Effect of Virtual Casts Superimposition Strategies on the Estimation of IOS Accuracy in Complete-Arch Scans

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ABSTRACT

Objectives: This study aims to assess the impact of three different strategies of best-fit (BF) alignments of virtual casts on the estimation of the accuracy of intraoral scanner (IOS) in complete-arch scans. Methods: A maxillary typodont, modified with an Implant Scan Body (ISB) in the retroincisive area, was digitized using a desktop scanner (SW Optor Lab) to obtain a reference STL file. The typodont was then scanned 10 times using two IOSs (Trios4, Itero). Each STL file obtained from the IOS was superimposed onto the reference cast using three methods in CloudCompare: full-arch BF (BF-full), BF at the starting tooth (BF-tooth), and BF at the ISB (BF-ISB). Discrepancies from the reference were recorded, and trueness and precision were compared for each method. Statistical analysis with the Kruskall-Wallis nonparametric test was performed (α = 0.05). Results: The Kruskall-Wallis test (p <0.05) revealed statistically significant differences in trueness and precision among the alignment methods. Post Hoc multiple comparison test p-values were all below the critical alpha value. Conclusions: Differences in BF methods lead to significantly different accuracy values of IOS complete-arch scans as different virtual casts' alignment discrepancy. BF-full had the highest accuracy followed by BF-ISB and BF-tooth.

INTRODUCTION

In the modern digital dentistry, the intraoral scanners (IOSs) are part of the everyday clinical practice and procedures.[1,2] They superimpose meshes generated at different times and in different ways in order to acquire a complete dental arch from subsequent photograms.[3,4] The accuracy of virtual casts obtained from IOS scans is affected by operator and patient factors that influence the meshes generation and the accuracy of the superimposition process performed by the artificial intelligence algorithms used by the IOS software.[5–7]

Comparative three-dimensional analysis yields variable results, as regards the accuracy, for the evaluated IOS.[8,9] In dentistry, the most common method for measuring overall deviations across complete-arch scans is the BF; thereby, two different files, the reference and the test, are superimposed to each other using an iterative closest point (ICP) algorithm in a metrology software.[8,10–12] 3D superimposition analysis has some limits: first, the BF algorithm threshold is subjectively configured with variable rigorousness level, possibly determining the underestimation of some inaccuracies.[13] Second, most 3D comparative analyses use data of the tooth and its surrounding soft tissue for BF algorithm. Because those data include adjacent anatomy, which is not the target of investigation, there is an increase in data gathering the full-arch BF alignment method.[14] Third, the BF alignment method forces the two objects to align as much as possible resulting in a lower average deviation. Thus, discrepancies are reduced to better align the two objects.[15] Consequently, some authors preferred to compare the digital scans by using a local BF at the tooth, where the scan started (scan origin).[16] This concept proposal may be useful to understand where deviations arise along the dental arch, using different scanning strategies or scanning paths that start at the same tooth. However, superimposition at the scan origin is strictly dependent on the accuracy of the first scanned tooth; it affects the accuracy of all the other teeth.[17] Moreover, the distortion of the intraoral scan grows as distance increases from the origin, generating an artifact of a constant linear increase in deviation from the scan starting point. However, during an intraoral scan the increase in deviation was neither linear nor constant.[16] In this sight, other authors proposed a different method which initially define two points on each dental occlusal surface on the reference file.[17] Those points are then reported on the test file using a local BF at each tooth. After that, a BF alignment of test and reference files is performed at the tooth where the scan started and the deviations between those identical points at each tooth are calculated. The increase in deviation cannot be necessary linear or constant, but it is more realistic. However, the superimposition issue at the scan origin remains, with no clear evidence about the correctness of the scan at the origin point. A possible error in the scan of the first zone is transmitted at all the subsequent scan regions resulting in the alteration of the arch discrepancies. In this view, a possible method to overcome these limits may be the superimposition of the two files by using an extraoral reference with a previously known geometry, after attaining the BF only at that reference. An Implant Scan Body (ISB) could be useful after its positioning outside -but not too distant from- the dental arch, not to modify the scanning path. The aim of this paper is to compare three different strategies of virtual cast superimposition in alignment discrepancies, by means of 3D analysis of IOS complete dental arch scans.

The null hypothesis was that no statistical differences would be found between the different superimposition methods.

