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The influence of the model superimposition method on the assessment of accuracy and predictability of setup models

Leonardo T. Camardella¹ · Oswaldo V. Vilella¹ · K. Hero Breuning² · Felipe de Assis Ribeiro Carvalho³ · Anne Marie Kuijpers-Jagtman^{4,5,6} · Edwin M. Ongkosuwito⁷

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Abstract

Introduction The aim of this study was to evaluate the influence of different superimposition methods on the accuracy and predictability of conventional and virtual diagnostic setups.

Materials and methods Ten finished cases were used to make a conventional setup and a virtual setup. Second molars were not moved in the two setup situations to allow a reference for superimposition. Conventional and virtual setups were superimposed and compared by second molar registration and the whole surface best fit method (WSBF). Conventional and virtual setups were compared to the posttreatment models with WSBF and palatal rugae best fit (PRBF). Anterior, intermediate, and posterior regions of the dental arches were compared. The paired *t*-test was used to compare the mean differences between conventional and virtual setups, posttreatment models and both conventional and virtual setups by the WSBF method, and between maxillary posttreatment and virtual setup models using the WSBF and PRBF methods.

Results Conventional and virtual setups differed depending on the two superimposition methods used. Superimposition of the posttreatment models and both setups using WSBF presented no statistically significant differences. There were statistically significant differences between posttreatment and virtual setup models using WSBF and PRBF superimposition methods.

Conclusions The model superimposition method influenced the assessment of accuracy and predictability of setup models. There were statistically significant differences between the maxillary posttreatment and virtual setup models using the WSBF and the PRBF superimposition methods. It is important to establish stable structures to evaluate the accuracy and predictability of setup models.

Keywords Digital models · Digital simulation · Three-dimensional diagnosis and treatment planning · 3D scanner · Orthodontics, corrective

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Der Einfluss der Modellüberlagerungsmethode auf die Bewertung der Genauigkeit und Vorhersagbarkeit von Setup-Modellen

Zusammenfassung

Einführung Ziel dieser Studie war es, den Einfluss verschiedener Überlagerungsmethoden auf die Genauigkeit und Vorhersagbarkeit konventioneller und virtueller diagnostischer Setups zu bewerten.

Materialien und Methoden Zehn abgeschlossene Fälle wurden verwendet, um ein konventionelles und ein virtuelles Setup zu erstellen. Zweite Molaren wurden in den beiden Aufstellungssituationen nicht bewegt, um als Referenz für die Überlagerung zu dienen. Konventionelle und virtuelle Setups wurden überlagert und an den zweiten Molaren sowie durch die WSBF („whole surface best fit“)-Methode verglichen. Konventionelle und virtuelle Setups wurden mit den Nachbehandlungsmodellen mit WSBF und der regionalen PRBF („palatal rugae best fit“)-Methode verglichen. Die vorderen, mittleren und hinteren Regionen der Zahnbögen wurden einander gegenübergestellt. Der gepaarte t-Test wurde verwendet, um die mittleren Unterschiede zwischen konventionellen und virtuellen Setups, Nachbehandlungsmodellen und sowohl konventionellen als auch virtuellen Setups nach der WSBF-Methode sowie zwischen Modellen zur Nachbehandlung des Oberkiefers und virtuellen Setups nach der WSBF- und PRBF-Methode miteinander zu vergleichen.

Ergebnisse Konventionelle und virtuelle Aufstellungen waren unterschiedlich, je nach den beiden verwendeten Überlagerungsmethoden. Die Überlagerung der Nachbehandlungsmodelle und der beiden Setups mittels WSBF ergab keine statistisch signifikanten Unterschiede. Es gab statistisch signifikante Differenzen zwischen Nachbehandlungs- und virtuellen Aufbaumodellen unter Verwendung von WSBF- und PRBF-Überlagerungsmethoden.

Schlussfolgerungen Die Modellüberlagerungsmethode beeinflusste die Beurteilung der Genauigkeit und Vorhersagbarkeit von Aufstellungsmodellen. Es gab statistisch signifikante Differenzen zwischen der Nachbehandlung der Oberkiefer und den virtuellen Setup-Modellen unter Verwendung der WSBF- und der PRBF-Überlagerungsmethode. Zur Beurteilung der Genauigkeit und Vorhersagbarkeit von Setup-Modellen ist es wichtig, stabile Strukturen zu entwickeln.

Schlüsselwörter Digitale Modelle · Digitale Simulation · Dreidimensionale Diagnose und Behandlungsplanung · 3-D-Scanner · Korrigierende Kieferorthopädie

Abbreviations

ICP	iterative closest-point
PRBF	palatal rugae best fit
RMS	root mean square discrepancy
WSBF	whole surface best fit

Introduction

A diagnostic setup can be used to simulate an orthodontic treatment and provides information regarding the possibilities and limitations of an orthodontic treatment plan. A setup can also be used to evaluate different treatment mechanics which will be applied and to evaluate the need for anchorage in a specific case. Conventional setups made on plaster casts, in which the segmented tooth crowns are positioned in wax, have been used in orthodontics for many years. Virtual setups using digital dental models have been increasingly adopted.

