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Original Article

Effects of Type and Amount of Orthodontic Tooth Movement on Digital Model Superimposition Accuracy

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Main Points

- Digital model superimposition (DMS) is a novel technique used to evaluate orthodontic tooth movements.
- There is not enough information in the literature regarding the most reliable algorithm to use in DMS.
- The performance of the local best-fit (LBF) algorithm was independent of the type and degree of movement of the teeth.
- Landmark-based (LB) algorithm success was negatively affected by the degree of tooth movement.
- From a clinical standpoint, however, both algorithms were very accurate, regardless of the degree of movement of the teeth and the type of movement.

ABSTRACT

Objective: To assess the impact of the type or degree of tooth movement on the success of 3D model superimposition using 2 different algorithms.

Methods: The sample consisted of pre-treatment digital maxillary models of 40 patients. Eight different groups were created by applying 8 different virtual setups (VS) to each model. Teeth crowns were moved by 1 mm or 2 mm in different directions (sagittal, transversal, vertical, combination) using the Ortho Analyzer software. Each model obtained from the VS was overlapped with the original model using the landmark-based (LB) and local best-fit (LBF) algorithms. In the post-superimposition assessment, the area of the palate vault which was not affected by teeth movements was selected. Both groups and algorithms were compared using the numeric data of root mean square (RMS) and percentage of perfectly matched areas (PMA). In addition, the displacement of the right canine (RC) was measured after superimposition. The comparison of the superposition outcomes among the groups was evaluated with one-way ANOVA and Kruskal–Wallis tests. The Student's *t*-test was used to compare the two algorithms.

Results: Both the algorithms were not affected by the type of tooth movement. However, the increase in the amount of tooth movement negatively affected the performance of the LB algorithm. LBF achieved the model superimpositions more effectively and faster than LB. No difference was found in RC measurements between the LB and LBF algorithms.

Conclusion: The results indicate that LBF offers more sensitive and successful 3D model superimposition. The performance of the LB algorithm was, however, acceptable for analysis of 3D tooth movement.

Keywords: Intraoral scanner, digital model superimposition, virtual setup

INTRODUCTION

Three-dimensional intraoral scanners are one of the most exciting inventions in general dentistry and orthodontics.[1] This evolutionary technology has enabled a wide range of innovations such as digital model analysis, virtual setup (VS), and customized appliance design.[2-4] By VS application, the crowns of the teeth can be moved digitally in the desired direction and to the desired degree.[5] Nowadays, VS is essential for the preparation of lingual bracket jigs and clear aligner production. In addition, VS can be used to visualize treatment objectives and to evaluate the quality of treatment outcomes.

The initial and final digital models are compared with the 3D superimposition technique for the assessment of treatment results. This superimposition enables an orthodontist to analyze 3D tooth crown movements.

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Before 3D digital modeling, movements of the teeth were evaluated with a number of measurements on the plaster model or via cephalometric superimpositions.[6-8] However, landmark identification errors could be seen in the cephalometric superimpositions, due to overlapping images of bilateral anatomical structures and teeth.[9,10] The assessment of teeth movement may also be adversely affected by factors such as magnification,[11] craniofacial growth during prolonged treatment,[12] type of reference planes used in the cephalometric superimpositions,[13] and wrong head position.[14] In addition, the 2D tooth movement is evaluated on a stable cephalometric image, while the model can be rotated in 3 directions of space during DMS so that more accurate and valid measurements can be carried out at the appropriate angle.

In 3D teeth movement analysis, digital models are superimposed using anatomical landmarks which can remain stable during orthodontic treatment.[15] Palatal rugae are used to identify stable anatomical landmarks on the palatal surface of the patient. However, due to orthodontic treatment, dimensional or positional changes in the pattern of palatal rugae may occur.[16] While the stability of rugae is widely disputed, there is consensus in the literature on the stability of the third rugae.[17-21] LB superimposition may not be reliable, because the stability of the palatal rugae is questionable. But could models be overlapped with another algorithm without the use of palatal rugae? A good alternative to the LB approach is the LBF algorithm. The basic working mechanism of the LBF algorithm is that digital models are overlapped by achieving maximum surface contact.

