

REGISTRATION OF ORTHODONTIC DIGITAL MODELS

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ABSTRACT

Current methods to assess outcomes and change in orthodontics are comparison of photographs, cephalometric measurements and superimpositions, and comparisons/measurements on dental casts. Digital models are a relatively new records modality in orthodontics. They offer numerous advantages in terms of storage space, spatial registration and superimposition. The purpose of this chapter is to determine the reproducibility of: 1) establishing occlusion of independently scanned digital models; and 2) registering digital models obtained after treatment on their homologous digital model setups produced before treatment. Reliability of both procedures was assessed with two random samples of five patient's models. In both experiments, three replicate positionings of the models per patient were created and variability in position was evaluated by the maximum surface difference between replicates, and the standard deviation of the surface distances between replicates respectively. Based on the data obtained, we concluded that it is reliable to register independently scanned models to a scanned surface of the models in occlusion. Surface-to-surface registration of final orthodontic digital models to planned setup models also is reproducible.

KEY WORDS: digital models, registration, digital orthodontic casts, orthodontic treatment outcomes, orthodontic tooth movement

Excellence in orthodontics depends on careful assessment of treatment outcomes. In order to evaluate and quantify changes, records and measurements are obtained at different time points and compared.

Current methods to assess outcomes and change in orthodontics are comparison of photographs, cephalometric measurements and superimpositions, and comparisons/measurements on dental casts. Photographs offer a qualitative assessment in orthodontics and are a valuable communication tool. However, due to the likelihood of different camera angulation during photograph acquisition, it is not practical to obtain

quantitative information for precise assessment of change (McKeown *et al.*, 2005).

Cephalometric superimpositions are the current gold standard for assessment of change in orthodontics and it has been shown that they provide great precision and accuracy (Björk, 1966; Johnston, 1996). Cephalometric measurements also can be compared to normative data (Hunter *et al.*, 1993). Their main disadvantage is that cephalometric radiographs are a two-dimensional (2D) representation of three-dimensional (3D) structures; due to the overlapping of the left and right sides of the dental arches, it is difficult to obtain a precise assessment of tooth movement.

Dental casts are the most frequently used 3D record in orthodontics and are, after the clinical evaluation, the most valuable orthodontic record (Han *et al.*, 1991). However, their physical nature prevents them from being superimposed in space and hence, only linear 2D measurements can be obtained. Moreover, they cannot be registered within the same coordinate system. Because we do not know the spatial relationship between models acquired at different time points, measurements of change are not directional. For example, we know that a change occurred between point 1 and point 2 but we do not know whether that change was due to movement of point 1, point 2 or both, and we cannot quantify the percentage of change at each point (Fig. 1).

The *American Board of Orthodontics* developed an Objective Grading System (OGS) in order to assess treatment outcomes in orthodontics (Casko *et al.*, 1998). This method has proven to be reliable and is now a standard method for orthodontic outcomes assessment. The OGS is based in linear measurements on dental casts and includes the disadvantages previously mentioned. A digital version of the OGS is currently under development but has not been validated yet (Okunami *et al.*, 2007; Hildebrand *et al.*, 2008).

Digital models are a relatively new records modality in orthodontics. They offer numerous advantages in terms of storage space, spatial registration and superimposition. Digital models are not different qualitatively from conventional dental casts in terms of diagnosis and treatment planning (Rheude *et al.*, 2005; Whetten *et al.*, 2006). Quantitatively, some differences have been found when comparing measurements between digital and dental casts, but these differences were not significant clinically (Motohashi and Kuroda, 1999; Tomassetti *et al.*, 2001; Bell *et al.*, 2003; Zilberman *et al.*, 2003; Quimby *et al.*, 2004; Stevens *et*

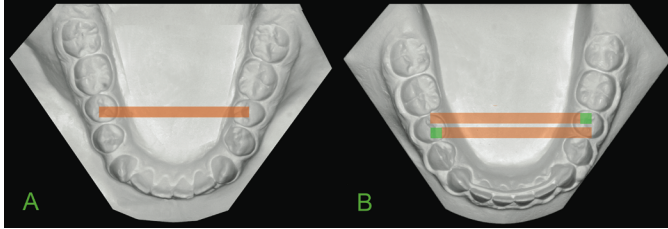


Figure 1. During treatment the width between the premolars and molars was increased. Dental casts allow for measurement of linear distances but not relative measurements. The orange bar represents the initial distance between second premolars (A). The green box represents the increase in interpremolar width (B). Measurements on dental casts do not allow for determination of whether interpremolar expansion occurred by the right premolar moving facially, the left premolar moving facially, or most likely both premolars moving facially.

al., 2006; Gracco *et al.*, 2007; Mullen *et al.*, 2007; Leifert *et al.*, 2009; Sjogren *et al.*, 2009).

