A Novel Methodology to Validate the Accuracy of Extraoral Dental Scanners and Digital Articulation Systems

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A Novel Methodology to Validate the Accuracy of Extraoral Dental Scanners and Digital Articulation Systems

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ABSTRACT

Purpose: The aim of the current study is to develop a novel method to investigate the accuracy of 3D scanners and digital articulation systems. Materials and Methods: An upper and a lower poured stone model were created by taking impression of fully dentate male (fifty years old) participant. Titanium spheres were added to the models to allow for an easily recognisable geometric shape for measurement after scanning and digital articulation. Measurements were obtained using a Coordinate Measuring Machine to record volumetric error, articulation error and clinical effect error. Three scanners were compared, including the Imetric 3D iScan d104i, Shining 3D AutoScan-DS100 and 3Shape D800, as well as their respective digital articulation software packages. Stoneglass Industries PDC digital articulation system was also applied to the Imetric scans for comparison with the CMM measurements. Results: All the scans displayed low volumetric error (p>0.05), indicating that the scanners themselves had a minor contribution to the articulation and clinical effect errors. The PDC digital articulation system was found to deliver the lowest average errors, with good repeatability of results. Conclusion: The new measuring technique in the current study was able to assess the scanning and articulation accuracy of the four systems investigated. The PDC digital articulation system using Imetric scans was recommended as it displayed the lowest articulation error and clinical effect error with good repeatability. The low errors from the PDC system may have been due to its use of a 3D axis for alignment rather than the use of a best fit.

INTRODUCTION

Digital dentistry is becoming the new standard for dental restorations due to its high productivity, reliability and cost-effectiveness.[1] It involves a Computer-aided Design/Computer-aided Manufacturing (CAD/CAM) process with three steps: data acquisition, data processing and manufacturing. Data acquisition involves either intraoral scanning directly from the mouth of the patient, or extraoral scanning of a stone model poured from a patient bite impression.[1]

The underlying principle of 3D scanning involves capturing many 2D images using a pair of cameras, which are used to gauge the distance of the captured surface from the camera. Point clouds are created from these images which are then merged into a triangle mesh. Data processing software is then used to digitally articulate the scanned models and convert the point cloud to a digital 3D image in the form of a stereolithography file (STL).[2] This data processing can introduce errors in the 3D scanned models which add to any errors brought about during the scanning process.[2,3] Due to this, it is difficult to determine whether the scanning process, the data processing, or a mixture of the two, causes the observed errors.

Thus, the most critical point in the CAD/CAM process is data acquisition and processing, as inaccurate data will always cause poor-fitting dental restorations to be produced with shorter lifetimes, irrespective of the quality of the material or manufacturing process.[4] Due to this, scanning accuracy in digital dentistry has been investigated in the literature using physical[4-8] and digital[9,10] best fit methods.

The physical best fit methods involve measuring any gap between the final manufactured restorations and either a replica model or a reference die, at particular predetermined locations of single unit teeth.[4-8] The issue with using a die as a reference is that it does not accurately represent in-vivo conditions, and the issue with selecting points of measurement for various single unit teeth is that the geometry of each tooth is different which does not provide a standardised reference.

The digital best fit methods involve a best fit procedure between the scanned point cloud data and the reference point cloud data of a master scan.[9,10] This method introduces error as the reference data itself is subject to unknown measurement errors originating from the scanning process. Various best fit algorithms will also alter the results which undermines the accuracy of the results, and therefore the conclusions drawn, in studies which utilise this method. Various studies reference the advertised manufacturers' error of each scanner,[4-10] however a single micron measurement cannot completely describe the capabilities of a scanner. This is due to scanner errors varying depending on the geometry of the model and the size of the model. Thus, quoting the advertised error of a particular scanner and incorporating it into the results does not validate these results, as the advertised error itself does not accurately encapsulate the capabilities of the scanner.

The current study proposes a novel methodology for validating the accuracy of both 3D scanners and digital articulation systems. It incorporates a holistic analysis of the accuracy of a scanner with a mixture of volumetric error (as commonly measured in engineering applications), articulation error and clinical effect error, which arise from both the scanning stage and the digital articulation stage.