Setups can be divided into two groups: diagnostic and therapeutic setups. The diagnostic setup is important to simulate treatment plans and to improve communication with the patient. The therapeutic setup can also be used for the mentioned goals, but it is also possible to fabricate orthodontic appliances such as clear aligners, customized

buccal or lingual fixed appliance systems, indirect bonding trays, and customized wires bent by a wire-bending robot [12, 13, 18].

Conventional setups have been used for a long time in orthodontics but, due to their advantages, virtual setups can be the next gold standard for diagnosis and treatment planning. Some studies evaluated differences between conventional and virtual setups by measuring distances or by assessing occlusal indices [3, 11, 15]. Earlier studies compared virtual setups with the posttreatment models by measuring distances [3] or by model superimposition using the best fit alignment method [13, 16–18]. Only one study compared the differences between conventional setups, virtual setups and the final outcome models. No statistically significant differences were found between the three types of models, but in this research only a few distances were measured (intercanine/intermolar widths and maxillary and mandibular dental arch length) [3] and these parameters are of less importance as they can be easily controlled during the setup manufacturing. Moreover, use of transversal parameters can show misleading results because both canines can be displaced to the right or left in the same model which leaves the intercanine width unchanged. Using a model superimposition method improves the assessment of displacements in the three planes of space.

Fig. 1 Example of maxillary and mandibular pretreatment models based on the inclusion criteria

Abb. 1 Beispiel für Vorbehandlungsmodelle von Ober- und Unterkiefer auf der Grundlage der Einschlusskriterien

Various studies that compared dental movements in progress models proposed a superimposition method using stable structures as a reference such as the palatal rugae in the maxillary model [7, 8, 10, 19] or the mandibular torus in the mandibular model [1]. The studies which compared therapeutic virtual setups with the posttreatment models used the best fit alignment technique for model superimposition using the dentition as a reference [13, 16–18]. These two superimpositions methods are paradoxical to compare dental changes between two models. To our knowledge there are no studies that investigated the influence of the type of model superimposition method in the comparison of accuracy and predictability of diagnostic conventional and virtual setups.

Therefore, the aim of this study was to evaluate the influence of two model superimposition methods (best fit and stable structure) comparing conventional and virtual setups, with actual posttreatment models. The differences between conventional and virtual setups were also evaluated.

Materials and methods

Materials

For this preclinical study, ten consecutive cases were selected from the long-term outcome archive of the Radboud University (Nijmegen, The Netherlands). This sample number is the same as in similar studies that compared virtual and conventional setups [11, 15]. Inclusion criteria were the following: finished orthodontic cases with a full permanent dentition including maxillary and mandibular second molars and treated without extractions; bilateral class I Angle molar relationship before and after treatment. Mild crowding (up to 6 mm) and spacing (up to 3 mm), mild deep

overbite and open bite (overbite from 5 to –2 mm), mild positive and negative overjet (up to 6 to –3.7 mm) and mild posterior crossbite before treatment were accepted (Fig. 1). Exclusion criteria were class II/class III Angle molar relationship, orthodontic/surgical cases, orofacial clefts and craniofacial anomalies. For all cases a set of initial and posttreatment radiographs (panoramic and cephalometric) and plaster models were available, and both the diagnosis and treatment plan were well described in a standardized manner as required in the postgraduate program. The selected cases were treated with preadjusted appliances by postgraduates in orthodontics, supervised by qualified orthodontists.

The selected participants of the sample in this study were treated between the years 2002 and 2007 and no ethic approval was required at that time. Furthermore, this was an observational study using routinely collected health data made pseudo-anonymous.

Conventional and virtual setups

The pretreatment plaster models were duplicated in a specialized orthodontic lab to fabricate the conventional setup. The initial plaster models were also scanned with the R700 scanner (3Shape®, Copenhagen, Denmark), using dedicated scanning software to acquire digital models to make the virtual setups.

Both the conventional and virtual diagnostic setups were made by the same orthodontist, who was equally experienced and skilled in both setup techniques. The orthodontist was not involved in the treatment of any of the patients and was blinded for the treatment outcome. The setups were made according to the treatment plan described for each patient. Parameters such as the maxillary and mandibular dental midline according to the median sagittal facial plane

and the planned correction, the mandibular arch form maintenance, the amount of stripping and buccal and lingual incisor movements according to the clinical and cephalometric analysis and the treatment plan were used as a guideline for each setup. The conventional setups were fabricated first, and after 15 days the virtual setups were made. The time needed to produce a setup was registered.

The conventional setups with segmented tooth crowns from plaster models were made according to the guidelines presented in the literature [2], adapted for the specific patient situation as described above. Virtual setups were carried out with the aid of Ortho Analyzer software (3Shape®, Copenhagen, Denmark). For the virtual setups, the arch form was digitally defined, the maxillary and mandibular dentitions were segmented and the long axis of each tooth was defined using the software tools. The maxillary and mandibular second molars were not moved in the conventional and virtual setups in order to obtain a stable reference for the comparison of the setups with the digital model superimposition.

Data acquisition

The conventional setups as well as the posttreatment plaster models of the ten cases were scanned with the R700 scanner to enable a comparison of the conventional and virtual setups and the posttreatment models by superimposition.