Digital models of the same patient obtained at different times can be registered in the same coordinate system, which allows for assessing change among time points. The challenge is finding stable references across time to be used as registration structures (Choi *et al.*, 2010). The rugae region of the palate has been suggested as stable region (van der Linden, 1978; Almeida *et al.*, 1995; Bailey *et al.*, 1996; Hoggan and Sadowsky, 2001; Ashmore *et al.*, 2002; Cha *et al.*, 2007; Christou and Kiliaridis, 2008; Jang *et al.*, 2009). It seems that once these difficulties are overcome, digital models will offer a quantifiable, directional, accurate and reliable way of assessing change.

The purpose of this chapter is to: 1) determine the reproducibility of establishing occlusion of independently scanned digital models; and 2) determine the reproducibility of registering digital models obtained after treatment on their homologous digital model setups produced before treatment.

ESTABLISHING OCCLUSION WITH INDEPENDENTLY SCANNED DIGITAL MODELS

One method of creating digital models from dental casts involves scanning each dental cast upper and lower independently and then scanning the facial surfaces of both models in occlusion. This last scan is

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used as mutual information to reposition the independently scanned upper and lower models in a spatial relationship that reproduces the patient's occlusion.

Methods

Sample: In order to register the dental arches in space to represent the patients' occlusion, a sample consisting of pretreatment models of five patients was selected randomly from a population of 94 consecutively treated patients. The originating sample is composed of consecutive cases treated with Incognito™ lingual technique and debonded between January 2008 and January 2009. In order to create the scanned surfaces, poly-vinyl siloxane impressions were made with Bisico™ impression material (Bielefelder Dentsilicone GmbH & Co. KG, Bielefeld, Germany) and poured with Type IV extra hard white stone. Models were scanned with an ATOS optical scanner (GOM mbH, Braunschweig, Germany) at a spatial resolution of 20 microns. For each patient, three scans were created: one surface of the upper arch, one surface of the lower arch and one surface of the models in occlusion. The latter scan included only the facial aspect of the models in occlusion (Fig. 2A).

Software

The upper arch surface was registered to the corresponding buccal upper arch surface on the occlusion models using Occlusomatch™ software (TopService, 3M, Bad Essen, Germany). Parameters for the registration were set to select 2500 points on each surface and with a search radius of 1 mm (reduced to 0.25 mm, factor of 0.5 mm). Iterations were performed automatically until a 0.06 mm average surface distance was obtained. The success threshold was set at 0.06 mm (Fig. 2B). This two-step process was repeated three times per patient for each dental arch, rendering three positions for the upper dental arch and three positions for the lower dental arch. Dental arches were compared pair-wise and average surface distances were computed between homologous dental arches in Geomagic Studio™ 10.0 software (Geomagic US, Research Triangle Park, North Carolina). The variable of interest was the maximum surface distance between homologous dental arches as a proxy for the maximum discrepancy due to the registration process (Fig. 3).

Statistical Analysis

In order to assess whether the discrepancy in positioning varies by dental arch, the largest discrepancy in replicate positioning was analyzed

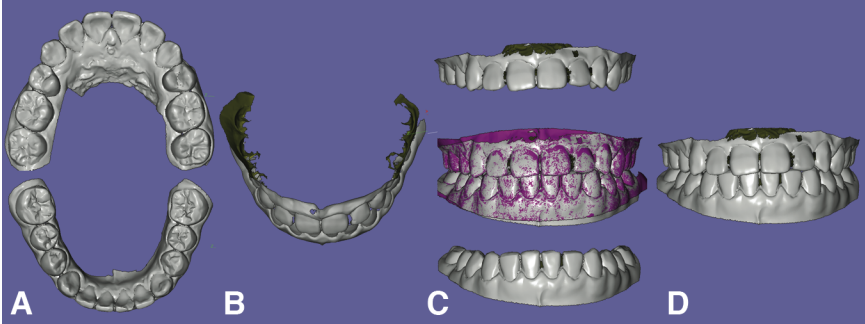


Figure 2. Independently scanned models (*A*) are registered using a scanned surface of the facial aspect of the models in occlusion (*B*). *C* and *D*: The scan of the models in occlusion is used only for the registration of the upper and lower models in occlusion.

