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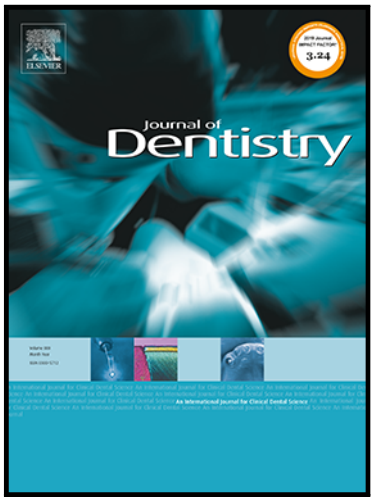

Influence of 3D analysis software on measured deviations of CAD-CAM resin crowns from virtual design file: an in-vitro study

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Influence of 3D analysis software on measured deviations of CAD-CAM resin crowns from virtual design file: an in-vitro study

Short title: Comparison of 3D analysis software

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Highlights

- The nonmetrology-grade 3D analysis software showed similar performance to the metrology-grade software while analyzing the deviations of CAD-CAM crowns from the virtual design file.

ABSTRACT

Objectives: To evaluate a nonmetrology-grade and a metrology-grade 3D analysis software when measuring the deviations of CAD-CAM fabricated crowns from the virtual design file.

Materials and Methods: A right first molar on a mandibular dentate model was prepared and scanned by using an intraoral scanner, i500 (Medit). A complete coverage crown was designed in standard tessellation language format and 20 resin crowns were fabricated by using computer aided design-computer aided manufacturing (CAD-CAM). The crowns were then digitized by using the same intraoral scanner (test-scans). Root mean square (RMS) method was used to evaluate the deviations between the test-scans and the design file of the crowns on 3 surfaces (overall, external, and internal) by using a metrology-grade, Geomagic Control X (3D Systems) and a nonmetrology-grade, Medit Link (Medit) software. The data were analyzed with Welch two-sample t-tests to compare two software for the non-inferiority of the nonmetrology-grade software with a 50 µm threshold and the potential superiority of the metrology-grade software ($\alpha = 0.05$).

Results: The Welch two-sample t-tests for the non-inferiority analysis showed that the differences between the nonmetrology-grade and the metrology-grade software were below the threshold of 50 µm for each surface tested (p <.001). The differences between the two-tested software were nonsignificant for each surface analyzed when superiority was considered (p ≥.194).

Conclusion: The nonmetrology-grade software performed similar to the metrology-grade software when analyzing the deviations of CAD-CAM crowns. Therefore, the nonmetrology-grade 3D analysis software may be considered for the deviation measurements of similar restorations.

Clinical Significance

The trueness of crowns after fabrication may affect their fit, and 3D analysis of trueness prior to the delivery appointment with the tested nonmetrology-grade software after fabrication may facilitate potential clinical adjustments and delivery of the crowns.

1. INTRODUCTION

Given the rapid development of digital technologies, computer aided design-computer aided manufacturing (CAD-CAM) systems' popularity increased significantly [1]. However, inaccurate fit of the restorations may still be encountered as many factors are involved in the fabrication of CAD-CAM restorations from impressions to CAM [2, 3].

Parallel with the developments of scanners, accuracy evaluation by using 3-dimensional (3D) technologies has also become viable [1, 4]. Metrology-grade industrial software have been commonly used in dental studies to analyze the 3D state of digital impressions, scan bodies, and restorations [5-8]. These software enable accuracy analyses for quality controls after fabrication. Dental restorations have free-form surfaces that require the superimposition of a test scan over the reference scan [9]. In this method, the CAD file of the test model is superimposed over the reference model through different methods [10]; best-fit alignment, which allows a fast and accurate analysis, is a commonly used superimposition method [11]. This method is based on iterative closest point algorithm that omits any operator-based decisions and calculates the mean distance between the corresponding points on the test scan and the reference scan by using the root mean square (RMS) [12]. The analyses by using the metrology-grade software require expertise, and the software and the service provided for analysis can be costly. Recently, a new nonmetrology-grade 3D analysis software (Medit Link, Medit, Seoul, Republic of Korea), which is also available to clinicians has been launched. The restorations can be scanned in the laboratory or chairside before the delivery appointment and their trueness after fabrication when compared with the design file can be analyzed with this software. The clinician may use the virtual output to understand the location and magnitude of potential deviations with the fabricated restorations as well as to check the quality of the manufacturing process.

