken for workflow. This becomes significant when attempting to analyse large numbers for clinical trials. Despite these advancements, there still remains little difference between the softwares. This indicates that the manual process of selective surface alignment requires further development for both accuracy and speed. It worth considering that Geomagic has several other functionalities

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	Average Defect Size in Geomagic (SD)	Average Defect Size in Wear Compare (SD)	Paired Samples T-test	Pearson Correlations
Volume (mm³)	11.83 mm³ (3.46)	11.86 mm³ (3.61)	p=0.771	0.998 p<0.001
Maximum Point Loss (µm)	305.36 µm (37.03)	302.53 µm (34.68)	p=0.343	0.971 p<0.001
Maximum Point Gain (µm)	206.56 µm (11.47)	206.68 µm (11.36)	p=0.133	1.000 p<0.001
Mean Profile Loss (µm)	214.13 µm (80.53)	219.61 µm (87.93)	p=0.343	0.983 p<0.001
Mean Profile Gain (µm)	16.12 µm (4.11)	16.29 µm (4.20)	p=0.376	0.991 p<0.001

Fig. 2 – Correlation between software measurements when quantifying the same defect (n = 10).

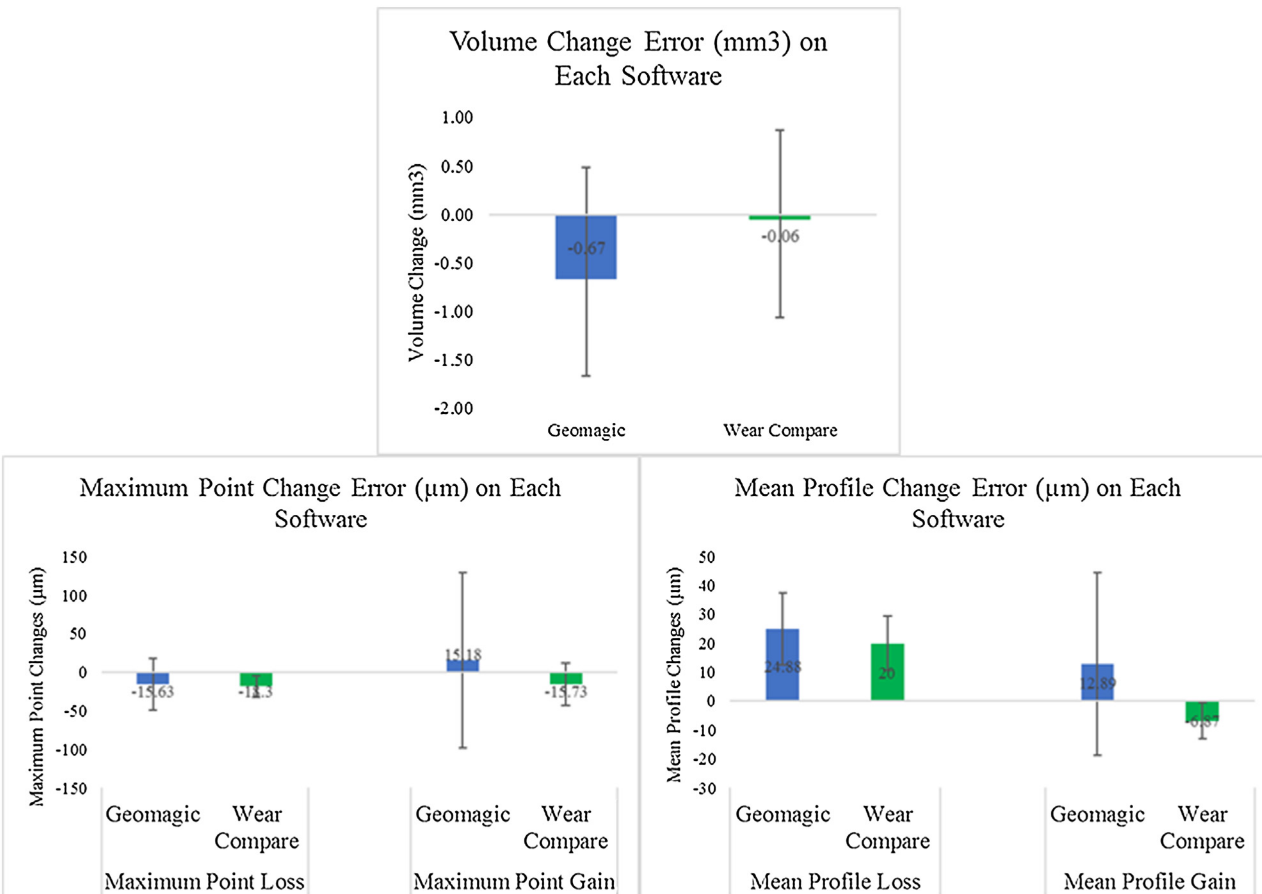

Fig. 3 – Measurement error in each software when quantifying the same defect after alignment (n = 10).

which may be useful for the advanced user but may add complexity and introduce error for the less advanced user.

There are several limitations of this study. Standard deviations were high for all measurements and indicates the complexity of the surface and the scope for operator error. This may be a reason for the lack of statistical difference between softwares, particularly when determining the alignment errors. There is potential for this to be improved with automation of the process. However, at present, operator error remains a significant limitation of the quantification process. For the third part of the study, data from a previously published clinical study were used to quantify change. There were errors with both systems and it is difficult to assess which was more accurate. It is highly unlikely that tooth tissue gain occurred over the 6 month period and is likely to represent error as a direct and known consequence of the alignment mathematics. WearCompare reported statistically less gain than Geomagic. Despite this limitation, it is promising to note that the two softwares were moderate-highly correlated.