The digital models were exported to Standard Tessellation Language Files (stl files). All digital models from the virtual setups, the conventional setups and the posttreatment dental models were superimposed using Geomagic Qualify 2013 software (3D Systems®, Rock Hill, SC, USA). For the model superimpositions, only the outline of the maxillary and mandibular dentition was used excluding the oral soft tissues as the latter are disturbed by the setup fabrication [13].

The conventional and virtual setups of each patient were compared using the maxillary and mandibular second molars as a stable reference for the superimpositions, as these teeth were not moved (Fig. 2a–d). Conventional and virtual setups were also superimposed by whole surface best fit method (WSBF) using the outline of the maxillary and mandibular dentition from first molar to first molar to su-

Fig. 2 Superimposition of the conventional with the virtual setup using the mandibular arch of the case in Fig. 1. Stable structure superimposition method: **a** Digital model from the conventional setup. **b** Digital model from the virtual setup. **c** Superimposition of conventional and virtual setups using the second molars as reference for alignment (*red*). **d** Color map of the models superimposition. Whole surface best fit (WSBF) superimposition method: **e** Digital model from the conventional setup. **f** Digital model from the virtual setup. **g** Superimposition of conventional and virtual setups using the WSBF method for alignment. **h** Color map of the models superimposition

Abb. 2 Überlagerung des konventionellen mit dem virtuellen Setup unter Verwendung des Unterkieferbogens des Falles in Abb. 1. Stabiles Strukturüberlagerungsverfahren: **a** Digitales Modell aus der konventionellen Aufstellung. **b** Digitales Modell aus der virtuellen Aufstellung. **c** Überlagerung von konventioneller und virtueller Aufstellung unter Verwendung der zweiten Molaren als Referenz für die Ausrichtung (*rot*). **d** Farbtabelle der Überlagerung der Modelle. WSBF („whole surface best fit“)-Überlagerungsmethode: **e** Digitales Modell aus dem konventionellen Setup. **f** Digitales Modell aus dem virtuellen Setup. **g** Überlagerung von konventionellem und virtuellem Setup unter Verwendung der WSBF-Methode zur Ausrichtung. **h** Farbtabelle der Überlagerung der Modelle

Fig. 3 Superimposition using the whole surface best fit (WSBF) superimposition method of the scanned posttreatment model with the scanned conventional setup and the virtual setup of a mandibular arch. **a** Digital model from the conventional setup. **b** Digital model from the virtual setup. **c** Digital model from the posttreatment model. **d** Superimposition of the posttreatment model with the conventional setup and the virtual setup models using the WSBF superimposition method

Abb. 3 Überlagerung mit dem WSBF(„whole surface best fit“-Überlagerungsverfahren des gescannten Nachbehandlungsmodells mit dem gescannten konventionellen Setup und dem virtuellen Setup eines Unterkieferbogens. **a** Digitales Modell aus dem konventionellen Setup. **b** Digitales Modell aus dem virtuellen Setup. **c** Digitales Modell aus dem Nachbehandlungsmodell. **d** Überlagerung des Nachbehandlungsmodells mit dem konventionellen Setup und den Modellen des virtuellen Setups mit dem WSBF-Überlagerungsverfahren

perimpose the models by best fit registration (Fig. 2e–h). The conventional setup models were the reference for these superimpositions.

The posttreatment models were compared with the conventional and virtual setup models by a superimposition method excluding the second molars, as they were not moved in both setup models. The posttreatment models were the reference for these superimpositions. The virtual setups were compared to the posttreatment models by two different superimpositions methods: WSBF, as done in other studies ([13, 16–18]; Fig. 3), and by the regional palatal rugae best fit (PRBF) on the maxillary models. In the latter method we used the medial 2/3 of the third rugae and a small area dorsal to them as the reference structure, as this region has been considered to have good anatomical stability ([7, 10, 19]; Fig. 4). One of the maxillary posttreatment models of the sample did not present a good definition of the anatomy of the selected reference area of the rugae, therefore only 9 models of the sample were evaluated by this method. After the model superimposition on the rugae region, all the oral tissues were digitally removed leaving only the outline of the maxillary dentition. It was not possible to use stable references for superimposition on the mandibular models of the virtual setups due to the absence of a stable structure such as the mandibular torus [1] in the analyzed sample. In the WSBF and PRBF superimposition methods the same algorithm was used (best fit) in the software program. The only difference between them was the structure used as a reference: the outline of the dentition from first molar to first molar in the WSBF

Fig. 4 Superimposition using the palatal rugae best fit (PRBF) method of the scanned posttreatment model and the virtual setups of a maxillary arch. **a** Reference area for rugae registration for model superimposition. **b** Color map of the rugae registration model superimposition. **c** Superimposition of the posttreatment model (green) and the virtual setup model (blue) using the PRBF superimposition method (occlusal view). **d** Superimposition of the posttreatment model (green) and the virtual setup model (blue) using the PRBF superimposition method (right lateral view)