The software used may affect the 3D analysis [13] as alignment algorithms and deviation measurements vary [12]. However, the number of studies, which compared 3D analysis software, are limited [12, 14]. The authors are unaware of a study neither focusing on the reliability of the new nonmetrology-grade software nor comparing it with a ISO-12836 recommended [15] and commonly used metrology-grade inspection software (Geomagic Control X v.2018.1.1; 3D Systems, Morrisville, NC, USA). Therefore, the aim of this study was to compare a nonmetrology-grade and a metrology-grade software program for their ability to measure overall, external, and internal deviations of crowns. The null hypothesis was that a recent nonmetrology-grade 3D analysis software’s ability to detect deviations would not be different from that of a commonly used metrology-grade software.

2. MATERIALS AND METHODS

2.1. Study Design

The present study followed the methodology of a previous publication [16]. A 1-mm-wide chamfer finish line preparation was performed on a mandibular right first molar typodont tooth placed in a dentate model (ANA-4, Frasaco GmbH, Tettnang, Germany) for a complete coverage crown. Digital impressions of maxillary and mandibular typodont models and occlusion were made by using an intraoral scanner (Medit i500 v. 1.2.1, Medit, Seoul, Republic of Korea). Standard tessellation language (STL) files were generated from these scans and imported to a software program (Exocad Dental CAD2.2, Exocad GmbH, Darmstadt, Germany) to design a complete-coverage crown with 30 µm cement space gap. The design was reverse engineered to an STL file to fabricate the crowns [16]. The STL was also saved to be used as a reference scan file (RS-STL).

A total of 20 resin crowns (Upcera, Shenzhen Upcera Dental Technology Co. Ltd., Shenzen, Guandong, and Nextdent Crown and Bridge Micro Filled Hybrid-MFH, C&B; 3D systems, Soesterberg, Netherlands) were CAD-CAM fabricated by using substractive (Wieland Zenotec mini, V6.12.04, Wieland Dental + Technik GmbH & Co.KG, Pforzheim, Germany (n=10)) and additive technologies (MoonRay S100, SprintRay Inc, California, USA (n=10)) The crowns were examined under optical magnification loupe (3.5×) to ensure that they were free from any defects, and no adjustments were made on the inner surfaces of the crowns [16]. All crown fabrication processes were performed by one operator (G. Ç). The crowns were then kept in dry and lightproof boxes to scan within 48 hours. A thin layer (2 µm) of antireflective powder (Vita powder scan spray, Vita Zahnfabrik, Bad Säckingen, Germany) was sprayed to the inner and external surfaces of the crowns from a distance of 1 cm and an intraoral scanner (Medit i500 v. 1.2.1, Medit, Seoul, Republic of Korea) was used for scanning. The same operator (G. Ç) sprayed and scanned the crowns after calibration of the scanner in a humidity and temperature-controlled room under ambient light. The scan files were converted to STL files (test-scan STL).

2.2. Deviation analyses

For the deviation analysis, 2 different software programs (Medit Link v 2.4.4; Medit, Seoul, Republic of Korea and Geomagic Control X v.2018.1.1; 3D Systems, Morrisville, NC, USA) were used by one experienced operator (V.R.). By using these software, test-scan STLs were superimposed over RS-STLs and root mean square (RMS) estimate resulting from the color-difference map was used to indicate how far the deviations were from zero between these datasets [16]. Color-difference maps allow the evaluation of the distances between specific points, globally and in x, y, and z planes. A high-degree of 3D matching of the superimposed data, which means high trueness, is obtained when a low RMS is present [17]. RMS values were calculated for 3 different surfaces of the crowns: overall, external, and internal (Figure 1). Overall surface included all internal and external surfaces and the marginal area, internal surface included marginal area, internal axial and internal occlusal surfaces excluding external surfaces, and external surfaces only included external surfaces without marginal area. To virtually isolate external and internal surfaces of RS-STL and test-scan STLs and to obtain a standardized data to be further used in tested software, RS-STL and test-scan STLs were imported to another software (Meshmixer v3.5.474, Autodesk Inc, San Rafael, CA, USA). With this software, the internal and external surfaces were virtually isolated and exported as STL files, and saved as internal surface of the test-scan STL and external surface of the test-scan STL.

