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On the augmented reproducibility in measurements on 3D orthodontic digital dental models and the definition of feature points

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Objective: The objective of this study was to explore digital measurement methodology on 3-dimensional (3D) dental models. Standardised manipulation and practices have lead to reliable measurements on plaster casts. Identifying landmarks on digital models or digitised plaster casts is fundamentally different from actual measurements. Three-dimensional models are represented on flat screens and landmarks are individually indentified. A procedure is proposed that resolves the deficiencies associated with a 2-dimensional (2D) display through an appropriate model representation and through local optimisation.
Methods: Fifteen models (OrthoProof) were exported to a locally developed 3D point indication software package, in which two measurement approaches were implemented involving standard projection with and without local search. Nine linear measurements were obtained from plaster casts and digital models. Statistical analysis included correlation and Friedman's non-parametric analysis of variance (ANOVA).
Results: For five out of nine linear measurements, digital indications yielded results significantly different from manual measurements (p = 0.05). Local search considerably improved measurement accuracy and reliability.
Conclusions: Measurements on plaster casts can differ significantly from those obtained through digital identification methods. These differences prove to be clinically relevant. Standardisation and optimisation resulted in improved and extremely reliable digital measurements.
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Introduction

Lateral cephalometric images, Cone Beam Computed Tomography (CBCT) images, when available, and 3D cast models provide the basis for orthodontic diagnosis and treatment planning. Three-dimensional digital models can be obtained without radiation exposure for the patient. This is achieved by micro-tomographic scanning of plaster models or impressions, or through the use of an intra-oral digitiser that allows for direct scanning of the patient's dentition.

While several studies on 3D models have recently been published, few compare manual linear measurements on dental plaster casts with their digital counterparts obtained using micro-tomographic scans.[1-4] Most often, more complexly-derived measures for crowding and alignment are compared and assessments based on measurements of individual teeth are used.[3] Digital models are gaining increasing acceptance as an alternative to traditional plaster models in orthodontics.

Although models are 3D, their digital representations are most often 2D. There is a lack of information regarding the impact of creating a 2D representation of a 3D measurement and also the identification of feature points on pseudo-3D representations. Several studies have determined that digital measurements may

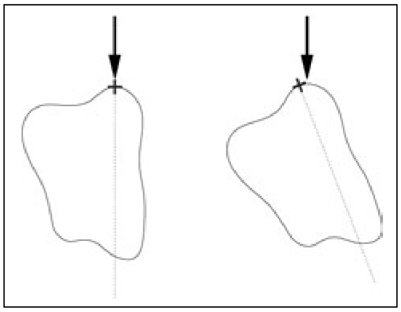

Figure 1. Indication of a tooth cusp using the horizontal plane as reference orientation (left) and the the same indication procedure applied on the inclined tooth (right).