Evaluation of tooth displacement via DMS is considered a reliable method.[22] However, it is not known which factors affect the success of both the LB algorithm and the local best-fit algorithms, and which method is more reliable and valid. We noted in our review that the literature on this subject does not contain adequate and satisfactory information.

The aim of the study was to assess the correlation between the dental movements (type and amount) and the accuracy of DMS, and to test the reliability of the 2 algorithms.

METHODS

Definition of the Groups

The experimental protocols of this study were approved by the Clinical Research Ethics Committee of Afyonkarahisar Health Science University. Forty different upper digital models were selected from our archive for the study. 3Shape TRIOS (Copenhagen, Denmark) had been used for the model acquisition. Accurately scanned models, particularly in the palatal area, were included in the study. Patients with missing teeth, partially erupted teeth, or decayed teeth in the maxilla were excluded. Informed consent forms were obtained from all the patients included in the study. First, each model was segmented; the segmented teeth then were moved virtually in 8 different variations. A total of 320 new digital models were divided into 8 groups: Group 1: 1 mm sagittal movement of all teeth (S1), Group 2: 1 mm transversal movement of the posterior teeth (canine to the second molar) (T1), Group 3: 1 mm vertical movement (extrusion) of all teeth (V1), Group 4: Combination of all 1-mm tooth movements (C1 = S1+T1+V1), Group 5: 2 mm sagittal movement of all teeth (S2), Group 6: 2 mm transversal movement of the posterior teeth (canine to the second molar) (T2), Group 7: 2 mm vertical movement (extrusion) of all teeth (V2), Group 8: Combination of all 2-mm tooth movements (C2 = S2+T2+V2).

Digital Model Segmentation and Virtual Teeth Movements

Ortho Analyzer software (Copenhagen, Denmark) was used at this stage of the study. The workflow that guides the virtual segmentation (dividing teeth into a separate 3D object) of teeth crowns was as follows (Figure 1):

- Setpoints: selecting the mesial and distal ending of each tooth.
- Define cut: the software automatically cut the marginal line of each tooth. The accuracy of all marginal lines was double-checked. In case of need, they were edited in accurate form.
- Sculpt: initialization of the segmentation. The accuracy of each segmentation was controlled, and if necessary, the previous steps were renewed.

After the segmentation, each tooth was individually moved in a certain direction and to a degree in accordance with the group definitions. All individual tooth movements were reviewed in a chart, and the new form of each digital model was saved and exported in STL format after ensuring that the defined tooth movement was achieved.

Superimposition of the Digital Models

The non-segmented original version of the models was used as a reference in the superimpositions. The reference models were overlapped individually with each model of the experimental groups using the Geomagic Control X (Geomagic; Morrisville, USA) software. Two different algorithms were preferred in the DMSs: LB and LBF. Four points were marked on the third rugae for the LB superimposition (Figure 2). LBF (i.e., the search for maximally perfectly matched areas between 2 models) overlapped the models automatically without needing a point marking. After the superimpositions, the horizontal reference plane was positioned 2-3 mm below the apical gingival margin, and all overlapping surfaces, except the palatal roof, were removed. Only surface deviations on the roof of the palate were evaluated, because in an ideal and accurate overlap, there should be no surface deviation in this region. In other words, the area should be completely green (perfectly aligned areas) after overlapping. The reason why the reference plane was placed 2-3 mm below the apical gingival margins was that the software was unable to precisely mimic the movement of soft tissue during the tooth crown movement (Figure 3).