For the deviation analysis by using the nonmetrology-grade software (Medit Link v 2.4.4; Medit, Seoul, Republic of Korea), RS-STL and test-scan STL files were imported for each surface (overall, external, and internal). Compare tool (Medit Compare v1.1.1.61, Medit, Seoul, Republic of Korea) of the software was used for the superimposition. First, RS-STL (overall, external, or internal surface) was moved to the reference data and test-scan STL (overall, internal, or external surface) was moved to the target data by using the alignment tool of the software. For the superimposition of the test-scan STL file over the RS-STL file, the automatic alignment tool of the software was used. For the quantitative (mean ± standard deviation (SD)) evaluation of 3D deviations between reference (RS-STL file) and the target (test-scan STL files) data, color-difference maps were generated by using deviation display mode of the software. The maximum/minimum deviation values were set at +50/-50 µm with a tolerance range of +10/-10 µm (green), respectively [18]. The software automatically calculated the RMS, considering all points from the analyzed corresponding surface files.

For deviation analysis by using the metrology-grade software (Geomagic Control X v.2018.1.1; 3D Systems, Morrisville, NC, USA), RS-STL and test-scan STL files were imported for each surface (overall, internal, and external), respectively. First, RS-STL (overall, external, or internal surface) was moved to the reference data, then an initial alignment was done by using the "initial alignment tool" of the software. For further alignment and to minimize errors, "best fit alignment" function of the software was used. For the quantitative (mean ± standard deviation (SD)) evaluation of the 3D deviations between reference (RS-STL file) and the target (test-scan STL files) data, color-difference maps were generated by using "3D compare tool" of the software. The maximum/minimum deviation values were also set at +50/-50 µm µm with a tolerance range of +10/-10 µm (green) [18]. This software also automatically calculated the RMS from the color-difference maps, without the need for an additional formula.

2.3. Statistical analysis

Minimum, maximum, average deviations, RMS, and standard deviation (µm) values at selected surfaces on each crown were recorded by using both analysis software. Data were analyzed by Welch two-sample t-tests on a statistical analysis software (IBM SPSS Statics

25.0, SPSS Inc, Chicago, IL) to evaluate the non-inferiority of the nonmetrology-grade compared with the metrology-grade software considering 50 µm as the minimal clinically meaningful difference. Potential superiority of the metrology-grade software to the nonmetrology-grade software was also evaluated with Welch two-sample t-tests ($\alpha = 0.05$) [19].

3. RESULTS

Table 1 summarizes the results of statistical analysis. Based on the non-inferiority test with a threshold of 50 µm, nonmetrology-grade software was not inferior to the metrology-grade software for overall, internal, and external RMS (P <.001). Figures 2-4 illustrate the distribution and comparison of RMS values from each surface for the tested 3D analysis software. In these figures, higher density indicates a higher concentration of observations at a certain RMS value.

For overall RMS, the distribution of the 3D analysis software was similar. For external and internal RMSs, the density plots of the tested software showed some differences, but the overall shape of the density was similar, and the peak values overlapped. The difference between the distributions of the tested software were less than 50 µm for each surface evaluated. Additionally, no statistically significant differences were observed between the tested 3D analysis software for overall, external, and internal surfaces according to the superiority test (P ≥.194).

4. DISCUSSION

No significant differences were found between the two-different software program (Medit Link and Geomagic X) in detecting deviations between the crowns and their respective CAD files. However, equating the finding of “no difference” and equality is a common misinterpretation in scientific literature [20]. Therefore, a non-inferiority test was applied additionally, which revealed the equality between the deviations detected by the two software. Therefore, the null hypothesis was accepted.