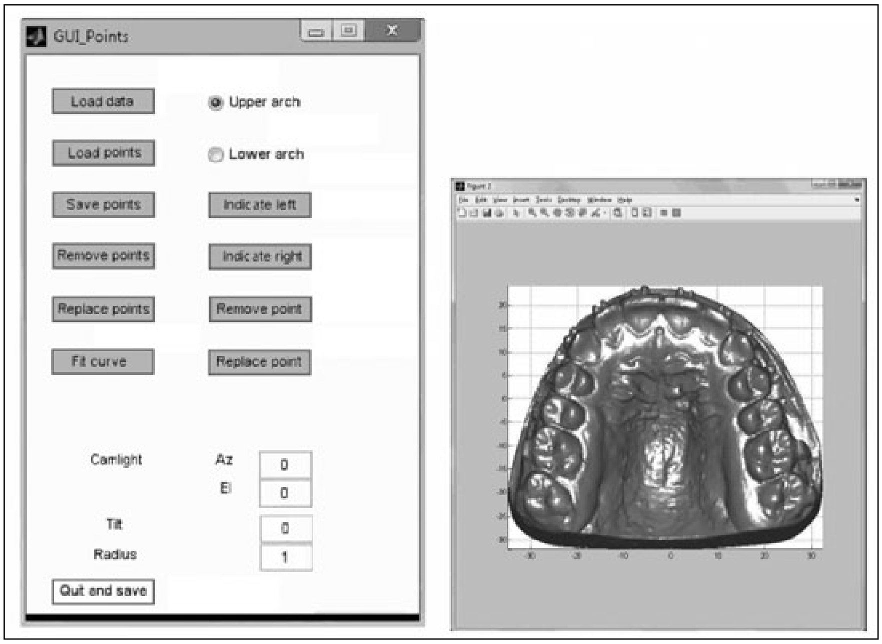

Figure 2. Left point indication GUI interface (left) and two dimensional pseudo 3D occlusal view of the 3D digital model of a plaster cast (right).

be significantly different from those made on plaster casts, but also considered that these differences were clinically insignificant.[4,5-8] The digital measurements were found to have comparable reliability or slightly less reliability compared with analogue measurements. A recent study by Dalstra et al. reported increased reliability of digital measurements on virtual models.[8] Schirmer and Wiltshire conducted digital linear measurements, including tooth measurements, on 2D digitised photocopies of plaster casts. Repeated digital linear measurements were almost identical (< 0.2 mm) when performed by a single examiner.[9] It was concluded that the computer-aided measurement system was reliable but not valid since the digital outcomes differed in a (clinically) significant way from corresponding manual measurements. Dalstra and Melsen established the reliability of digital 3D measurements through the reproduction of seven linear measurements repeated on a 2D representation of a 3D digital virtual model.[8] Good agreement was found between direct and the digital measurements. Because measurements were performed on the same 3D digital object represented two-dimensionally in a standardised way, the result had to be extrapolated with caution.

The accuracy of the identification of a feature point depends on several factors. Apart from technical issues, the definition of the feature point itself can be a major source of confusion. The definition of a cusp as an occlusal eminence on a tooth is inadequate for the unambiguous identification of a feature point that would indicate the location of the cusp. The highest point can only be defined with respect to a reference plane or an orientation (Figure 1). Traditionally, a plaster cast has, as a reference, the bottom of its base which is usually created parallel to the occlusal plane.

An additional source of uncertainty with respect to the identification of cusp tips is the 2D representation of 3D digital models on a flat computer screen. To create the impression of a 3D object based on a 3D digital model, a 2D image is produced by rendering its surface as illuminated by an imaginary light source (pseudo-3D). The reflection characteristics of the surface and the shadows resulting from its shape, create the illusion of three dimensionality. Reflections and shadows however, depend on the position of the light source, and consequently influence the indication of the tooth cusps.

The aim of the present study was to compare current general digital practice with a new digital technique that combines the skills of the practitioner with the opportunity to search for extrema provided by the digital representation. It is anticipated that the new digital technique would increase reliability, reduce dependency on the light source and lead to the exploitation of full 3D digital model information.

Materials and methods

Fifteen digital models were obtained from plaster casts scanned by OrthoProof® (Nieuwegein, the Netherlands) and exported to an in-house developed, Graphical User Interface (GUI)-based, 3D point-indication software package (Figure 2). The plaster casts were randomly accessed from the records of patients at the end of orthodontic treatment. Matlab (R2008a) (The MathWorks, Inc., Natick, MA, USA) provided the platform for the development of the GUI, model handling and statistical analyses.

Two point indication strategies were incorporated: the 'pure' standard projection and a standard projection combined with a local search for an extremum. For the identification of tooth-gingiva transitions, the latter approach was extended with an adaptive search space.

Indication of tooth cusps

The representation of the digital 3D model was orientated in an occlusal view (Figure 2-right) for the identification of standard features. A pseudo-3D rendered 3D model, created the illusion of an image seen by observing the model perpendicularly through a 2D window (i.e. the image plane displayed on screen) (Figure 3). The marking of a tooth cusp (*C'*) on the surface of this model was achieved by indicating a point *W* on the window (i.e. pointing with a mouse and clicking). In order to find the corresponding point *C'* in the 3D scene, a line was drawn perpendicular to the window through *W* and the intersection of this line (shown on Figure 3 as a white arrow) with the model is determined. This construction was called a 'standard projection'.