Abb. 4 Überlagerung unter Verwendung der PRBF(„palatal rugae best fit“-Methode des gescannten Nachbehandlungsmodells und der virtuellen Setups eines Oberkieferbogens. **a** Referenzbereich für die Rugae-Registrierung zur Modellüberlagerung. **b** Farbtabelle der Überlagerung des Rugae-Registrierungsmodells. **c** Überlagerung des Nachbehandlungsmodells (grün) und des virtuellen Aufstellungsmodells (blau) mit der PRBF-Überlagerungsmethode (Okklusalan-sicht). **d** Überlagerung des Nachbehandlungsmodells (grün) und des virtuellen Aufstellungsmodells (blau) mit der PRBF-Überlagerungsmethode (Ansicht von der rechten Seite)

Fig. 5 Regions selected in the study: **a** Maxillary arch of a virtual setup model. **b** Anterior region. **c** Intermediate region. **d** Posterior region

Abb. 5 In der Studie berücksichtigte Regionen: **a** Oberkieferbogen eines virtuellen Setup-Modells. **b** Vordere Region. **c** Mittlere Region. **d** Hintere Region

method and the above-mentioned region of the palate in the PRBF method. All these superimpositions were made with the same software and by one examiner.

The conventional setups were compared to the posttreatment models using only the WSBF superimposition method because the loss of the palatal rugae during the dental segmentation process did not allow for superimposition on these stable structures on the maxillary models [15].

After the model superimpositions, the superimposed models were divided into three regions to evaluate possible differences between them: anterior region (central and lateral incisors), intermediate region (canines and first premolars), and posterior region (second premolars and first molars; Fig. 5). The second molars were excluded from this analysis because they were only used as a stable reference to perform the comparison between the conventional and virtual setups and could not be used in the comparison with the posttreatment models because they were moved during the orthodontic treatment.

All the superimposed models were analyzed by the Mesh Valmet 3.0 software (<https://www.nitrc.org/projects/meshvalmet>).

Data analysis

Color displacement maps were generated by iterative closest-point algorithm in the Mesh Valmet 3.0 software to evaluate the differences in tooth position between the models. Maximum and minimum distances, root mean square discrepancy (RMS) and the 95th percentile values were recorded. Maximum and minimum distances are the largest differences between any points in the comparison between the models. RMS is the arithmetic mean of the squares of a set of numbers that is calculated to mitigate the trend of underestimation produced by the average, which is influenced by positive and negative values, which tend to level out each other, thus, producing a value close to zero [6].

The 95th percentile means that the distances between two given surfaces lie above 5% and below 95% of all values. This parameter is important since it is less prone to include outliers in the central trend calculation.

Statistical analysis

According to the results of Shapiro–Wilk normality test, we used parametric tests in this study. Paired *t*-test was used to compare the differences between the conventional and virtual setup models by second molar registration and WSBF superimposition methods. The paired *t*-test was also used to compare differences between posttreatment models and both the conventional and virtual setup models by WSBF superimposition method, and to compare the differences between maxillary posttreatment models and virtual setup models using the WSBF and PRBF superimposition methods. *P*-values <0.05 were considered to be significant. The tests were performed using the SPSS program, version 20.0 (IBM, Armonk, NY, USA).

Results

The average time to manufacture a conventional setup was 270 min and the average time for making a virtual setup was 45 min. The setup manufacturing time lasted from the beginning of teeth segmentation until the conclusion of the setup.

Table 1 shows the comparison by paired *t*-test between conventional and virtual setups using the second molar registration and WSBF superimposition methods. Only the maximum deviation in the anterior region of the mandibular models presented a statistically significant difference between the models, but all parameters presented smaller differences between the models with the WSBF method compared to the second molar registration method. The mean RMS was lower than 1.00 mm in all parameters, except in the anterior region of mandibular models superimposed on second molars. The means of all parameters were smaller in the posterior region compared to the other regions.

Table 2 presents the results of the paired *t*-test for the differences between the posttreatment models superimposed by the WSBF method on the conventional and virtual setup models, considering the anterior, intermediate and posterior regions. The results demonstrated statistically significant differences between the models only for the maximum deviation in the posterior region of the maxillary models and for the 95th percentile in the intermediate region of the mandibular models. Therefore, it can be assumed that there were few differences between the two setup models compared to the posttreatment models using the WSBF superimposition method.

Table 1 Comparisons using the paired *t*-test of the differences between the conventional and virtual setups superimposed by second molars as a stable reference and by the WSBF method, considering the anterior, intermediate and posterior regions of the maxilla and the mandible, with 95% confidence intervals**Tab. 1** Vergleiche unter Verwendung des gepaarten *t*-Tests der Unterschiede zwischen den konventionellen und virtuellen Setups, die mittels zweiter Molaren als stabile Referenz und durch die WSBF-Methode überlagert werden, unter Berücksichtigung der vorderen, mittleren und hinteren Bereiche des Ober- und Unterkiefers, mit 95%-Konfidenzintervallen