The number of studies using different software to analyze surface data, and their ability to analyze deviations between corresponding data sets is limited. Son et al. [12] evaluated four different software while analyzing deviations between the test and the reference data sets for full-arches, half-arches, and a single crown tooth preparation. The deviations found with different software were significantly different for the half-arch and the preparation scans. Since the effect sizes were larger for the tooth preparation scan than for the half-arch scan, the authors [12] concluded that the ability of different software is most apparent when small areas were analyzed. The single crown analyzed in the present study is comparable to the situation of the single crown preparation in the study by Son et al [12]. However, even when comparing individual surfaces on the single crown in our study, which makes the data set even smaller relative to the single crown preparation, no differences were detected between the software. This contradiction between the present study and Son et al's [12] study may be attributed to the fact that the nonmetrology-grade software was not included in Son et al's [12] study. Peroz et al. [14] evaluated the trueness and precision of two software (Geomagic Control X and GOM inspect) based on the inter-molar width, applying different superimposition algorithms. The authors [14] showed that rather than the software used, the alignment algorithm had an effect on the trueness. When they used the automated best-fit algorithm of the two software, the difference was the smallest and was around 10 µm. The repeatability of this result was also the highest with the automated best-fit algorithms. In the present study, such automated best-fit algorithms were used, and even smaller differences were found between the two software, which support the hypothesis of the comparability of the software analyzed in the present study. The advantage of the analyzed nonmetrology-grade software is that it is a freeware program that can be downloaded without any additional costs, whereas the metrology-grade software is not free. In addition, the metrology-grade software is sold with a training course, because it is relatively complex and difficult to use. The nonmetrology-grade software, in the authors opinion, was easy to use and intuitive. In addition, the nonmetrology-grade software allows the analysis of any STL output acquired either with an intraoral or a laboratory scanner. Therefore, the software functions and performs the analysis regardless of the scanner type or brand. Considering the similarity of the deviation analyses in the present study, which are well below the threshold described as clinically detectable [21, 22], the nonmetrology-grade software may be considered as a feasible analysis tool for clinical or dental laboratory quality controls of single crowns. Nevertheless, future studies should be performed to investigate this software's ability when deviations in different objects are analyzed.

Many studies have analyzed the trueness of single crowns using different CAD-CAM methods during fabrication [1, 16, 18, 23]. The trueness shown by these studies was in a similar but mostly lower range compared with the present study. The difference may be attributed to the fact that an intraoral scanner was used in the present study to digitize the crown, whereas other studies used either a laboratory scanner or an industrial-grade scanner [1, 16, 18, 23]. The authors have deliberately scanned the crowns with an intraoral scanner in the present study because higher deviations can be expected due to the lower accuracy of these scanners compared to laboratory scanners [24]. Since the aim of the present study was not to test the clinical quality of the manufactured crowns, but the ability of the software to detect such deviations, potentially higher deviations were advantageous for this purpose.

3D analysis software tested in the present study were compared by the calculation of RMS values, which is a commonly utilized method [10]. However, recent studies have shown that calculations such as absolute average value and (90-10)/2 percentile result in significant differences when compared with RMS values while evaluating the trueness [25, 26]. Given the fact that the present study was the first to compare the nonmetrology-grade software with the metrology-grade software, the results of the present study should be substantiated with future studies by using different calculation methods. In addition, Yatmaz et al. [26] reported that the selection of reference and test files affect the trueness evaluation, which might be an interesting subject to investigate in future studies involving the nonmetrology-grade software.

Previous studies using RMS while evaluating the deviations in scans reported 100 µm as the threshold for the inadequate fit of the definitive restoration [1, 11, 27]. However, other studies on the internal fit of the restorations reported values ranging from 50 to 200 µm as the threshold for clinically acceptable misfit, yet the exact value is debatable [28]. Nevertheless, all deviations found in the present study were well below the threshold described as clinically relevant.

Evaluating a restoration after fabrication by using the 3D analysis software tested should be considered as a quality check that shows how much the manufactured crown deviated from the CAD file. However, even if the manufactured restoration presents a perfect congruence with the CAD file, the fit of the restoration may still not be optimal due to the errors and inconsistencies at the impression or design stages; the findings of this study in terms of trueness evaluation should be interpreted taking into account these factors.

The main limitation of the present study was that the nonmetrology-grade software was compared with only one software available on the market. However, the reference metrology-grade software (Geomagic X) is probably the most frequently used software for trueness analyses in research studies, and is even mentioned in the ISO standards [15]. A spray was used to facilitate the scans made, which may lead to inconsistent thicknesses of the powder on the surface and therefore affect the results. However, the spraying procedure was standardized to minimize the variabilities that may also occur due to scanning errors depending on the reflections from the material surface. Another limitation of the present study was that the deviation analyses did not involve the margins of the restorations, which are critical considering the fit and the success of restorations. In addition, only crowns were analyzed and different results may be obtained with different type of restorations, which should be further investigated. The crowns were made of resin materials and the scans of the restorations may be affected when different types of materials are used. Nevertheless, the same scan, accordingly, the same STL file was used by each of the analysis software to compare it with the virtual design file. Therefore, even though material's effect on the scan would potentially affect the scan and the deviation values detected by each of the software, the deviations would be expected to vary consistently across software groups, and the surface properties of the material would not be expected to directly affect the comparison of the ability of different software to measure deviations. Nevertheless, future studies may be performed to investigate the effect of different materials on detected deviations by different software. Since the present study was the first one that evaluated the new nonmetrology-grade software for its ability to detect deviations, the sample size was determined on similar studies, using 10 or 20 specimens per study group [12, 14]. For future studies, it would be interesting to analyze the nonmetrology-grade software's performance in varying clinical scenarios with different materials, and to compare the software to different available software.