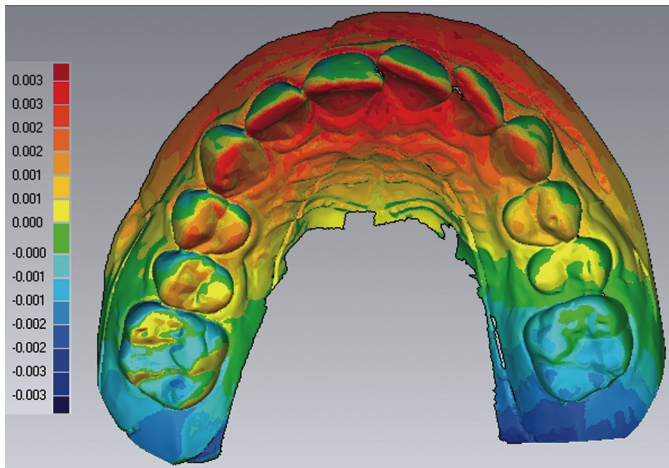


Figure 3. Three-dimensional comparison of the models is performed by Geomagic Studio™ 10.0 (Geomagic US, North Carolina). Replicate positions are compared based on the absolute value of the maximum distance between surfaces and graphically displayed as color maps. Color segments correspond to distance (mm) between surfaces.

using a repeated measures analysis, allowing for different compound symmetry covariance structures for each dental arch.

Results

The estimated maximum difference in replicate positioning is shown in Table I. Three positions per dental arch were compared pair-wise across patients. The summary of the statistical model analysis is displayed in Table 2.

Table 1. Estimated maximum difference in replicate positioning by dental arch.

Dental Arch	Estimate (mm)	Standard Error (mm)
Upper	0.007	0.003
Lower	0.009	0.004

Table 2. Type 3 tests of fixed effects.

Effect	DF	F-statistic	P-value
Dental Arch	1,24	0.21	0.65

These data suggest that there is no statistically significant difference between the upper and lower arches in the average discrepancy in replicate positioning and that there are no statistically significant differences between replicate positioning across the entire sample. Positioning the digital models in occlusion by using the scanned surface of the buccal surface of the models in occlusion is reproducible.

DISCUSSION

Even though it is likely that validation studies like this one have been conducted, we could not find any publication of a similar approach.

A second method to position the digital models in occlusion involves using a 3D surface scan of a wax bite – an interocclusal record – to obtain a reference to which the digital models could be registered in space. This method is based in registering the upper model to the upper surface of the wax bite and the lower model to the lower surface of the wax bite. The structures involved in this surface-to-surface registration are the upper and lower cusps and incisal edges in the digital models and their homologous indentations produced in the wax material while the patient bit on it. This second method requires surface-to-surface registration of complimentary surfaces (*e.g.*, dental cusps and indentations on the wax bite) rather than homologous surfaces (*e.g.*, facial surfaces of dental model in occlusion and not in occlusion); it is likely to involve a

greater error of the method due to approximation operations during the complementary surfaces registration.

A third method of establishing occlusion of the digital models would involve scanning the models mounted in an articulator. By using fiducial structures attached to the articulator, the relative position of the upper model to the lower model could be calculated. This is a potentially accurate method, but requires constant recalibration of the scanner to register the spatial position of the articulator to the scanner coordinate system.

Currently the scanned surface of the models in occlusion to register digital models (but with different registration parameters) is used widely by clinicians thanks to the introduction of in-office model scanners. The 3Shape model scanner (3Shape, Copenhagen, Denmark) is a relatively economical device that allows the user to scan models independently and in occlusion. Through the proprietary OrthoAnalyzer™ software, the user can establish the occlusion of the models and perform measurements, digital setup and export the models as non-proprietary files (stereolithography or .STL extension). It is important that when the models are locked in occlusion, this position remains the same throughout the entire scanning process. There are different devices to maintain the models in a fixed position while the scanner platform is moving to allow scanning of all surfaces of the models. Extreme care should be taken because a minimal movement of the models in occlusion during scanning will render a non-valid occlusion registration.

We have chosen the absolute value of the maximum discrepancy between surfaces (homologous dental arches were compared pair-wise in three replicate positioning) as our variable of interest. This variable is representative of the maximum error between registration instances and it may overestimate the error. However, given the small variability obtained, we considered it safer to overestimate rather than to underestimate. This small magnitude estimates for the upper and lower dental arch are not considered significant clinically.