Parameter	Measurement (mm)		Measurement (mm)		Mean difference between comparisons (mm)	SD (mm)	95% CI of the difference		P-value
	Conventional setup vs. virtual setup (second molar) (N= 10)		Conventional setup vs. virtual setup (WSBF) (N= 10)				Min (mm)	Max (mm)	
	Mean	SD	Mean	SD					
Maxillary model									
Anterior region									
Minimum deviation	-2.594	0.511	-2.119	0.683	-0.475	0.825	-1.065	0.116	0.102
Maximum deviation	2.325	0.824	1.765	0.587	0.561	0.799	-0.011	1.132	0.054
RMS	0.830	0.303	0.632	0.265	0.197	0.360	-0.060	0.455	0.117
95th percentile	1.109	0.664	0.860	0.386	0.249	0.570	-0.159	0.657	0.201
Maxillary model									
Intermediate region									
Minimum deviation	-2.533	0.667	-2.326	0.706	-0.207	0.787	-0.770	0.356	0.427
Maximum deviation	2.414	0.846	2.144	0.672	0.270	0.904	-0.376	0.917	0.369
RMS	0.908	0.366	0.733	0.252	0.176	0.344	-0.071	0.422	0.141
95th percentile	1.537	0.799	1.090	0.523	0.448	0.849	-0.159	1.055	0.130
Maxillary model									
Posterior region									
Minimum deviation	-1.755	0.832	-1.560	0.678	-0.195	0.415	-0.492	0.102	0.171
Maximum deviation	1.599	1.143	1.406	0.567	0.193	0.859	-0.421	0.807	0.495
RMS	0.522	0.454	0.428	0.302	0.094	0.317	-0.133	0.321	0.374
95th percentile	0.883	0.923	0.774	0.563	0.109	0.706	-0.396	0.614	0.637
Mandibular model									
Anterior region									
Minimum deviation	-2.615	0.546	-2.104	0.470	-0.511	0.726	-1.069	0.046	0.067
Maximum deviation	2.831	0.576	2.073	0.592	0.758	0.826	0.123	1.393	0.025
RMS	1.066	0.390	0.683	0.285	0.383	0.540	-0.032	0.798	0.066
95th percentile	1.385	0.730	1.059	0.485	0.326	0.809	-0.295	0.948	0.261
Mandibular model									
Intermediate region									
Minimum deviation	-2.664	0.896	-2.311	0.408	-0.353	0.778	-0.952	0.245	0.210
Maximum deviation	2.189	0.983	1.704	0.480	0.485	1.022	-0.301	1.270	0.192
RMS	0.817	0.302	0.607	0.162	0.210	0.282	-0.006	0.427	0.056
95th percentile	1.254	0.958	0.845	0.258	0.409	1.060	-0.406	1.224	0.281
Mandibular model									
Posterior region									
Minimum deviation	-1.917	1.056	-1.479	0.419	-0.438	0.741	-1.007	0.132	0.114
Maximum deviation	1.894	1.286	1.533	0.614	0.360	0.791	-0.248	0.969	0.209
RMS	0.484	0.415	0.385	0.244	0.099	0.188	-0.045	0.243	0.153
95th percentile	0.783	1.091	0.648	0.562	0.135	0.555	-0.292	0.561	0.487

RMS root mean square, WSBF whole surface best fit, SD standard deviation, min minimum, max maximum, 95% CI 95% confidence interval

Table 3 presents the results of the paired *t*-test for the differences in the maxillary models between the posttreatment models and the virtual setup models superimposed by WSBF and PRBF superimposition methods, considering the anterior, intermediate and posterior regions. Most of the

parameters showed statistically significant differences for the comparisons considering the three regions studied, with exception of the 95th percentile parameter of the intermediate and posterior regions. Comparisons using the PRBF superimposition method presented larger differences in the

Table 2 Comparison using the paired *t*-test of the differences between the posttreatment models superimposed by WSBF method with the conventional and virtual setups, considering the anterior, intermediate and posterior regions of the maxilla and the mandible, with 95% confidence intervals

Tab. 2 Vergleich mittels gepaartem t-Test der Unterschiede zwischen den durch die WSBF-Methode überlagerten Nachbehandlungsmodellen mit den konventionellen und virtuellen Setup-Modellen unter Berücksichtigung der vorderen, mittleren und hinteren Bereiche des Ober- und Unterkiefers, mit 95%-Konfidenzintervallen