METHODS

REFERENCE TYPODONT AND SCANNING PROCEDURE

An anatomical typodont (ANA-4 Frasaco; Tettnang, Germany) of a complete maxillary dental arch was used. The typodont was modified by inserting an ISB (Scan body SQ, New Ancorvis, Bargellino, Italy) in retroincisive region, at 11 mm from the interincisal papilla *(Figure 1)*. An ISB without any geometry bevel features was chosen to avoid interferences related to the position of that feature on the scan accuracy.[18] The ISB was placed in the area by performing a measured hole and assuring it to the model using a resinous dual-curing auto mixing cement (SoloCem, Coltene, Altstätten, Switzerland). The typodont was left for three days from the ISB fixation, to as-

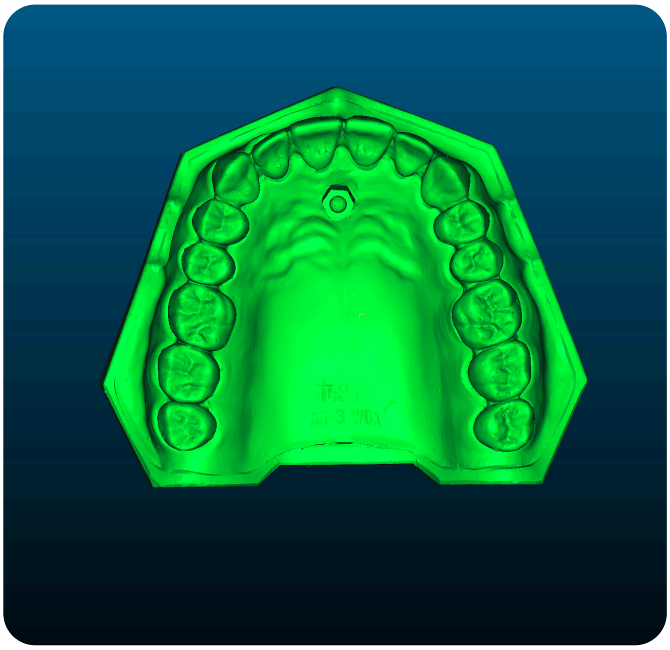

Figure 1: STL file of the modified cast used for this study.

sure complete cement polymerization. Then, it was scanned using a desktop scanner with a 5 µm accuracy (SW Optor Lab Performance Laboratory Scanner, Open Tech 3D Srl, Rezzato, Brescia, Italy), to obtain a Standard Triangulation Language (STL) file that was used as the reference. This scanner was previously calibrated according to the manufacturer's instructions. Then, the modified typodont was scanned by a single right-handed operator using two different IOSs (Trios 4 Wireless, software version 20.2, 3Shape A/S, Copenhagen, Denmark; Itero Element 5D, software version 2.7.0.990, Align Technology, San Jose, USA) to avoid bias related to the use of only one device. To simulate an *in vivo* intraoral scan, this modified maxillary typodont and the mandibular arch (ANA-4 Frasaco; Tettnang, Germany) were mounted on a mannequin head (Frasaco 7001 ABS; Tettnang, Germany) with a standard interincisal opening of 40 mm. The head was fixed on the head support of a dental chair and the IOS was positioned on the left side of the chair with the operator on the right. According to previous similar *in-vitro* studies[19–22] and to a power analysis to detect a mean difference of 15 µm with a target power of 80% and a significance level of 5%, a total of 8 scans were considered enough. So, we took a sample of 10 scans (n=10) totally, five for each IOS. All the scans were performed by a 4 years experienced operator (F.G.) with the same environmental conditions: 23 °C with 45% of humidity and a room artificial lighting conditions of 500-lx measured with a light meter (Digital light meter LX1010BS; Dr. Meter) and a white spectrum color temperature (4100 K).[19,23] To reduce the accuracy difference according to the proficiency of the IOS and the operator habits, the first 5 scans were deleted for each IOS, and the following 5 scans were used for evaluation. Trios 4 was previously calibrated for 3D and colors according to the manufacturer's instruction while Itero has an autocalibration system. The scanning strategy recommended by each manufacturer was followed for each IOS. The scans were exported as STL files and used for further processing.

PROCESSING OF STL FILES BEFORE SUPERIMPOSITIONS PROCEDURE

Firstly, for both reference and test scans, the ISB mesh was matched with the corresponding ISB library file using Exocad (Exocad Gmbh, Dramstadt, Germany) to check their accuracy before further processing. In all STL files, the 3D discrepancies between the ISB mesh and ISB library was within 5 µm, which represents the manufacturing tolerance.[24] In this way, we were sure that the further alignment processes of local BF at the ISB were all performed in the same manner by the software.