Registration of Setup Models to Final Models to Assess Treatment Precision

Digital models offer a clear advantage over dental casts in assessing longitudinal changes given that they can be registered and superimposed in space (Jang et al., 2009; Choi et al., 2010). Among other methods of treatment results assessment in orthodontics, outcomes in orthodontics also can be assessed by comparing the obtained outcome

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with the planned setup. Spatial registration of the setup model on the final digital models is achieved by an iterative closest point (ICP) algorithm or “best fit” of surfaces. In order to evaluate the reliability of the ICP registration of setup models to their homologous final outcome model, the following study was accomplished.

Methods

Sample: In order to assess the reliability of registration of final digital models to digital models of initial setups, a second sample consisting of models of five patients was selected randomly from the population of 94 consecutive treated patients. For each patient two sets of models were available: final models post-orthodontic treatment obtained the day of bracket de-bonding and setup model made on a duplicate of the malocclusion models before orthodontic treatment. Models were scanned with an ATOS™ optical scanner (GOM mbH, Braunschweig, Germany) at a spatial resolution of 20 microns.

Software

Models were repositioned in space to reproduce their occlusion relationship using method described in the first part of this chapter. The surfaces were simplified to 50,000 points using the Qslim 2.0 tool (Garland and Heckbert, 1997) and then cleaned to delete the gingival tissues. Once simplified, the upper setup model was registered to the upper final model using eModel™ 9.0 software (Geodigm Corporation, Chanhassen, MN) to combine both models in the same coordinate system. The same process was followed for the lower setup model.

The registration process was repeated three times per dental arch, per patient, rendering three relative positions of the upper and lower setup arches to the final models (Fig. 4). Setup and final dental arch positions were compared pair-wise and average surface distance was computed between homologous record arches. The variable of interest was the absolute value of the standard deviation surface distance between final and setup models as a proxy of the average discrepancy due to the registration process.

Statistical Analysis

In order to assess whether the error in replicate positioning varies by dental arch, the standard deviation was used to summarize the deviation

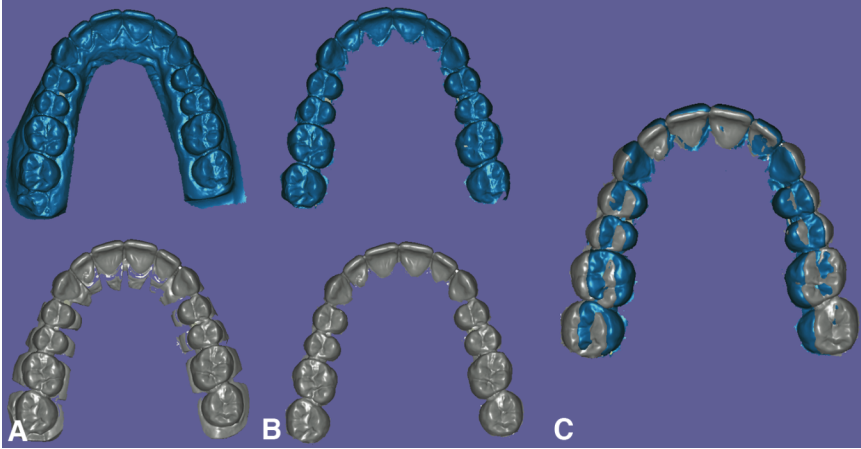


Figure 4. *A*: Final and setup orthodontic digital models are registered. *B*: The surfaces corresponding to the gingival tissues are removed. *C*: Registered digital models can be superimposed in space.

between replicates. A repeated measures analysis was performed, allowing for different compound symmetry covariance structures for each dental arch.

Results

The estimated maximum difference in replicate positioning is shown in Table 3.

The average difference in absolute value of the standard deviation was not different significantly from zero for the upper jaw ($P = 0.08$) or for the lower jaw ($P = 0.22$). The summary of the statistical model analysis is displayed in Table 4.

Table 3. Estimated standard deviation by dental arch.

Dental Arch	Estimate (mm)	Standard Error (mm)
Upper	0.07	0.04
Lower	0.05	0.03

Table 4. Type 3 tests of fixed effects.

Effect	DF	F-Statistic	P-Value
Dental Arch	1,24	0.15	0.71

These data suggest that there is no statistically significant difference between the upper and lower arches in the average discrepancy in replicate positioning and no statistically significant differences between replicate positioning across the entire sample.

DISCUSSION

Longitudinal change assessment using sequential digital models is based in the following process:

1. A coordinate system has to be defined;
2. Models from different time points must be registered to that coordinate system; and
3. Models are superimposed and the differences among them are evaluated.