For both softwares, understanding the underlying digital process and errors of the system is important to prevent misinterpretation. An understanding of how to read and apply

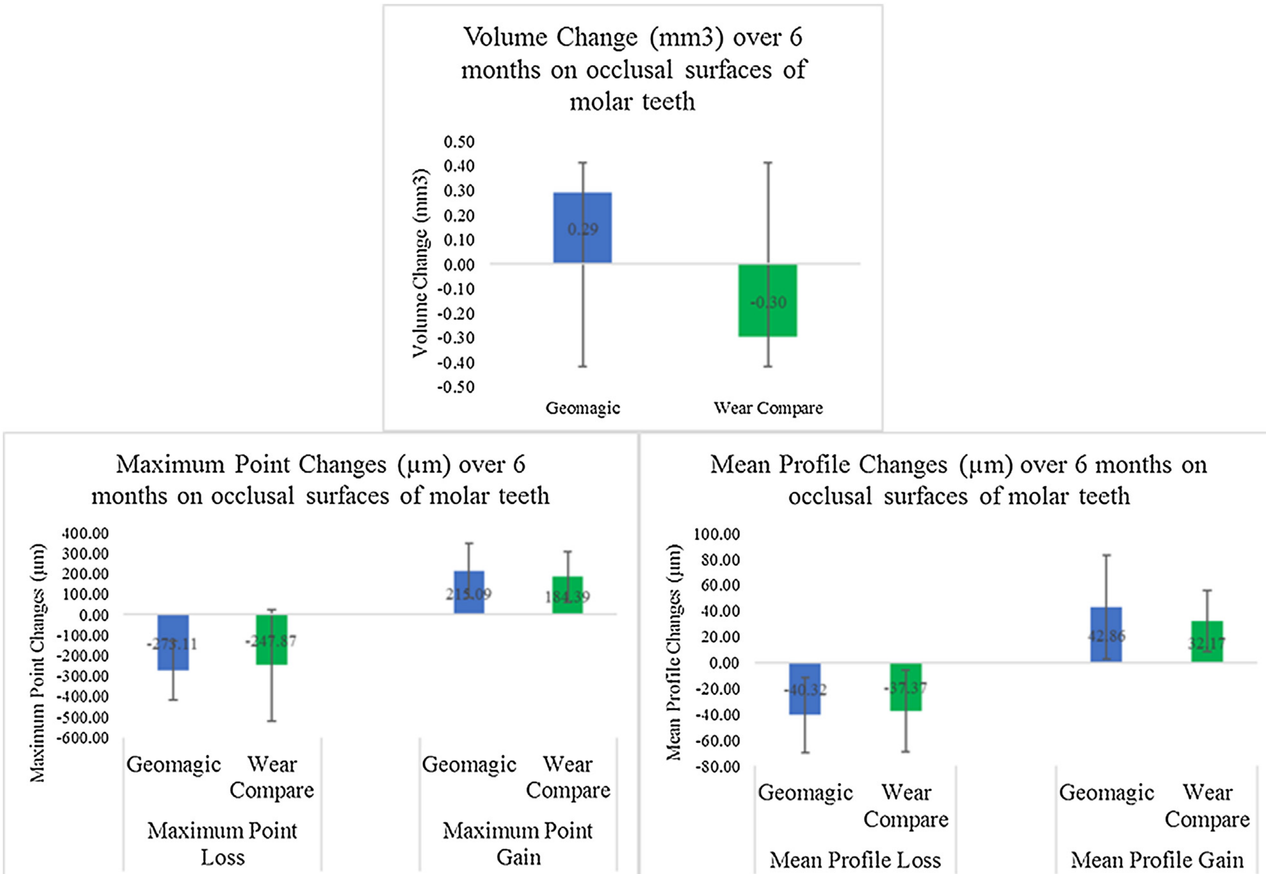

Fig. 4 – Graphs comparing the changes observed on the occlusal surfaces of 60 molar teeth from 30 patients over a 6-month period when using each software.

	Paired Samples T-test	Pearson Correlations
Volume (mm^3)	p=0.194	0.607 p<0.001
Maximum Point Loss (µm)	p=0.516	0.623 p<0.001
Maximum Point Gain (µm)	p=0.015	0.765 p<0.001
Mean Profile Loss (µm)	p=0.412	0.678 p<0.001
Mean Profile Gain (µm)	p=0.048	0.523 p<0.001

Fig. 5 – Correlation between softwares when quantifying clinical tooth wear progression over 6 months (n = 60).

the results is important, in addition to making the subjective decision that the alignment has not been successful and clinical data cannot be used. Bearing these limitations in mind, it appears that WearCompare is a suitable freeware alternative to Geomagic for the purpose of quantifying tooth wear progression. The speed of use is particularly convenient for researchers wishing to analyse large datasets, while the lack of cost makes WearCompare accessible to the general dentist wishing to monitor individual patients for tooth wear progression. Geomagic may be more suitable for advanced users who seek to use the additional functionality of the software. There are other potential applications with both softwares such as quantifying soft tissue changes following periodontal therapy or surgery which would require further validation.

5. Conclusion

WearCompare is a suitable freeware tool for quantifying erosive tooth wear and comparable to the previous gold-standard Geomagic software. Although WearCompare reported statistically less gain on the clinical dataset, there are errors

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regardless of the software used. Further research is needed to reduce the human errors associated with the alignment process to enable confident quantification of wear progression.

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