Since not all the virtual casts had the same three-dimensional position and orientation in the virtual space, an initial matching of the casts was performed with the "Align" and "Point base gluing" functions on an open-source mesh processing software (MeshLab2022.02; MeshLab). This operation was necessary for the ICP algorithm to better process the different sets of points selected for the alignments. To avoid data gathering for 3D surface deviation measurements, unnecessary areas located under the gingival margin were trimmed away from each scan, included the reference typodont according to Güth *et al*.[14] Then, from each mesh file, three different objects were obtained by cutting the mesh:

- the full dental arch without gingiva;
- the tooth where the scan started (#18);
- the implant scan body (ISB).

SUPERIMPOSITIONS PROCEDURE

Once obtained the objects of each mesh as separate STL files, another open-source program (CloudCompare v2.12) (CC) was used for the superimposition. Three different strategies of BF alignment were identified and compared according to the literature:

1. Full-arch best fit (BF-full)
2. Local best-fit on the tooth were the scan started (BF-tooth)
3. Local best-fit on the implant Scan Body (BF-ISB)

For the BF-full, the two virtual casts of the reference and mesh file were aligned using the "best-fit" function and then computing the mesh distances obtained.

For the BF-tooth and BF-ISB, the virtual cast was initially aligned with the transformation matrix obtained from the BF of the reference tooth or ISB with the mesh file. Thus, the linear distances between the meshes of the reference and the test files were computed to evaluate trueness and precision of each virtual cast compared to the reference.

A Gaussian curve highlighting the linear 3D discrepancies was obtained for each superimposition method and a related colorimetric scale was displayed on the mesh surface. A csv file containing all the linear deviations between reference and test files relative to each superimposition technique was also exported and used for statistics.

Statistical Analysis

The trueness for each virtual cast was defined as the median value of all the linear discrepancies between each virtual cast and the reference while the precision was represented by the interquartile range (IQR) of single distances. All the csv data were imported in MATLAB R2022a to perform statistical analysis. Similarly to previous studies,[19,25] extreme outlier values, occurred due to data points misalignments at the boundary of the scanned and reference mesh, were not considered for the statistical analysis. This was addressed by identifying and removing the values that lied more than 3.0 times the interquartile range below the first quartile or above the third quartile. The alpha value was assumed to be 0.05 for the one sample Kolmogorov-Smirnov test performed for all the data distribution. Then, due to not normally distributed data, a nonparametric test (Kruskall-Wallis) with a Post Hoc Bonferroni correction was performed between the 10 distributions of linear deviations for each of the three superimposition methods.

RESULTS

The main results were summarized in figures 2, 3 and 4 where all the deviance distributions with 60 bars histograms and their normalized area, are plotted. Each of them is fitted with a gaussian curve that highlights the non-parametric data distribution. On the right top corner of each chart, the median (MEDIAN) and interquartile range (IQR) values are displayed. The histograms on the bottom of the figures represent the average error distribution of the single aligning method and gives data about the presence of a systematic bias in data and of their dispersion.

All the linear discrepancies were considered as absolute values so all the positive and negative deviations from the reference virtual cast were treated as the same type of error. On the Boxplot in figure 5, the following descriptors are reported for each superimposition strategy:

- For BF-full: trueness value = 55 µm; precision value (IQR): 71 µm.
- For BF-tooth: trueness value = 100 µm; precision value: 216 µm.
- For BF-ISB: trueness value = 86 µm; precision value: 142 µm.

The Kruskall-Wallis nonparametric test revealed significant differences between the averaged distribution of discrepancies for the three different strategies of superimposition, that were statistically confirmed by the Post Hoc Bonferroni correction test ($p < 0.01$) *(Table 1)*. For accuracy values, a statistically significant difference was found between BF-full and BF-tooth ($p<0.01$), between BF-full and BF-ISB ($p=0.037$), while it was not found between BF-ISB and BF-tooth ($p>0.05$) *(Table 2)*. For precision values, a statistically significant difference was found between BF-full and BF-tooth ($p<0.01$), while it was found a less statistically relevant difference between BF-full and BF-ISB ($p=0.064$) and between BF-ISB and BF-tooth ($p>0.05$) *(Table 3)*.