In order to combine different records in the same coordinate system, stable structures – which did not change with time or treatment – are defined and used as registration regions. Once registered, structures that did change can be described qualitatively and quantitatively.

While the orthodontic community is waiting for a reliable longitudinal registration of sequential dental models to assess tooth movement, other methods to assess treatment outcomes are being used. The ABO OGS is a validated tool to assess orthodontic outcomes. Even though it is one of the best methods available at this point, it depends on fixed anatomical relationships rather than on actual tooth movement. Due to that limitation, its results often are influenced by the tooth anatomy.

Researchers have been looking for stable structures within the dental models to be used as registration landmarks or surfaces (Baumrind *et al.*, 2003; Beers *et al.*, 2003; Miller *et al.*, 2003; Kravitz *et al.*, 2009). The main problem using rugae as stable registration surfaces is that, as in any registration process, the further away from the registration surface a point is, the greater the registration error becomes (Cha *et al.*, 2007; Choi *et al.*, 2010). While the rugae may be reliable to assess tooth movement in the premolar region (mainly in cases treated with no extractions), it may not be precise enough to assess changes in the molar region. In addition, small changes in rugae morphology will have great effects on the relative vertical position of molars between time points. Recently Jang and colleagues (2009) compared the rugae registration method with registration on miniscrews placed in the maxilla and concluded that the medial points of the third palatal rugae and the palatal vault could be used as reference landmarks.

An efficient way to assess treatment outcomes, not tooth movement, would be to register and superimpose the models obtained after orthodontic treatment on the setup or planned correction. While this method does not allow for calculation of tooth movement due to treatment and growth, it does allow for calculation in the discrepancy between planned position and obtained position relative to intra-arch tooth alignment. The first step for such method is the establishment of reproducible registration method. ICP registration does not depend on stable structures, but rather utilizes the whole surface during the computation of the registration parameters. Given that the differences between surfaces (final treatment and planned setup) are relatively small, the registration error is divided among all teeth based on their size.

The reliability of this method depends on the relative initial position of the surfaces before registration process, because ICP registration uses optimization methods to identify a minimum surface distance value between surfaces. Given that the surfaces we register are similar but not equal, we have chosen the standard deviation as a proxy variable for the registration variability. If we use the average surface distance between surfaces, we would underestimate the error in registration because positive errors would cancel negative ones. The absolute value of the maximum distance between surfaces also is not representative of the discrepancy between registration instances given that the surfaces are not equal.

CONCLUSION

Based on the data presented above, it is reliable to register independently scanned models to a scanned surface of the models in occlusion. Surface-to-surface registration of final orthodontic digital models to planned setup models also is reproducible.

Further research is needed to establish the most stable landmarks/surfaces for longitudinal registration of sequential digital models. Once surfaces are registered, the difference between positions of individual teeth can be measured and expressed in terms of six degrees of freedom (Fig. 5).

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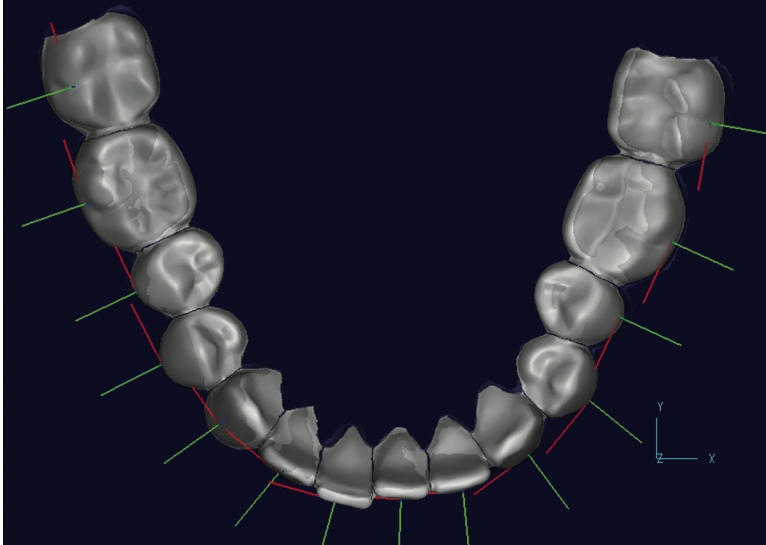


Figure 5. Once registered in the same coordinate system the six degrees of freedom describing tooth movement can be computed (Euler system). Computation of translation is based on the relative position of the tooth centroid. From eModel™ software (Geodigm Corporation, Chanhassen, MN). Computation of rotation is based on the relation of the local coordinate system of each tooth and the general coordinate system.

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