Parameter	Measurement (mm)		Measurement (mm)		Mean difference between comparisons (mm)	SD (mm)	95% CI of the difference		P-value
	Posttreatment models vs. conventional setup (N= 10)		Posttreatment models vs. virtual setup (N= 10)				Min (mm)	Max (mm)	
	Mean	SD	Mean	SD					
Maxillary model									
Anterior region									
Minimum deviation	-2.043	0.450	-1.881	0.425	-0.162	0.702	-0.664	0.340	0.485
Maximum deviation	1.594	0.685	1.178	0.314	0.416	0.828	-0.177	1.008	0.147
RMS	0.611	0.334	0.447	0.119	0.164	0.381	-0.108	0.436	0.206
95th percentile	0.899	0.609	0.525	0.106	0.374	0.652	-0.092	0.840	0.103
Maxillary model									
Intermediate region									
Minimum deviation	-1.811	0.695	-1.762	0.499	-0.049	0.834	-0.645	0.547	0.857
Maximum deviation	1.489	0.316	1.451	0.523	0.038	0.374	-0.229	0.305	0.755
RMS	0.552	0.128	0.561	0.171	-0.008	0.143	-0.111	0.094	0.861
95th percentile	0.898	0.326	0.856	0.357	0.042	0.218	-0.114	0.198	0.557
Maxillary model									
Posterior region									
Minimum deviation	-1.779	0.802	-1.503	0.458	-0.276	0.522	-0.649	0.097	0.129
Maximum deviation	1.806	0.642	1.439	0.500	0.367	0.457	0.040	0.694	0.032
RMS	0.561	0.259	0.491	0.237	0.071	0.146	-0.034	0.175	0.161
95th percentile	0.936	0.408	0.888	0.423	0.048	0.285	-0.155	0.252	0.605
Mandibular model									
Anterior region									
Minimum deviation	-1.606	0.279	-1.630	0.197	0.024	0.348	-0.243	0.291	0.843
Maximum deviation	1.299	0.290	1.117	0.436	0.181	0.602	-0.282	0.644	0.393
RMS	0.521	0.162	0.444	0.136	0.077	0.209	-0.084	0.237	0.303
95th percentile	0.752	0.279	0.668	0.345	0.084	0.535	-0.327	0.495	0.650
Mandibular model									
Intermediate region									
Minimum deviation	-1.846	0.520	-1.881	0.567	0.035	0.609	-0.434	0.503	0.869
Maximum deviation	1.681	0.575	1.311	0.436	0.371	0.490	-0.006	0.747	0.053
RMS	0.531	0.151	0.535	0.161	-0.004	0.135	-0.107	0.100	0.936
95th percentile	1.006	0.404	0.711	0.324	0.295	0.376	0.006	0.584	0.047
Mandibular model									
Posterior region									
Minimum deviation	-1.819	0.622	-1.576	0.363	-0.243	0.584	-0.692	0.206	0.247
Maximum deviation	1.714	0.723	1.596	0.449	0.118	0.787	-0.487	0.723	0.664
RMS	0.549	0.253	0.529	0.169	0.020	0.165	-0.107	0.148	0.721
95th percentile	0.967	0.530	0.976	0.357	-0.010	0.454	-0.358	0.339	0.951

WSBF whole surface best fit, SD standard deviation, *min* minimum, *max* maximum, 95% CI 95% confidence interval, RMS root mean square discrepancy

Table 3 Comparison using the paired *t*-test of the differences between the posttreatment models and the virtual setups, by WSBF and PRBF superimposition methods, considering the anterior, intermediate and posterior regions of the maxilla, with 95% confidence intervals

Tab. 3 Vergleich mit dem gepaarten *t*-Test der Unterschiede zwischen den Nachbehandlungsmodellen und den virtuellen Setups durch WSBF- und PRBF-Überlagerungsmethoden unter Berücksichtigung der vorderen, mittleren und hinteren Bereiche des Oberkiefers, mit 95%-Konfidenzintervallen

Parameter	Measurement (mm)		Measurement (mm)		Mean difference between comparisons (mm)	SD (mm)	95% CI of the difference		<i>P</i> -value
	Posttreatment models vs. virtual setup (WSBF) <i>N</i> =9		Posttreatment models vs. virtual setup (PRBF) <i>N</i> =9				Min (mm)	Max (mm)	
	Mean	SD	Mean	SD					
<i>Maxillary model</i>									
<i>Anterior region</i>									
Minimum deviation	-1.907	0.443	-3.898	2.454	1.992	2.309	0.217	3.766	0.032
Maximum deviation	1.210	0.316	3.289	1.643	-2.079	1.570	-3.286	-0.873	0.004
RMS	0.442	0.125	0.944	0.332	-0.502	0.327	-0.754	-0.251	0.002
95th percentile	0.534	0.108	1.207	0.659	-0.673	0.673	-1.189	-0.156	0.017
<i>Maxillary model</i>									
<i>Intermediate region</i>									
Minimum deviation	-1.782	0.525	-4.419	3.174	2.637	3.142	0.221	5.052	0.036
Maximum deviation	1.496	0.534	2.352	0.886	-0.856	0.710	-1.402	-0.310	0.007
RMS	0.579	0.170	0.945	0.269	-0.366	0.273	-0.576	-0.155	0.004
95th percentile	0.887	0.363	1.150	0.522	-0.263	0.497	-0.645	0.119	0.151
<i>Maxillary model</i>									
<i>Posterior region</i>									
Minimum deviation	-1.473	0.476	-2.826	0.924	1.353	0.894	0.666	2.040	0.002
Maximum deviation	1.383	0.497	2.290	0.651	-0.907	0.787	-1.512	-0.301	0.009
RMS	0.443	0.193	0.880	0.301	-0.437	0.307	-0.672	-0.201	0.003
95th percentile	0.819	0.385	0.904	0.283	-0.085	0.343	-0.349	0.178	0.476

PRBF palatal rugae best fit, *WSBF* whole surface best fit, *SD* standard deviation, *min* minimum, *max* maximum, *95% CI* 95% confidence interval, *RMS* root mean square discrepancy

parameters studied on the posttreatment and virtual setup models than the WSBF superimposition method.