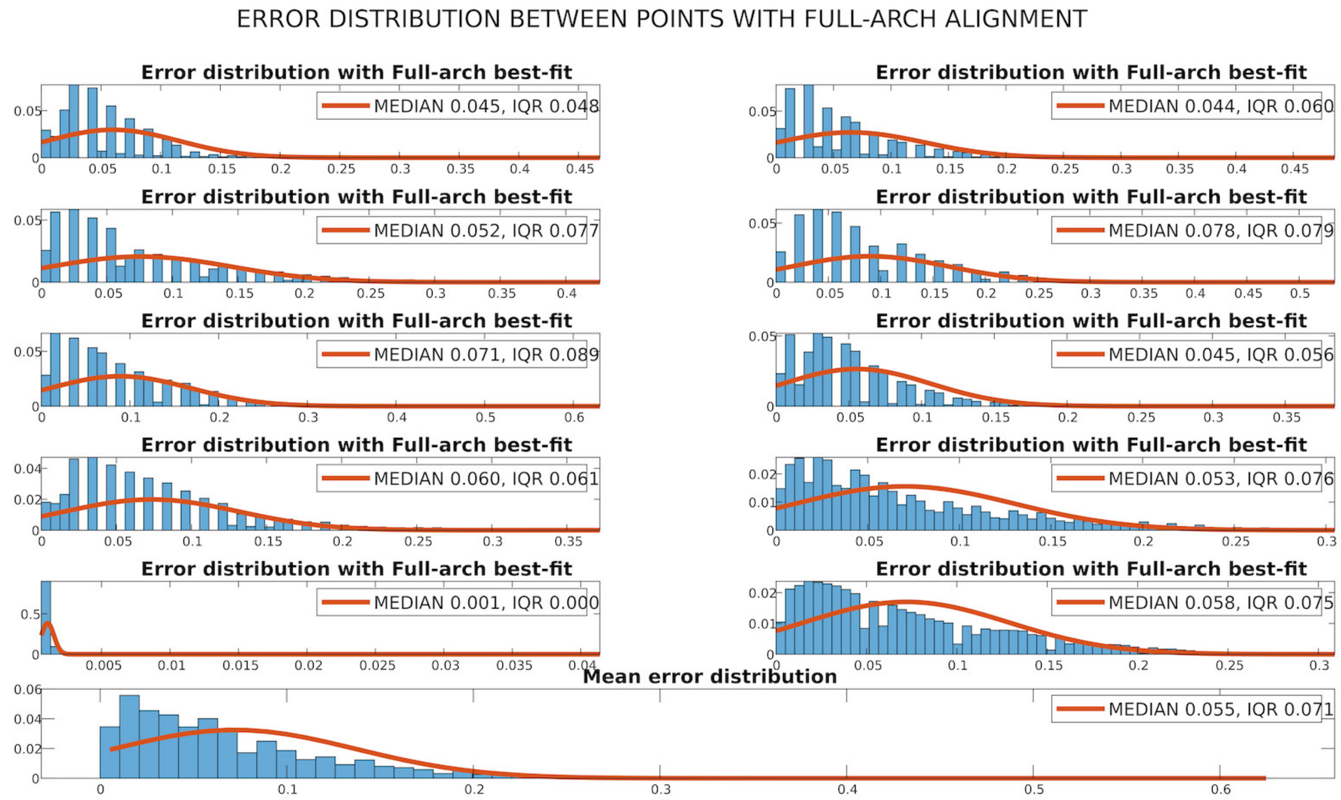

Figure 2: Error distributions between the reference virtual cast and the compared ones after BF-full.