The optimised authentication of tooth cusps consisted of the identification of the cusp in the 2D occlusal view using standard projection, *C'* of the indicated point *W*, followed by a local search for the highest point *C* of the 3D model in the circular vicinity of *C* (optimised projection) (Figure 4). In all experiments involving tooth cusps, the radius of the circular vicinity was chosen to be one millimetre, under the assumption that it was likely that the operator would be able to identify the tip of the tooth cusp with an error of less than one millimetre, and that tooth cusps were, in general, at distances exceeding two millimetres.

The following tooth cusps were used: the cusps of the canines (3B), the buccal (4B) and palatal (4P) cusps of the first premolars, the buccal (5B) and palatal (5P) cusps of the second premolars, the buccal (6BM) and palatal (6PM) mesial cusps of the first molars and the buccal (6BD) and palatal (6PD) distal cusps of the first molars.

One orthodontist performed the linear measurements on the plaster casts (base standard), and digitally indicated all points twice at a time interval of four weeks. A second orthodontist digitally indicated all points once. Both projection methods were applied to the outcomes of the tooth cusp identifications by both orthodontists. Nine linear measurements were obtained from the original plaster casts using an analogue dental calliper (Zürcher Modell, accuracy 0.1 mm).

The nine linear measurements considered were:

One intercanine distance - the distance between:

- the cusps of the canines.

Four interpremolar distances - the distances between:

- the buccal cusp tips of the upper first and second premolars,
- the palatal cusp tips of the upper first and second premolars.

Four intermolar distances - the distances between:

- the mesiopalatal cusp tips of upper first molars,
- the mesiobuccal cusp tips of the upper first molars,
- the disto-palatal cusp tips of the upper first molars,
- the disto-buccal cusp tips of the upper first molars.

Statistical analysis was based on descriptive statistics, correlation analysis and Friedman's non-parametric ANOVA with the Tukey-Kramer difference criterion. For each of the 9 distance measurements, Friedman's ANOVA was applied to reveal differences between the 3 measurement methods under study, in which each of the 13 plaster casts defined one set of matching data.[10] Since the purpose of the test was to show significant differences within a pool of 9 measurements, the test required the multiplication of the significance level by 9 (a Bonferroni correction). In order to explore the reliability of the projection methods under different lighting conditions, both examiners identified the palatal cusps once for the simulated light source tilted 30 degrees to the left and once for the light source tilted 30 degrees to the right (all other experiments

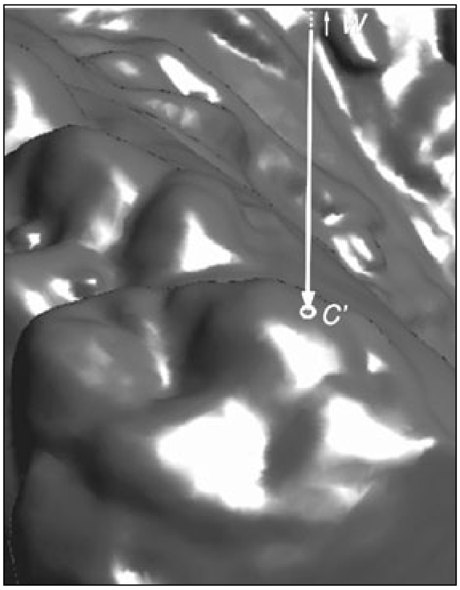

Figure 3. Standard projection: *C′*, a cusp point on the model surface is obtained by projection of the indicated point *W* perpendicularly to the 2D view onto the 3D model surface.