5. CONCLUSIONS

Given the limitations of the present study, it can be concluded that the tested nonmetrology-grade software performed similar to the metrology-grade software in detecting the deviations of CAD-CAM fabricated resin crowns from the virtual design file.

Declaration of interest

The authors declare no conflict of interest. The authors do not have any financial interest in the companies whose materials are included in this article.

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Credit author statement

Burak Yilmaz: Design, Data interpretation, Critical revision of the article, Approval of the submitted and final versions

Vinicius Rizzo Marques: Design, Data collection, Data interpretation

Mustafa Borga Donmez: Drafting article, Critical revision of the article

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Wei-En Lu: Data analysis, Data interpretation, Statistical analysis

Samir Abou-Ayash: Drafting article, Critical revision of the article

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TABLES

Table 1. Mean RMS values of each surface according to 3D analysis software

	Geomagic X	Medit Link	*P* value*	*P* value**
Overall (µm)	94.7	94.4	< .001	.935
External (µm)	87.3	85.3	< .001	.525
Internal (µm)	82.4	76.7	< .001	.194

*Non-inferiority test, **Superiority test

FIGURES

Figure 1. Color maps generated by the superimposition of test-scan STL file over the RS-STL (A: Medit Link, B: Geomagic X; 1: Overall RMS, 2: External RMS, 3: Internal RMS)