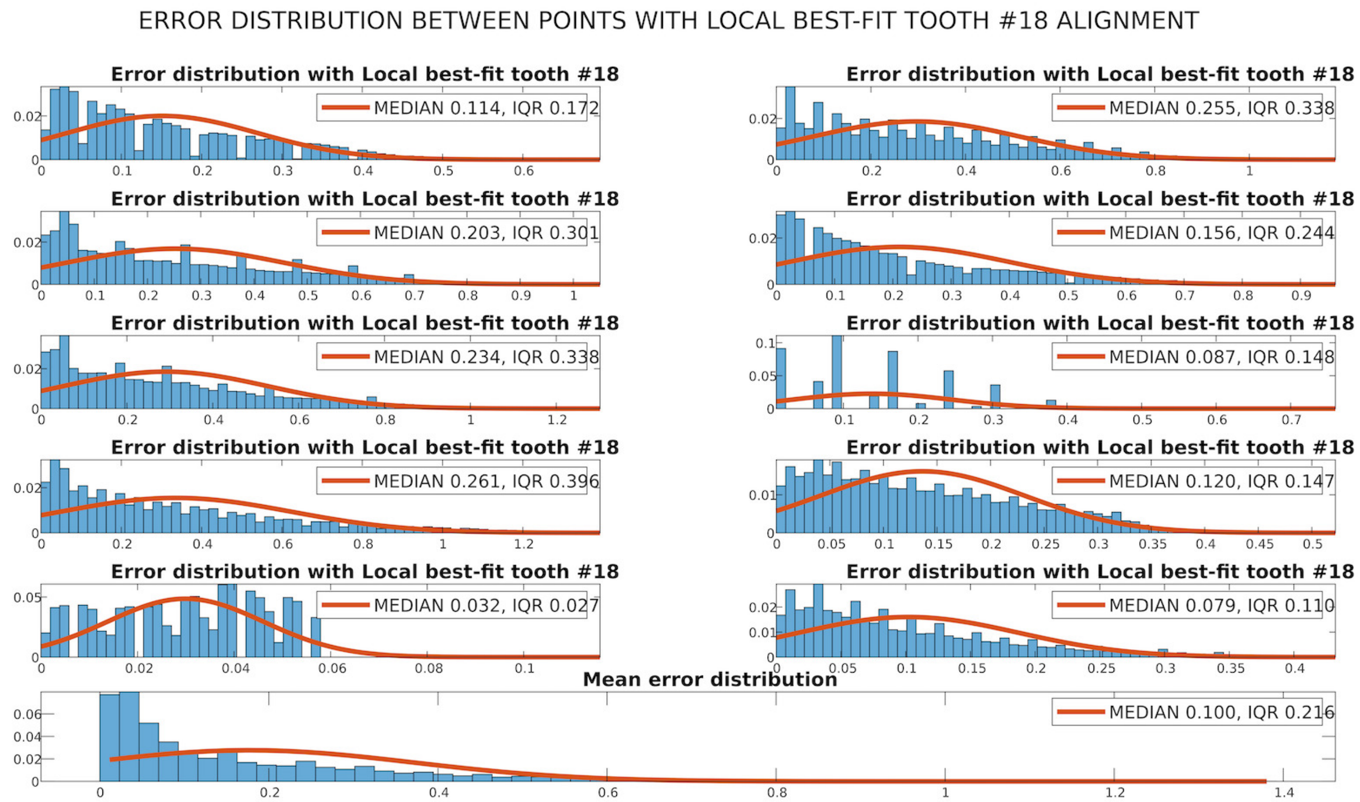

Figure 3: Error distributions between the reference virtual cast and the compared ones after BF-tooth.