Three-dimensional surface deviations were shown with color-coded maps. The color codes had the following meanings: green: perfectly aligned areas, red; positively positioned areas relative to the reference model, and blue; negatively positioned areas. Ideally, the algorithms should overlap the upper digital models

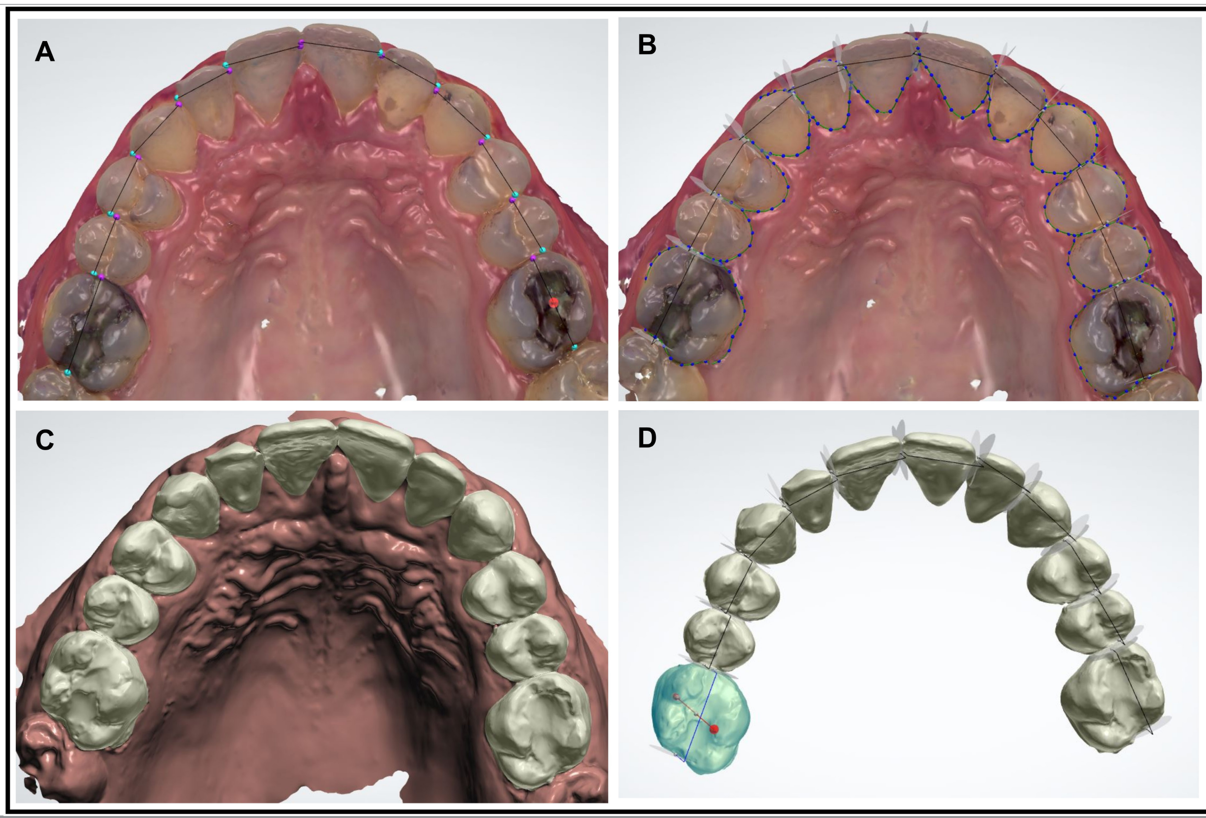

Figure 1. A-D. The workflow that guides the virtual segmentation. (A) Marking the teeth's mesial and distal points; (B) Automatic determination of marginal boundaries; (C) Segmentation of each tooth; and (D) Illustration of segmented teeth.

on the palatal roof region that are not affected by tooth movements, and no surface deviation should be seen on the palate roof. Therefore, to test the performance of the 2 algorithms, only the palatal roof was selected and only the surface deviations in this region were assessed (Figure 4). The following numerical surface deviation data, which were calculated automatically by the software, were used to compare the groups with statistical analysis: RMS (the square root of the arithmetic mean of the squares of