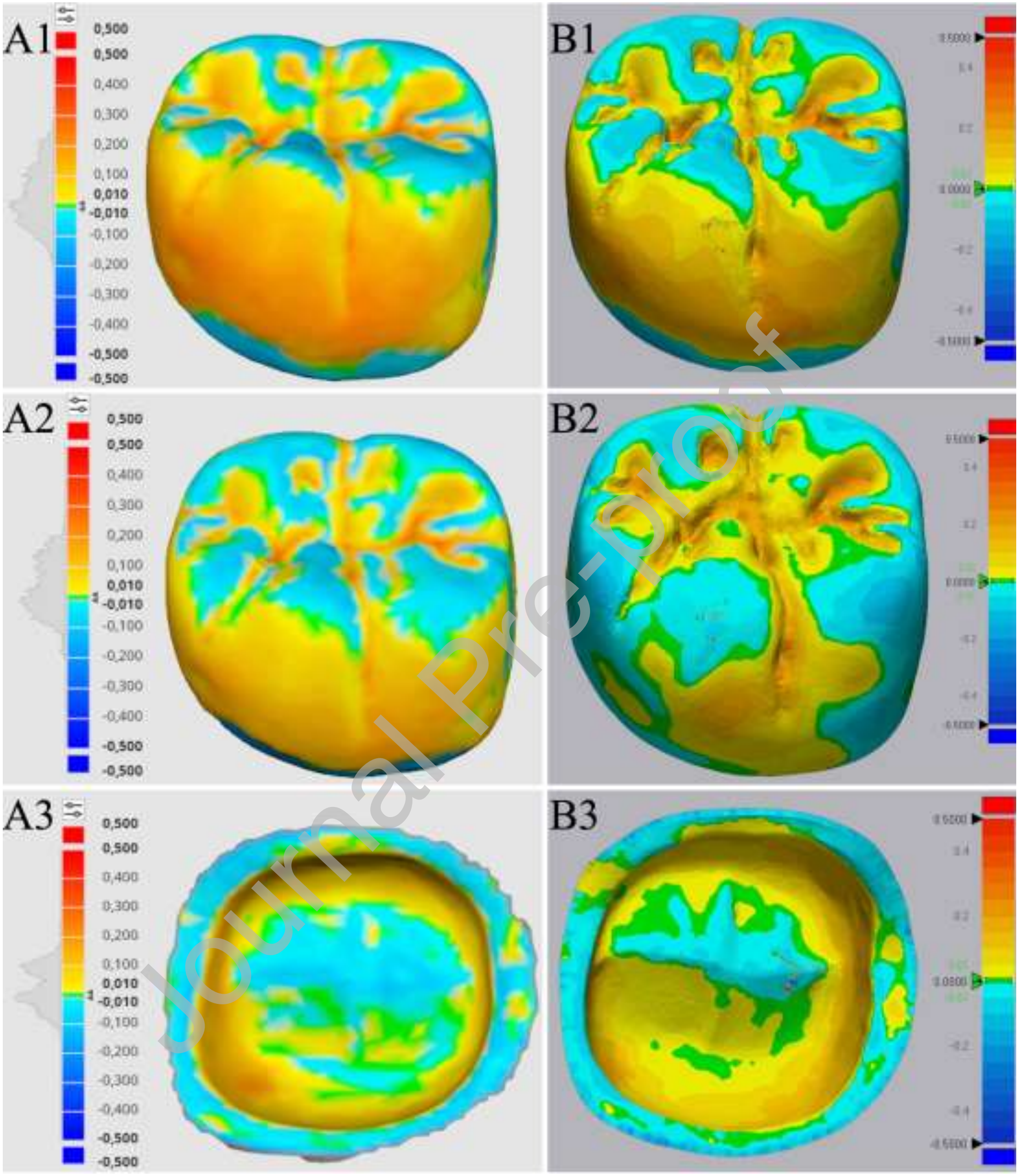

Figure 2. Density plot of the overall RMS (GMC: Geomagic Control X, MDT: Medit Link)