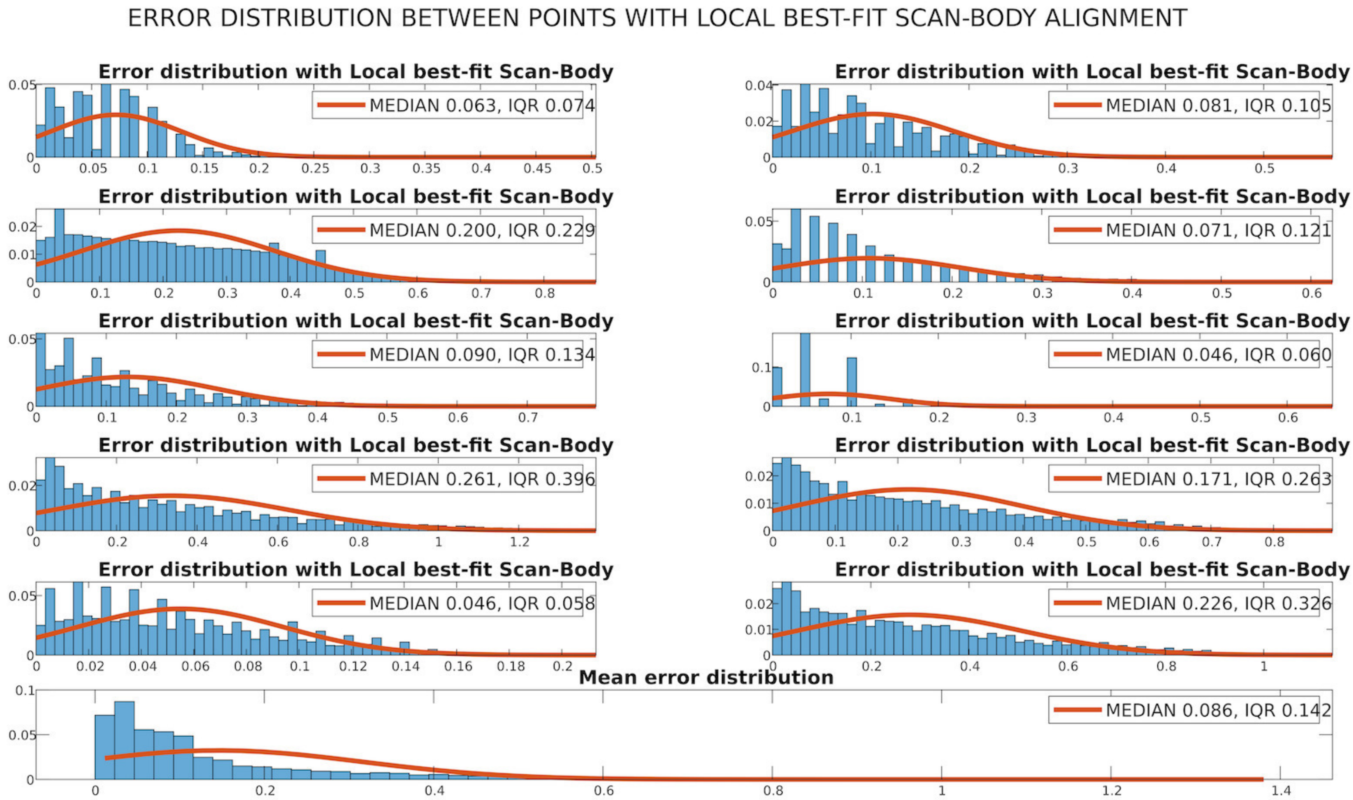

Figure 4: Error distributions between the reference virtual cast and the compared ones after BF-ISB.