MATERIALS AND METHODS

Models of both the upper and lower jaw were created from the impressions of fully dentate male (fifty years old) participant (Alginoplast, regular set). Six titanium spheres (10mm diameter) were milled and attached to the upper and lower casts which acted as geometrically recognisable reference points for measurement, as spheres have been found to deliver the most accurate results in 3D scans.[11] Three spheres were glued to the upper cast and three spheres were glued to the lower cast (Araldite) using pockets which were added to the casts (*Figure 1*a). A Coordinate Measuring Machine (CMM/ Figure 1b-c) (Discovery II D-8) was then used to obtain accurate measurements of the upper and lower spheres separately. Ten points were measured on each sphere using the touch probe of the CMM, with nine points being measured around each sphere and the tenth point at the top of each sphere. The dimensions of a column (Splitex Key) were also measured using the CMM, which was fabricated to accurately represent the exact height of a particular articulator (*Figure 2*) (Artex). Three points were measured with the CMM touch probe on each side of the articulator column to create two planes. Two points on each edge of each side at the same height, were measured using the CMM touch probe to create four lines on both sides of the column.

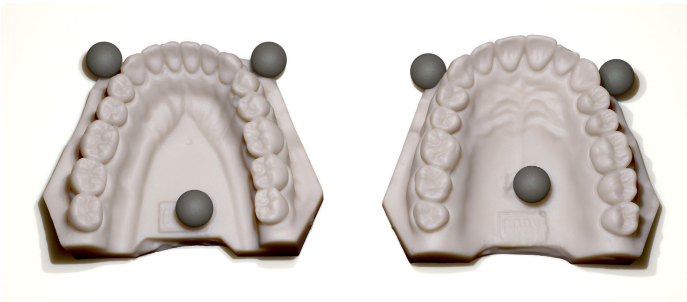

Figure 1a: Upper and lower models with spheres

Figure 1b and c: The measurement of the implant features for each model was completed using a Sheffield Discovery II D-8 Coordinate Measuring Machine (CMM). As shown in Figure 3 the CMM was fitted with a Probing System comprising a Renishaw PH6A Probe Head, TP20 Medium Force Body and a ø1mm Stylus.

Figure 2: Articulator column

The CMM data were imported into a CAD package (PowerSHAPE) whereby measurements between sphere centres could be more easily measured, and the articulation of both the upper and lower models could be obtained based upon the column measurements. The column measurements were converted to 3D planes to assist in the alignment. The models were articulated in the CAD package by creating a plane through the midpoint of the two anterior spheres, with the x-axis related to the incisal line in both models *(Figure 3)*. The axis of the upper model was then rotated about the axis of the articulator which was created based upon the column measurements. Twenty-nine measurements between the sphere centres as measured on the CMM were recorded in the CAD package. These measurements were used as a reference for each measurement in this experiment.

The models were then scanned twice in each of the iScan d104i (Imetric 3D), the AutoScan-DS100 (Shining 3D) and the D800 (3Shape). Each of the scans were then digitally articulated using the respective alignment software of each scanner. The digital articulation system, PDC (Stoneglass Industries), was also used for the digital articulation of the IScan d104i scans. Reference scans of the poured models were also taken using the AutoScan-DS100 and the IScan d104i scanners. These were created by manually digitally articulating the separately scanned models using 3D axes in a CAD package. The results from the reference scans are expected to be very similar to the CMM results, which will confirm the validity of using 3D axes to articulate the CMM results for comparison.

The STL files of the aligned models were imported into an STL viewing and editing package (CopyCAD) to manually extract the point cloud of each sphere. To find the centres of each sphere for measurement, the point cloud of each sphere was parsed into an algorithm which implemented a least-squares method for minimising error.[12] These centres were then imported into the CAD package to compare against the CMM reference results by obtaining twenty-nine measurements as illustrated in Figures 4-7. The measurements from four digital articulation systems were assessed by comparing the scanned measurements (volumetric error, articulation error and clinical effect error) to the reference CMM measurements.