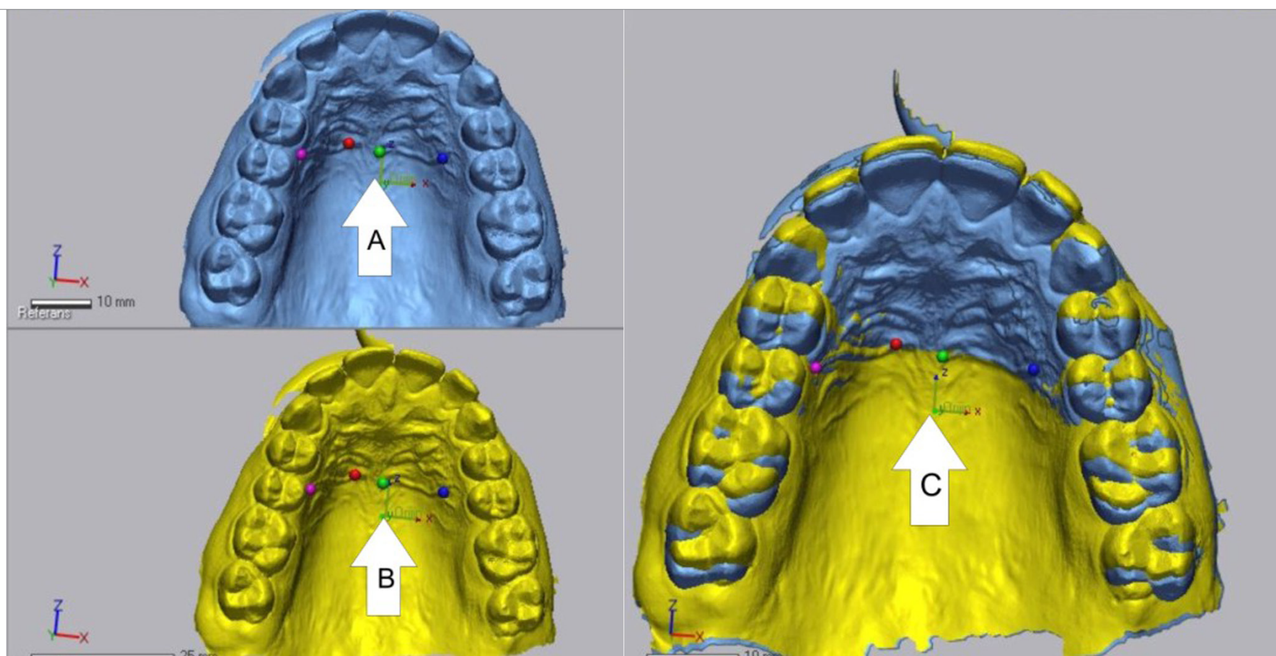

Figure 2. The point marking for the LB method. (A) Pre-setup model; (B) Post-setup model; (C) Superimposition of the 2 models. Pink dot: lateral tip of the right third ruga, red dot: medial tip of the right third ruga, green dot: medial tip of the left third ruga, and blue dot: lateral tip of the left third ruga.

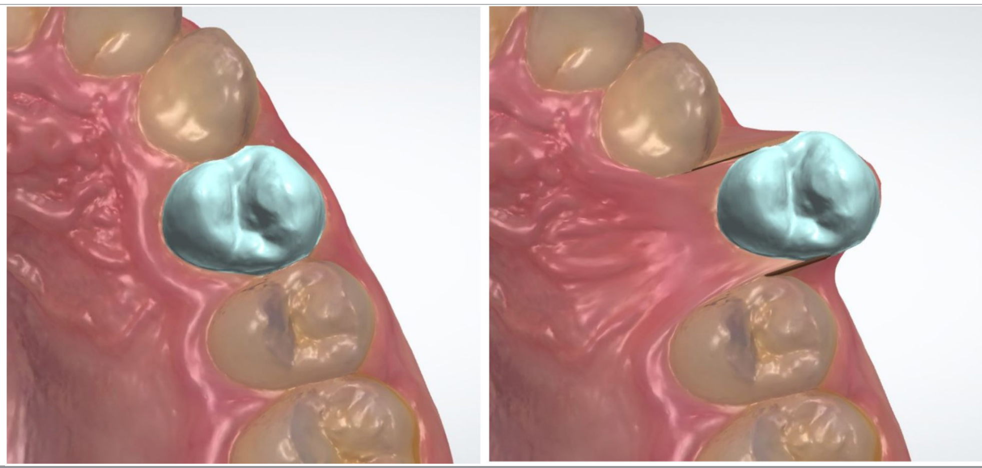

Figure 3. Illustration of poor imitation of soft tissue movements during the crown movements.