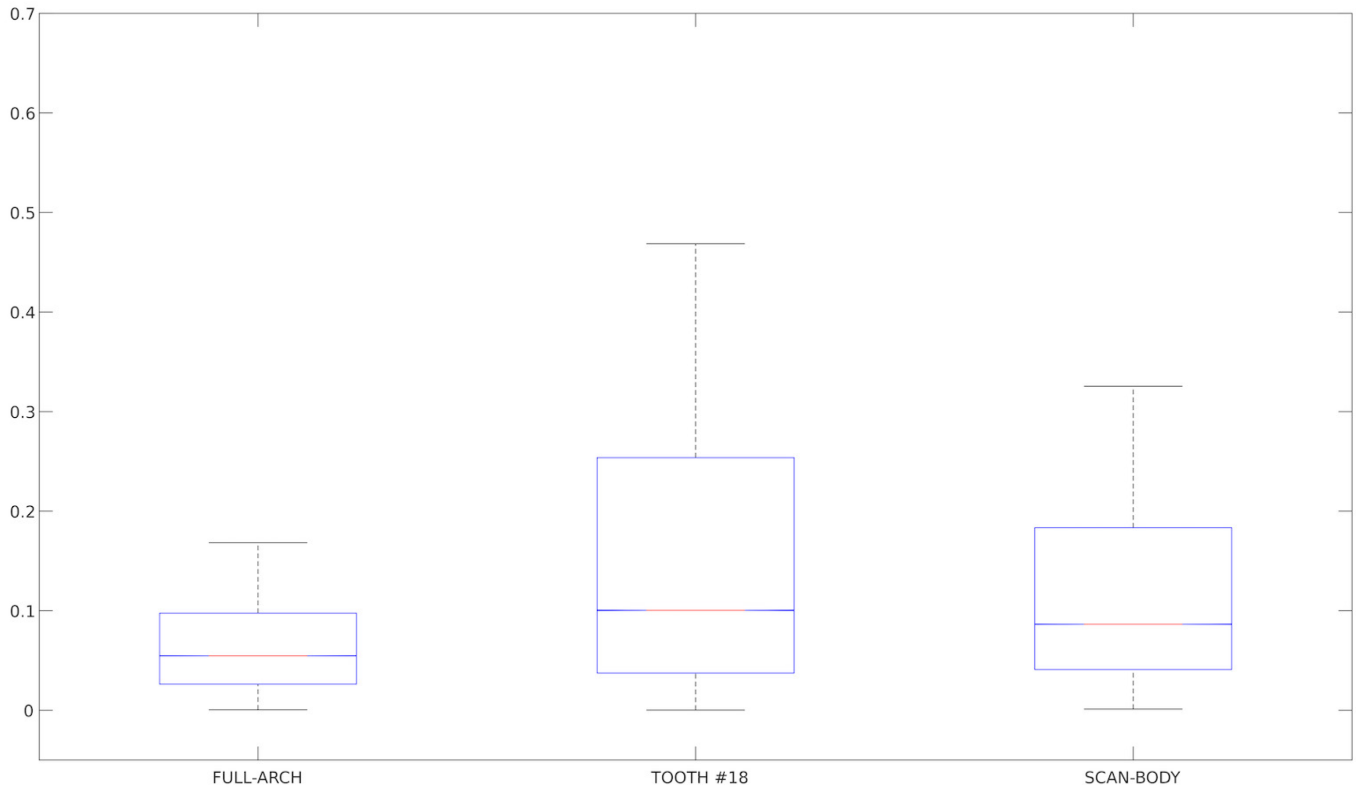

Figure 5: Boxplot of the linear deviations with three different types of alignment.

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Table 1. Resulting p-values of the multi comparison test of discrepancies distributions with Bonferroni correction.

Group A	Group B	p-values
BF-full	BF-tooth	1.3 E-40
BF-full	BF-ISB	2.3 E-120
BF-tooth	BF-ISB	3.2 E-23

Table 2. Resulting p-values of the multi comparison test between the accuracy values, with Bonferroni correction

Group A	Group B	p-values
BF-full	BF-tooth	0.003
BF-full	BF-ISB	0.037
BF-tooth	BF-ISB	1.000

Table 3. Resulting p-values of the multi comparison test between the precision values with Bonferroni correction

Group A	Group B	p-values
BF-full	BF-tooth	0.003
BF-full	BF-ISB	0.064
BF-tooth	BF-ISB	0.939

In figure 6, the colorimetric scale across the dental arch showed the different results obtained by comparing one test scan with the reference one using the three superimposition methods.

DISCUSSION

In literature, the comparison between 3D data taken with IOS showed different results depending on the superimposition method. The aim of this study was to assess the effect of three different strategies of superimposition on the accuracy of ten IOS scans of a modified maxillary typodont. From the analysis of the data, the null hypothesis was rejected because statistically significant differences were found between the three different strategies of superimposition.

The BF-full arch showed the lowest alignment discrepancies followed by the BF-ISB and BF-tooth.

Clear differences were also shown for IQRs between the different BF methods. For BF-full, differences in IQR between reference and test files were within the clinical acceptability of misfit for a fixed dental prosthesis.[26,27] However, for the other alignment methods and especially for BF-tooth, discrepancy values may be higher than 200 µm that could be considered critical for marginal and internal fit.[26,27]

From a descriptive point of view, we observed that discrepancies follow different pattern model depending on the alignment type. For BF-tooth, the deviations generated between reference and test files were greater the greater the distance from the tooth. This phenomena was also observed in another study, where authors pointed out that local BF limited to one tooth may have less accuracy compared to full arch alignment because it could generate an artifact of a constant linear increase in deviation from the starting point.[16]

For the BF-full and BF-ISB, discrepancies between test and reference scans did not follow a specific pattern as for BF-tooth. However, the highest discrepancies were found in the molar and anterior regions for both methods. This could be probably due to an improper stitching of the images caused by movements or rotations of the IOS head to scan the complex angles and undercut surfaces in the molar and incisor area.[28,29] No differences in the distribution of inaccuracies along the dental arch were found between BF-full and BF-ISB.

Figure 6: Representative images showing discrepancies along the dental arch after the different alignments. Grey areas depict perfect fit, green areas indicate where the reference scan contained the test scan while yellow ones describe the opposite.

Then, the only differences found between the two methods were in the value ranges and in the data dispersion that were higher for BF-ISB.