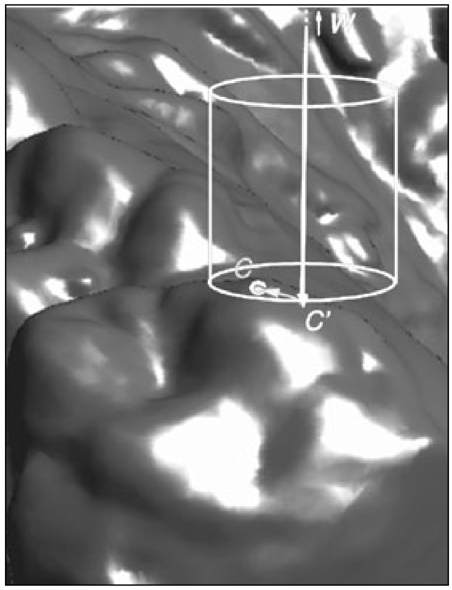

Figure 4. Optimised projection: *C*, the optimised version of *C′* is obtained starting from *C′* and searching for a local maximum of the model surface in a search area bounded by a cylinder with a prespecified radius.

were conducted with a central light source). Wilcoxon signed rank tests were performed, with a Bonferroni correction, on the absolute values of the differences of the coordinates.

Results

Linear measurements between dental cusps

Despite the small sample size, for five out of the nine linear measurements, those based on the digital indications were significantly different from the base standard (p = 0.05) (Table I). The local search increased the minimal test-retest correlation for the digital linear measurements from r = 0.978 to r = 0.998 (Table II). The minimal correlation for a digital linear measurement between the two examiners was r = 0.960 for the standard projection and r = 0.991 for the local search algorithm (Table II).

Influence of lighting

All mean absolute differences differed significantly for all but one measurement (Wilcoxon signed rank, N = 30, p = 0.05 with Bonferroni correction) and were systematically lower for the optimised projection (Table III).

Discussion

Fleming et al. stated that 'digital models offer a valid alternative to plaster models, although the available evidence is of variable quality'.[3] The present findings indicate that, in order to guarantee that individual measurements will not differ significantly from a clinical viewpoint, additional error factors need to be taken into consideration.

The results regarding reliability presented by Schirmer and Wiltshire, and Dalstra and Melsen matched the present findings which established the need for standardisation of lighting and view to obtain reliable measurements.[8,9] If lighting was not controlled, errors in linear measurement could increase up to (0.66 ± 0.41 mm) for one coordinate (Table III, y6D value). The benefits of 3-dimensionality need to be assessed, if the identification of feature points and measurements on digital models is performed on standardised 2D representations of those models. A significant advantage of a 3D model is that it permits a comprehensive visual check by the rotation of the 3D image, along with the indicated feature point, to eliminate gross identification errors. Moreover, from the 3D digital models, mathematical and algorithmic definitions and calculations of feature points and measurements can be derived.

Table I. Mean distance between corresponding tooth cusps for the base standard, the standard projection method, and the optimised projection method.

	Base standard (mm)		Standard projection (mm)		Optimised projection (mm)		
	Mean	SD	Mean	SD	Mean	SD	S
6BM	52.5	2.5	52.7	2.5	52.2	2.4	7.54
6BD	53.7	2.5	51.7	2.5	51.4	2.3	21.38 a
5B	48.2	2,0	47.4	2.2	47.2	2.0	17.23 a
4B	43.5	2.0	42.6	2.0	42.4	1.7	18.00 a
3B	35.8	1.4	35.0	1.7	35.3	1.2	12.15 a
6PM	41.1	2.8	41.0	2.6	40.8	2.5	2.92
6PD	41.4	2.8	40.7	2.4	40.6	2.5	11.23 a
5P	37.3	2.0	37.2	1.8	37.2	1.8	0.46
4P	32.6	1.5	32.7	1.5	32.5	1.5	2.92

Column S= scores for Friedman's ANOVA test variable, obtained for each of the corresponding interdental distance measures
a = significantly different (Friedman – Bonferroni corrected, N = 13, k = 3, a = 0.05, S > 9.846 (see Table A.22 Hollander and Wolfe 1973)[10]

Table II. Correlations for both projection methods, between on the one hand the first measurement by the first expert and on the other hand the base standard, the second measurement by the first expert, and the first measurement of the second expert.