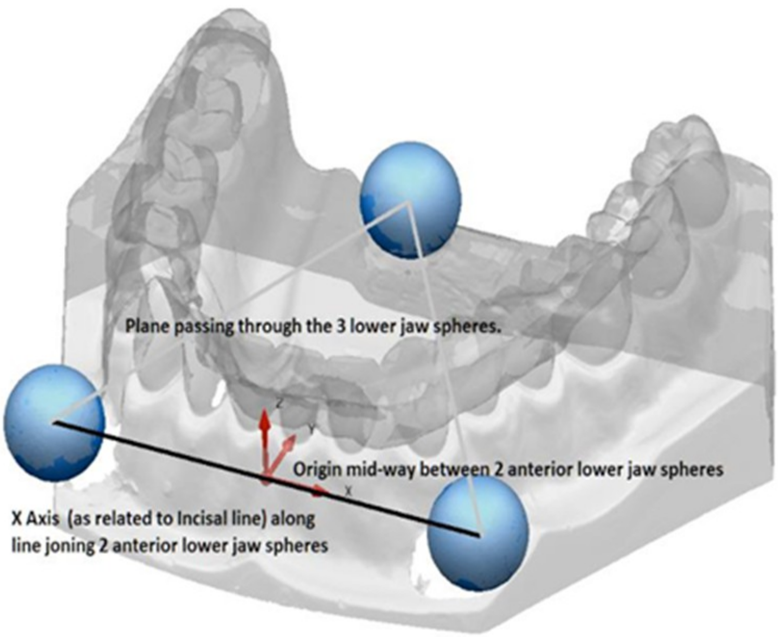

Figure 3: Creation of a plane for digital articulation using the centres of the spheres