Indeed, the lowest data dispersion can be observed by using BF-full. This is because the ICP algorithm reduces as much as possible the discrepancies between the two objects compared. This is also in accordance with other studies that preferred to use other methods of comparison in order to understand where the real discrepancies along the arch are located.[15,16]

BF-tooth and BF-ISB produced the higher data dispersion. This could be because the alignment is performed on points located in a specific single localized area and not widespread. Furthermore, statistical differences in data dispersion between the two local best-fit methods were also found. Those differences are likely due mainly to the geometrical complexity of the considered mesh, which leads to a more complex matching of the surfaces for the aligning software. The best-fit on the single tooth may increase the deviations between test and reference scans in relation not only to the distances from the scanning origin but also to the matching accuracy on the tooth. Then, if the tooth where the scan started is not properly scanned, the deviations arise.[17]

Using an ISB for the local best-fit may reduce this probability, as the ISB has a simple design and allows a better matching of the surface. With this method, it is also easier to point out the zones and directions of discrepancies between the tested scan and the reference one; in other words, focusing the matching area on a well-defined, unchanged and known region, easily captured for the IOS does not compensate the possible morphological distortion that may arise during the reconstruction process, due to the misalignment of photograms. In addition, the superimposition on an object outside the dental arch, which means outside the regions where discrepancies are calculated, is more advantageous, providing a more realistic discrepancies between the scans.[30] In addition, the low discrepancies (< 5 μm) between the ISB mesh and the corresponding library file make sure that the further alignment processes at the ISB (BF-ISB) were all performed in the same manner by the software.

For those reasons, we considered the distortions of the digital scans more realistic when the comparison is made through the BF-ISB instead of BF-full or BF-tooth. In literature, the concept that a “reference BF alignment” on unchanged and well-defined surfaces lead to more realistic results than conventional BF alignment, was also demonstrated by O’Toole *et al.*[31] They showed that this method resulted in a more accurate quantification of the true defects created in a tooth sample and could be clinically significant especially when there are changes in tooth morphology and position. A comparison between O’Toole and the present study is difficult; however, the best-fit of the entire dataset resulted in the highest alignment trueness as in our study. The same was also found in the study of Revilla-León *et al.*[32] who compared different BF algorithms (the entire data set, only some landmarks on the teeth or a single portion of the dental arch) on the virtual casts’ alignment discrepancy and found that the entire dataset or section-based BF algorithms obtained the highest virtual casts’ alignment trueness and precision compared with the landmark-based method. For BF-full arch they obtained slightly higher linear discrepancies then ours (70 vs 55 μm for median and 80 vs 71 μm for IQR) that can be related to the IOSs used and to the fact that they didn’t cut the virtual casts under the gingival margin before the alignment procedure. So, they didn’t avoid data gathering[14] that may have led to a different alignment process then ours.

This study has several limitations. Firstly, the *in-vitro* nature and then the absence of all the intraoral factors affecting the IOS complete-arch scan. Secondly, regarding methodology a limit could be constituted by the ISB type used in our study. This may have an influence on the results because of its flat surfaces that may be subjected to sliding during the superimposition process. It was shown in literature that a dome-shaped surface provides less deviations in the virtual alignment, because of the rounded edges and smooth surfaces that prevent the sliding of the aligned surfaces during the matching procedure.[33] However, we chose an ISB without any geometry bevel features, to avoid interferences related to the position of ISB bevel feature on the scan accuracy. In fact, the ISB geometry bevel feature position in relation to the orientation in the patient’s mouth has been demonstrated to affect the scan.[18] Other limitations of this study were the ISB positioning, in the retroincisive area, that was impossible in an *in-vivo* setting and the use of only one object to do the superimposition. Maybe the use of more objects, external to the dental arch, could reduce the possibility of improper alignment along one of the three spatial planes, providing at the same time a more realistic comparison between 3D digital data set.[34]

As we performed the experiment using a free open-source program, that could be used by everyone without costs, this may have resulted in different accuracy level compared to other software package. That would be a focus of future works in addition to other type of superimposition method that could be preferrable to find the best IOS accuracy estimation method.

CONCLUSIONS

The use of a superimposition method taking into consideration an object that is located outside the dental arch results in different discrepancies between test and reference virtual casts compared to a full-arch best-fit or a local best-fit on the tooth where the scan started both for trueness and precision. This means that the alignment technique has a clear impact on the IOS scanning accuracy assessment values. Differences between groups were also found in the distribution of the discrepancies along the arch. Deviations seen after BF-ISB can be considered more realistic because such method of superimposition is independent from the shape of the teeth and of the entire arch, suggesting the true deviations emerging from IOS full-arch scans. Further studies need to be conducted to understand if this or other methods of superimposition of digital data, lead to more realistic results.

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