Density indicates the concentration of observations at a certain RMS value

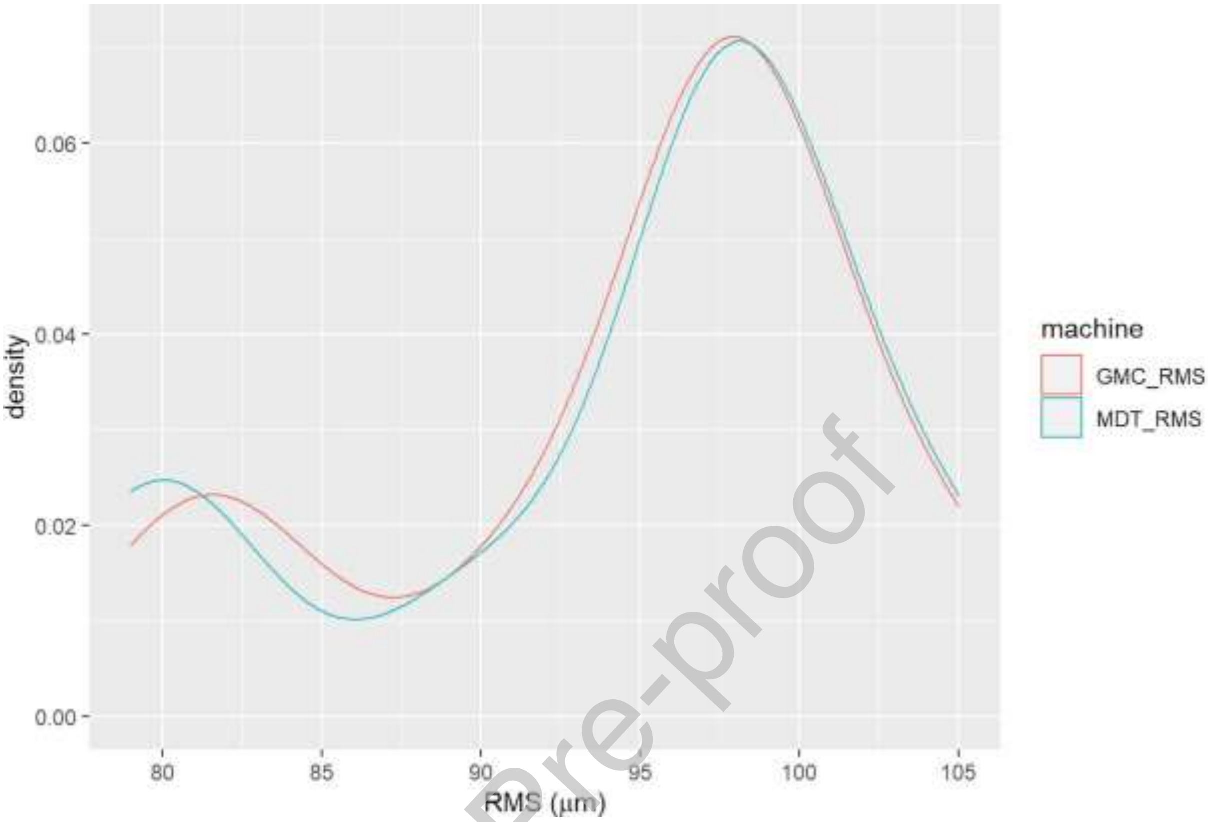

Figure 3. Density plot of the external RMS (GMC: Geomagic Control X, MDT: Medit Link)

Density indicates the concentration of observations at a certain RMS value

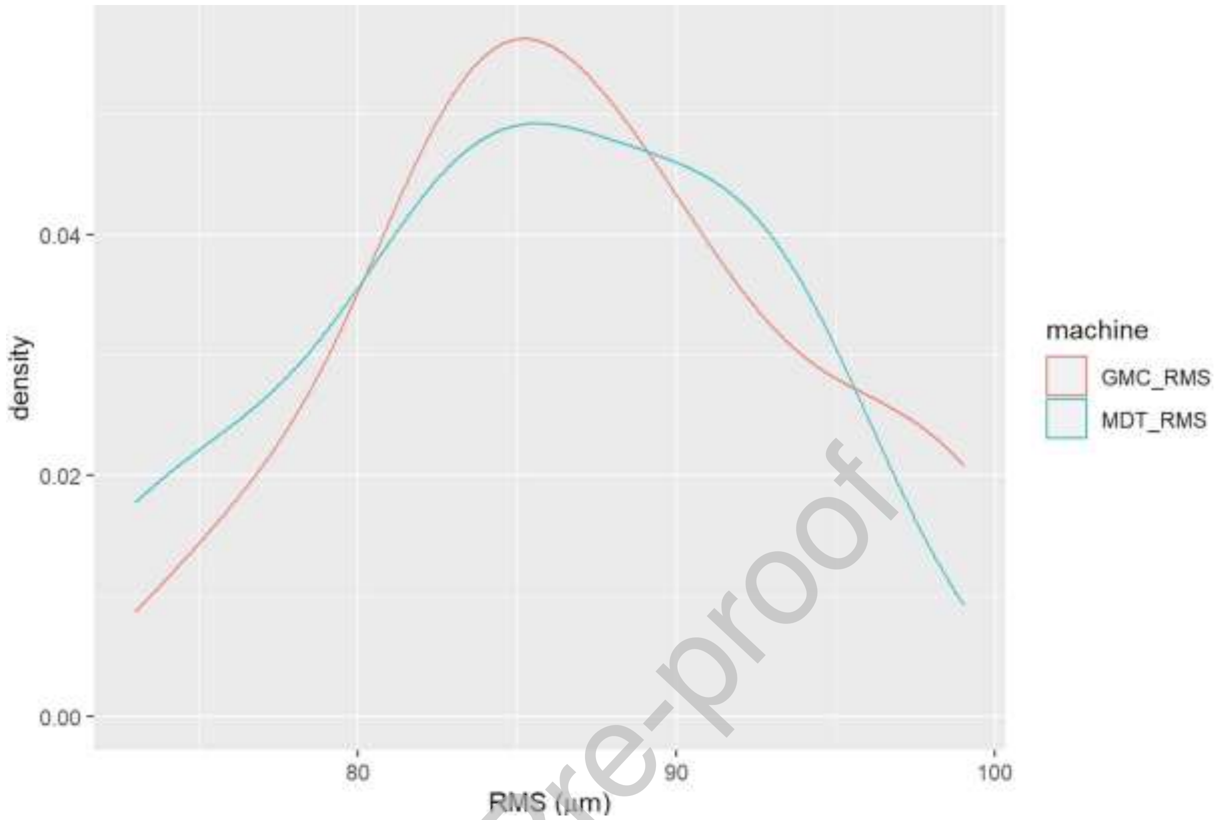

Figure 4. Density plot of the internal RMS (GMC: Geomagic Control X, MDT: Medit Link)

Density indicates the concentration of observations at a certain RMS value