Discussion

In this study we used a new methodology of model superimposition to investigate the accuracy and predictability of conventional and virtual diagnostic setups. For the evaluation of the differences between the setups, tolerance limits (clinically relevant differences) are needed and these are subjectively described in the literature. Larson et al. [16] used mean discrepancies of 0.5 mm for mesiodistal, buccolingual, and vertical discrepancies and 2° for crown torque, tip, and rotation as a reference. Im et al. [15] considered a mean difference of 1° in the “tip” value between virtual setups and conventional setups as not clinically relevant. Grauer and Proffit [13] mentioned in their study where they compared the virtual setup to the final outcome of lingual appliance treatment that average differences less than 1.0 mm for translational discrepancies and less than 4° for rotational discrepancies were not considered clinically relevant.

From the literature, it can be concluded that the differences between conventional and virtual setups can vary between studies and between samples in a specific study. These differences mainly occur because of the subjective manufacturing technique of positioning the teeth [9]. Even though some guidelines have been described to prepare a setup [2], both the conventional and the virtual setup can differ when performed by different operators. The final setup will be based on the clinical experience of the orthodontist and even the same clinician can make a different setup when the setup procedure is repeated [9]. As there are different software programs available which use different procedures to make virtual setups, the setups made with the use of these programs can also differ [9]. The experience of the operator with a specific virtual setup software program may play a role. Thus, in this study only one orthodontist made the setups using only one software.

In this study, it was not possible to perform the model superimposition of the conventional and virtual setups using stable structures in the maxilla or mandible such as the palatal rugae [7, 8, 10, 19] or the mandibular torus [1] because these structures are removed during the conventional setup manufacturing. Furthermore, none of the selected pa-

tients had dental implants or temporary anchorage devices which could be used as a stable structure for superimposition. Therefore, the second molars, which were not moved during the manufacturing of both setups, were used as a stable reference for the model superimposition between the conventional and virtual setups. The WSBF superimposition method was compared with the stable structure superimposition method.

Our study showed that conventional and virtual setups differed when superimposed on each other dependent on the superimposition method. The second molar registration superimposition method presented more differences between the setups compared to the WSBF method, but only the maximum deviation in the anterior region of the mandible demonstrated a statistically significant difference (Table 1). In general, with both model superimposition methods, the anterior region showed mainly small differences in the incisors' anteroposterior relationship with more protrusion in the conventional setup models. In the vertical relationship there was more extrusion in the conventional setup models, and, in the intermediate and posterior regions, small differences were found in the transversal relationship with more expansion and more extrusion in the conventional setups compared to the virtual ones. However, considering the three regions studied, the differences for RMS were lower than 1.0 mm, with the exception of the anterior mandibular region with the second molar registration method, which was 1.066 mm (Table 1). These differences are within the threshold for translational discrepancies suggested by Grauer and Proffit [13]. There were no statistically significant differences between the two superimposition methods used for most parameters, and all differences were minimized using the WSBF method compared to the stable structure superimposition method (second molars not moved).

Our sample comprised class I nonextraction cases. Maybe a sample with class II, class III or extraction cases would show more and larger differences between conventional and virtual setups using the stable structure or WSBF superimposition methods because movements like protrusive and retrusive incisor movements and dental midline changes may be better evaluated using the stable structure superimposition method. Furthermore, the absence of interproximal collisions in the virtual setups can reduce the arch length and most likely the arch perimeter in these simulations [11]. Therefore, the digital setup process should be managed with delicate adjustments to avoid tooth collision in the proximal and occlusal contacts [11, 15].

It is important to compare the accuracy of conventional and virtual setups, but it is also paramount to verify their predictability. Therefore, the digitized posttreatment models were compared to both pretreatment setups by model superimposition from first to first molar in both arches because

the second molars were not moved in the conventional and virtual setups. In the maxillary models of virtual setups, two model superimposition methods were applied: WSBF and PRBF. Although the WSBF superimposition technique was used in other similar studies and showed high accuracy and reproducibility [13, 16–18], this method does not use a stable structure as a reference as all teeth usually move during orthodontic treatment. Best-fit methods are usually based on iterative closest point (ICP) algorithm. A study explained that the ICP algorithm fails to conduct a correct superimposition as soon as the two objects differ too much in their morphology [10], which is why studies which analyze dental movements during fixed appliance treatment frequently use stable structures as a reference for the model superimposition such as the palatal rugae [7, 8, 10, 19].

According to the superimposition by the WSBF method, the mean differences between the posttreatment and conventional setup models were, for most of the parameters, larger than the mean differences between the posttreatment and virtual setup models. However, with the paired *t*-test, most of these differences were not statistically significant in the three regions studied, except the maximum deviation parameter in the posterior region of the maxillary models, and the 95th percentile parameter in the intermediate region of the mandibular models (Table 2). From these results, it can be concluded that both the conventional and virtual setups can be efficiently used to visualize the treatment outcome because the RMS and 95th percentile differences between both setup modalities and the posttreatment models were small (mean differences were less than 1 mm) and not statistically significant. These differences can be considered not clinically relevant according to the literature [13].