	Standard projection correlation first measurement first expert with			Optimised projection correlation first measurement first expert with		
	Base standard (mm)	Second measurement First expert (mm)	Measurement Second expert (mm)	Base standard (mm)	Second measurement First expert (mm)	Measurement Second expert (mm)
Cusps						
6BM	0.451	0.824	0.890	0.363	0.978	0.934
6BD	0.773	0.934	0.934	0.751	0.978	0.978
5B	0.884	0.890	0.912	0.840	0.912	0.956
4B	0.729	0.846	0.846	0.796	0.934	0.956
3B	0.744	0.934	0.846	0.833	1.000	1.000
6PM	0.692	0.978	0.934	0.714	0.978	1.000
6PD	0.729	0.912	0.956	0.663	1.000	1.000
5P	0.824	0.978	0.912	0.824	0.956	0.956
4P	0.811	0.868	0.868	0.922	0.978	0.978

Table III. Absolute values of differences between the point indication with the light coming from the left and the light coming from the right on coordinate level.

	Mean	SD	Mean	SD
x6M	0.16	0.15	0.05	0.11 a
y6M	0.28	0.28	0.10	0.28 a
z6M	0.06	0.08	0.01	0.03 a
x6D	0.18	0.18	0.05	0.13
y6D	0.33	0.29	0.11	0.35 a
z6D	0.03	0.05	0.01	0.02 a
x5	0.15	0.12	0.01	0.04 a
y5	0.18	0.17	0.02	0.06 a
z5	0.03	0.03	0.00	0.00 a
x4	0.18	0.12	0.00	0.00 a
y4	0.23	0.22	0.00	0.00 a
z4	0.04	0.04	0.00	0.00 a

a = significantly different (Wilcoxon signed rank, $N = 30$, $p = 0.05$ with Bonferonni correction).

Since the information contained within the model can be easily detailed far beyond the precision of the original cast, it is possible to improve reliability and accuracy beyond the thresholds considered as clinical relevant. Clinically relevant measurements in orthodontics range from 0.2 mm up to 1 mm: 0.20 mm (Schirmer and Wiltshire),[9] 0.27 mm (Bell et al.),[11] 0.30 mm (Hirogaki et al.),[12] 0.5 mm (Quimby et al.),[6] while manual measurements are typically performed with 0.1 mm tolerance. Even if statistical testing reveals no significant difference at a group level, the variation for a single patient may be extreme. With the assumption of normality and zero difference for two measurement methodologies, a standard deviation of 0.3 mm means that, for approximately 5% of cases, the difference between measurements will exceed 0.6 mm. A standard deviation of 0.5 mm means that, for approximately 5% of cases, the difference between the measurements will exceed 1 mm. Therefore to take measurements that are reliable for an individual patient, it is necessary to use digital models and exploit their digital nature to create appropriate measurements and procedures. This digital nature provides the opportunity to introduce novel measurements and to eliminate undesired variability.

A change of artificial lighting between measurements significantly altered points identified on artificial 2D representations of 3D models. The position of the light source should be consistent with respect to the point to be identified in order to obtain measurements that exceed the precision and reliability of manual measurements. Therefore, the direction of light should always be clear to the user identifying the measurement points. As well as the influence of shading, the resolution of the mesh or the preservation of the sharpness of features during digitalisation and post processing could influence the accuracy of measurements.[13]

Conclusion

It is concluded that:

Manually taken linear measurements on plaster casts can differ significantly from measurements obtained through the described digital identification methods.

Through standardisation, extremely reliable digital measurements can be achieved.

Local search improves reliability and significantly reduces the influence of lighting, notably when tooth cusps need to be indicated.

Conditions regarding the representation of the 3D models should be clear to the user.

The present study showed that clinically relevant errors in 3D digital measurements can be limited through a controlled protocol in combination with calculation methods exploiting the digital nature of 3D models.

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