the point-to-point distance between the areas with an identical coordinate system) and PMA (the ratio of the perfectly matched area to the total area). In addition, the right canine (RC) displacement was calculated to test how accurately the 1 mm or 2 mm of crown movement was measured using the digital superimposition technique.

Statistical Analysis

The Statistical Package for Social Sciences (SPSS) 22.0 package program (IBM SPSS Corp., Armonk, NY, USA) was used to calculate the mean values and standard deviations of each parameter. For certain parameters, one-way ANOVA and post hoc Tukey tests were performed to compare the data between the groups, and the Kruskal–Wallis and post hoc Tamhane tests were used for some non-homogeneous data.

Student's *t*-test and Mann-Whitney U test were used to compare the results of LB and LBF algorithms. RC measurements were repeated 10 days later by the same researcher to detect the intra-examiner error rate (F.S). Repeated measurements were compared with the intraclass correlation coefficient (ICC) test. Similarly, 10 randomly selected patient models were superimposed for the second time to test the repeatability of the LB technique and the results were compared with the ICC test.

RESULTS

Comparison by Type of Tooth Movement Assessment of 1-mm Displacements

The mean percentage of the perfectly matching area (PMA) of all groups (S1, T1, V1, and C1) was 99.6% for LBF and 73.6% for

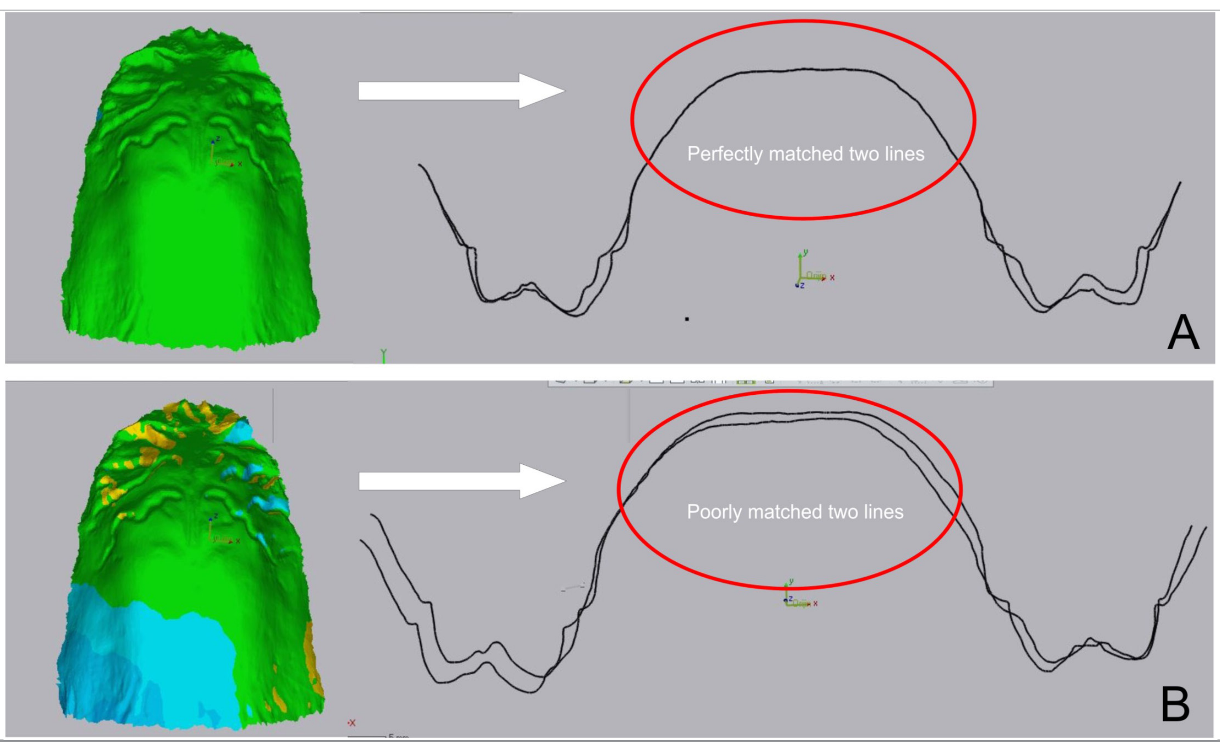

Figure 4. A, B. (A) Illustration of the LBF algorithm results; (B) Illustration of the LB algorithm results. Color distribution in the palate was expressed as PMA value. RMS meant the distance between the 2 poorly matched lines.

Table 1. Comparison of PMA values between LB and LBF

	LB	LBF	
	PMA	PMA	*P*
S1	74.82 ± 19.4[a]	99.61 ± 0.5[a]	
T1	72.18 ± 17.2[a]	99.68 ± 0.3[a]	
V1	72.39 ± 19.3[a]	99.52 ± 0.5[a]	
C1	75.20 ± 19.2[a]	99.77 ± 0.2[a]	
Total 1	73.65 ± 18.7[A]	99.65 ± 0.4[A]	.80