In this study, the comparison between maxillary posttreatment and virtual setup models was also performed using the rugae registration as a reference [19]. The sample selection of this study, with cases without extractions, favors the preservation of the palatal rugae mesh anatomy in the virtual setup model due to minor incisor retrusion during the orthodontic treatment. Another movement that can change the palatal anatomy in a virtual setup is a large amount of arch expansion, which was also not performed in our sample. That is why we could use the medial 2/3 of the third rugae and a small area dorsal to them, which is considered a stable reference for the model superimposition [7, 10, 19]. We found statistically significant differences in the comparison of posttreatment and virtual setup models for nearly all parameters regarding the two superimpositions methods used (WSBF and PRBF). The WSBF superimposition technique presented smaller differences between the models compared to the PRBF superimposition method in all parameters (Table 3). This suggests that the WSBF method minimizes the differences between the models presumably because this technique uses an ICP algorithm to

align the posttreatment digital models and the setup models according to the best fit without considering stable structures as reference [10], which can mask the results.

Therefore, we conclude that the WSBF method can be used accurately to superimpose the same model created by different acquisition methods to analyze their possible differences [4, 14]. It is not wise to use the WSBF superimposition method to compare different models such as progress models during an orthodontic treatment or a planned setup model and a posttreatment model. In this case, it is important to establish stable structures as a reference to compare the dental positions. It is a challenge to establish stable references using only the teeth because they are frequently moved during an orthodontic treatment. Possibilities are to use dental implants or teeth that will not be moved according to the virtual plan in an aligner treatment. According to our study the superimposition with the PRBF method showed some vertical changes such as dental extrusions in the posttreatment models that are more difficult to predict in virtual planning. These changes can be caused by the orthodontic mechanics or as a result of the patient's growth. Therefore, it is fundamental to include the palatal area in every intraoral scan in order to allow future reliable follow-up model superimpositions.

The results of this study showed that the orthodontic treatment outcome will not be exactly the same as presented in the diagnostic setup. During each orthodontic treatment, complications such as an individual response to treatment mechanics, bony and/or periodontal restrictions, lack of cooperation in the use of extraoral appliances or elastics can cause a difference between the planned and the actual treatment outcome. These diagnostic setups should be used for patient communication and help care providers to finalize the treatment plan, and should not be presented as a precision tool for treatment outcome.

This study does not deal with therapeutic setups. Diagnostic and therapeutic setups are significantly different. Specifically, therapeutic setups are used to fabricate custom appliances, robotic bending of wires and clear aligner therapy, while diagnostic setups are used more to simulate the outcome. The question whether appliances designed based on therapeutic setups can consistently deliver the simulated outcome cannot be answered with the present study setup.

According to the results, the accuracy of conventional and virtual setups was similar compared to the posttreatment models according to the WSBF superimposition method. Therefore virtual setups could be selected as a preferred option to simulate treatment because of their advantages, which include the following: less time needed for making the setup; digital storage of the setup; easy data transfer; the possibility to show different treatment options with one set of digital dental models; the visualization of the tooth movement and the amount of tooth size reduction

needed; the possibility to undo planned dental movements and stripping performed; and the option to use the palatal rugae as a reference for model superimposition. Furthermore, the virtual setup is a valuable communication tool, using videos of the planned dental movements to show to the patient [5].

There are some limitations in this study. This study of diagnostic setups was performed retrospectively and it was restricted to class I Angle malocclusions treated without extractions. It is possible that predicted and final outcome differ more for class II and class III Angle malocclusions in growing patients because more assumptions must be made about growth and compliance. Furthermore, only intra-arch evaluations were performed in the superimpositions, and inter-arch changes could not be evaluated in this study. In addition, only the differences in the three segments of each arch were evaluated and not individual teeth positions.

We evaluated the differences between two model superimposition methods (best fit vs. stable structure reference) on the accuracy and predictability of conventional and virtual setups. Therefore, we can report that there are differences between them, but it is not possible to affirm which one is the most accurate. However, we understand that by using stable structures that were not moved during the orthodontic treatment as a reference the orthodontist will probably achieve more faithful results. Future studies on the accuracy and predictability of conventional and virtual diagnostic setups in orthodontics using the superimpositions methods proposed in this study should also focus on the evaluation of other malocclusions.

Conclusions

This study showed that the model superimposition method applied has an effect on the assessment of accuracy and predictability of setup models. There were statistically significant differences between the maxillary posttreatment and virtual setup models using the WSBF and the PRBF superimposition methods. The PRBF method showed larger differences between the models compared to the WSBF method. It is not possible to affirm which superimposition method used in this study is more accurate; however, in line with the literature, it will be important to establish stable structures as a reference to evaluate the accuracy and predictability of setup models.

Compliance with ethical guidelines

Conflict of interest L.T. Camardella, O.V. Vilella, K.H. Breuning, F. de Assis Ribeiro Carvalho, A.M. Kuijpers-Jagtman and E.M. Ongko-suwito declare that they have no competing interests.

Ethical standards Ethical approval was not required in the author's country as this was an observational study using routinely collected health data made pseudoanonymous. Written informed consent for publication of Figs. 1–5 was obtained from the patient or parents in case of minor.

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