S2	65.02 ± 24.9[b]	99.03 ± 1.0[a]	
T2	66.59 ± 22.9[b]	99.34 ± 0.6[a]	
V2	70.52 ± 27.1[b]	98.93 ± 1.0[a]	
C2	62.01 ± 24.7[b]	99.53 ± 0.5[a]	
Total 2	66.03 ± 24.9[A]	99.21 ± 0.8[B]	.001
	P < .001	*P > .05*	

[a,b]Statistically significant difference between the columns, [A,B]Statistically significant difference between the lines.
LB, landmark based; LBF, local best-fit; PMA, perfectly matching area; S1, sagittal 1 mm; T1, transversal 1 mm; V1, vertical 1 mm; C1, combination 1 mm; S2, sagittal 2 mm; T2, transversal 2 mm; V2, vertical 2 mm; C2, combination 2 mm

LB. This difference between the 2 methods was statistically significant. The RMS value in the LBF group (1.1 μ) was quite small compared to the LB group (9.5 μ) ($P < .001$) (Tables 1 and 2).

When the performance of the 2 algorithms was statistically compared in terms of the type of tooth movement, it was observed that neither the LB nor the LBF algorithm was affected by the type of tooth movement.

Comparison by Type of Tooth Movement Assessment of 2-mm Displacements

The average PMA of the 4 groups in the LBF superimpositions was 99.2%. The mean value of RMS in the LBF group was 1.8 μ.

Table 2. Comparison of RMS values between LB and LBF (One-way ANOVA and Kruskal-Wallis tests)

	LB	LBF	
	RMS	RMS	*P*
S1	9.5 ± 5.2[a]	1.2 ± 0.7[a]	
T1	9.7 ± 3.9[a]	0.9 ± 0.5[a]	
V1	9.9 ± 5.3[a]	1.2 ± 0.6[a]	
C1	8.9 ± 4.4[a]	0.9 ± 0.4[a]	
Total 1	9.5 ± 4.7[A]	1.1 ± 0.6[B]	.001
S2	12.7 ± 7.9[b]	2.1 ± 1.5[a]	
T2	11.7 ± 8.2[b]	1.7 ± 0.9[a]	
V2	11.4 ± 9.4[b]	2.0 ± 1.2[a]	
C2	14.2 ± 9.6[b]	1.4 ± 0.6[a]	
Total 2	12.5 ± 8.8[A]	1.8 ± 1.2[B]	.001
	P < .5	*P > .05*	

[a,b]Statistically significant difference between the columns, [A,B]Statistically significant difference between the lines.
LB, landmark based; LBF, local best-fit; ,RMS, Root mean square; S1, sagittal 1 mm; T1, transversal 1 mm; V1, vertical 1 mm; C1, combination 1 mm; S2, sagittal 2 mm; T2, transversal 2 mm; V2, vertical 2 mm; C2, combination 2 mm.

No significant differences were observed in the comparison of PMA and RMS parameters among the groups (S2, T2, V2, and C2) ($P > .05$) (Table 1).

The average PMA of the 4 groups in the LB superimpositions was 66.0%. The mean value of RMS in the LB group was 12.5 μ (Table 2). There was no statistically significant difference in RMS and PMA values between the groups. When comparing the efficiency of LBF and LB algorithms using RMS and PMA values, it was found that the effectiveness of the LBF technique was greater.

Effect of Degree of Movement 1 mm vs 2 mm

In LB superimpositions, the PMA value was 73.6% for 1-mm displacements and 66.0% for 2-mm displacements. The difference was statistically significant, in other words, the LB algorithm was affected by the amount of movement of the teeth.

The LBF algorithm's PMA value for 1-mm displacement was 99.6% and 99.2% for 2-mm displacement. This small difference (0.4%) was not statistically significant ($P = .135$). In RMS, another parameter that demonstrates the success of the LBF algorithm, there was no significant difference between 1 mm and 2 mm of displacement ($P = .147$).

Results ot Right Canine Measurements

The success of the LB and LBF algorithms allowed the 1-mm or 2-mm tooth movements obtained in the VS to be measured as very close to the original (Table 3). No statistically significant differences were observed between groups in the RC measurements. The intraclass correlation coefficient results performed to test the accuracy of the RC and LB data are shown in Table 4.

DISCUSSION

DMS is a practical method for 3D visual and quantitative analysis of changes that occur with orthodontic treatment or growth

Table 3. Comparison of RC measurements between LBF and LB

	LBF	LB	
Groups	Mean ± SDs	Mean ± SDs	*P*
S1	0.99 ± 0.03	0.97 ± 0.3	787
T1	0.98 ± 0.03	1.05 ± 0.2	693
V1	0.96 ± 0.02	1.04 ± 0.2	834
S2	2.01 ± 0.09	2.02 ± 0.3	901
T2	1.99 ± 0.07	2.09 ± 0.2	854
V2	1.97 ± 0.05	2.09 ± 0.3	729

($P > .05$).
SD, standard deviation; S1, sagittal 1 mm; T1, transversal 1 mm; V1, vertical 1 mm; S2, sagittal 2 mm; T2, transversal 2 mm; V2, vertical 2 mm.

Table 4. Intraclass correlation coefficient (ICCs) results

	PMA	RMS	RC
ICCs	0.968	0.974	1.00

PMA and RMS value belong to the LB algorithm.

and development. There are a variety of software packages used to superimpose the initial and final models, and they use a wide range of algorithms.[23] Overlaps can be made by selecting points (LB) or areas (surface-based) in the palatal region.[24,25] The combination of point selection and area selection is also an option.[26] A number of researchers have conducted studies to test the accuracy of these methods.[18,27,28] Talaat et al. [25] reported that the LB algorithm is reliable, valid, and reproducible for the 3D model superimposition. However, there is no standard for determining the number and location of points when using the LB algorithm.

The selection of different areas of the palate (in terms of size and location) has been shown to influence the results of surface-based (SB) superimpositions.[24] The LBF algorithm, on the other hand, is a fast and practical method that superimposes models without the need for field or point selection.[29] However, there is insufficient data on the reliability of the LBF algorithm and its superiority or deficiency over other methods. To our knowledge, this research was the first study to assess whether the algorithms used in model superimpositions are affected by the degree and type of tooth movement.

During the orthodontic treatment of growing patients, the reference points or areas used for model superimposition change depending on the development of the maxilla. Rugae are unique to individuals, like fingerprints, and provide repeatability in dot positioning.[30] Rugae may exhibit dimensional or positional changes at the end of treatment due to growth and development. Researchers have suggested that the longitudinal model analysis of the medial ruga area, similar to the third ruga, could be used as a stable reference area.[17] Maxillary expansion is another factor that affects the stability of the rugae, and its impact on the rugae is still controversial.[31,32]

Both the LB and SB methods are time-consuming and computing-intensive. However, the LBF algorithm is very simple and practical to use. Only the 2 models for overlap need to be selected. The LBF procedure is more accurate than other methods because the algorithm continues to work with complex computer calculations until the deviation between the surfaces is minimized and maximum surface matching is achieved.[33] The success of LB is correlated with the number of points marked or their position. So, does LBF provide a strong alternative to LB?

Our findings showed that the PMA value for LBF was 99%, which indicated the high success of LBF. Additionally, neither the type of tooth movement nor the degree of it influenced the performance of the LBF algorithm. The average RMS value in the LBF group (1-2 μ), which shows the distance of the surface deviation between the 2 models, revealed how accurate the algorithm was. Although the LB algorithm was not affected by the movement type, the performance of the algorithm decreased from 73.6% to 66.0% as the amount of displacement increased. However, we believe that the sensitivity of measuring tooth movement after superimposition was related to the RMS value, rather than to the PMA. The primary factor that could affect RC measurements was the RMS value that indicates the distance between matching surfaces. RC measurements were not affected as the RMS was as small as 1-2 μ for LBF and 9-12 μ for LB. The smaller the RMS value, the greater the possibility of identifying the more exact tooth movements. Although the RMS value showed a statistically significant difference between LB and LBF, this difference at the micron level did not affect the accuracy of the RC measurements. This was evidence of the precise identification of the points by the operator and the efficient use of the LB technique. By measuring the displacement of the palatal ruga points and the central incisor movement, Jang et al.[18] compared the LB algorithm to the miniscrew-assisted superimposition method and reported no difference between the 2 methods. According to Talaat et al.,[15] 3D LB digital dental model superimposition using 3 reference points marked along the mid-palatal raphe was a valid and reliable technique. Choi et al.[27] emphasized that using the palatal surface provides reliable results in the DMS, but the effects of growth and orthopedic treatments on the palatal surface should be investigated. Abdi et al.[28] also suggested that rugae points are clinically reliable for superimposition. Our RC measurement results were consistent with the findings of previous studies.

In our study, displacement of the teeth was performed using VS technology. The reality was imitated by a virtual approach. This could be considered as a limitation of the research. In real life, the height and width of the palatal alveolar process increases with the effect of craniofacial growth that continues during orthodontic treatment in some patients.[34] Therefore the pattern and location of rugae can possibly change.[35] In addition, when we achieve transverse tooth movement with maxillary expansion, the palatal vault expands and the rugae also undergo dimensional and positional changes.[32] All of these changes in the stability of the rugae may negatively affect the performance of the LB algorithm. However, with the method followed in our study, these factors that could have affected the results were eliminated, because no changes were observed in the rugae during the VS.

CONCLUSION

- It was not the type of tooth movement, but its degree that negatively affected LB superimposition performance. This was however too small (at micron level) to affect the measurements that evaluate the quantum of tooth displacement.
- The LBF method provided faster, easier, and more efficient overlaps. The performance of the LB algorithm was acceptable, but it required the operator to be very careful and precise with marking.
- The displacement of the RC measured after the LB method was not significantly different from the LBF method, which indicated that the 2 methods could be used reliably to evaluate the degree of teeth displacement.

Ethics Committee Approval: This study was approved by Afyonkarahisar Health Science University Clinical Research Ethics Committee.

Informed Consent: Written consent for publication was obtained from all the patients included in the study.

Peer Review: Externally peer-reviewed.

Author Contributions: Concept - H.C.; Design - H.C.; Data Collection and/or Processing - H.C., F.S.; Analysis and/or Interpretation - H.C., F.S.; Writing - H.C.; Critical Review - H.C.

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