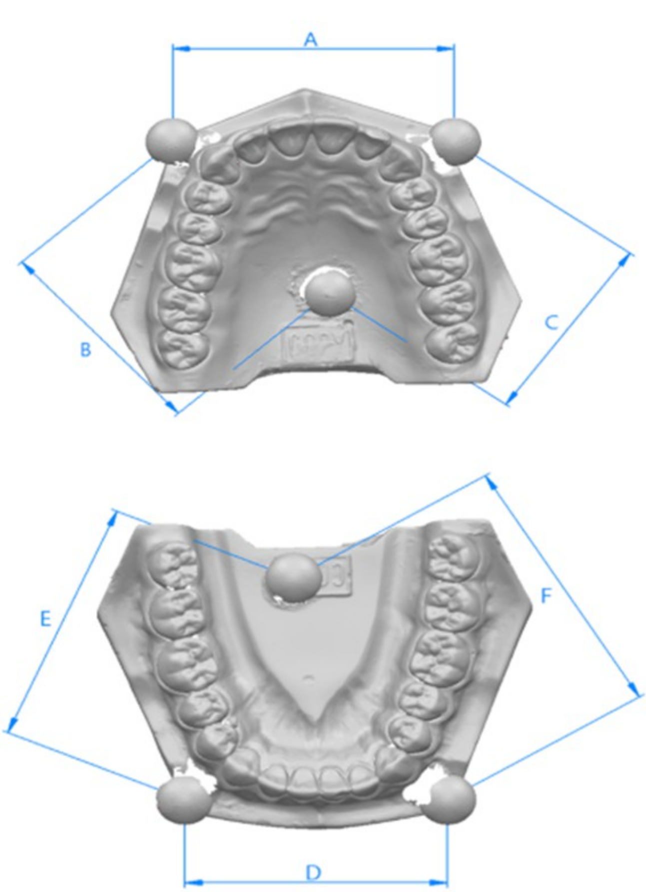

Figure 4: Volumetric measurement dimensions

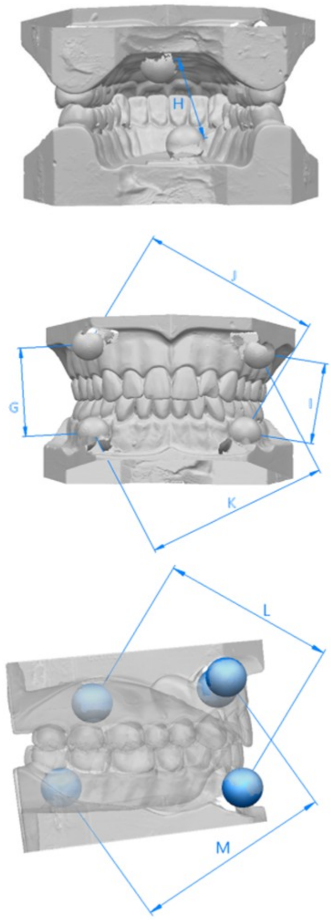

Figure 5: Articulation measurement dimensions

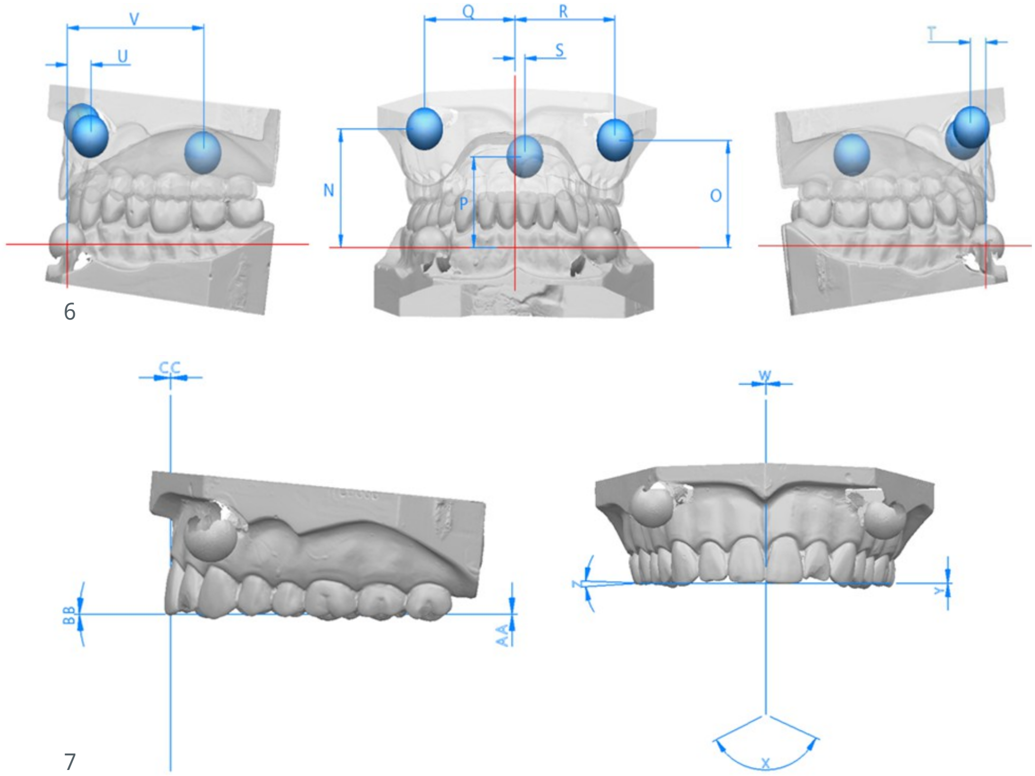

Figure 6 and 7: Clinical effect measurement dimensions

All measurements recorded from scan 1 and 2 using three scanners were statistically analysed using ANOVA followed by *post hoc* Tukey's test. Level of significance was set at 0.05.

RESULTS

The results corresponding to the measurements of each scan are displayed in Table 1. A graph of the average errors of each digital articulation system is displayed in Figure 8.

Volumetric error is the distance error present between specific points on a model in 3 Dimensions. Volumetric error results purely indicate the accuracy of a scanner without the effects of digital articulation. All the scans displayed low volumetric error (p>0.05), indicating that the scanners themselves had a minor contribution to the articulation and clinical effect errors.

Articulation error is the error present in the representation of occlusion in a digital articulation system. The PDC system displayed the lowest articulation error in the current study. The 3Shape and Shining systems displayed similar articulation errors, though the Imetric system displayed the highest error. However there is no significant (p>0.05) difference between the four tested groups in each scan

Clinical effect error is defined in the current study as error, which is clinically relevant, including errors in the midline, vertical dimension, occlusal plane, incisal plane and incisal edge. PDC was found to have the lowest clinical effect error in the current study which is significantly (p=0.044) different from the Imetric system *(Table 2*). The Shining system displayed lower clinical effect error than the Imetric and 3Shape systems, which both displayed similar clinical effect errors.

Repeatability indicates that an articulation system provides consistent results between scans. From Figure 7 it is clear that across both scans conducted, the volumetric errors of all four digital articulation systems had similar repeatability. The articulation error also had similar repeatability in all digital articulation systems except for the Imetric system, which had significantly poorer repeatability. The clinical effect error had good repeatability in the PDC and Shining systems, though the Imetric and 3Shape systems displayed poor repeatability.

The reference scans displayed very small errors compared to the CMM values, which validates the process of digitally articulating the CMM models using 3D axes from the Splitex Key in the CAD package.

DISCUSSION

There are many data processing packages available for digital articulation, which introduce errors into the process, adding to the error originating from the scanning and post-processing. Volumetric error accounts for inaccuracies of distances between specific points on a model, which indicates the ability of a scanner to maintain volumetric relationships between different points on a model. A high volumetric error could indicate errors in the ridge line, centreline or tooth alignment, which will greatly affect the fit and longevity of the final restoration. Articulation error is introduced in the data processing stage during the digital articulation. Articulation error indicates the measurement error of the upper and lower models between the digital articulation and the true analogue articulation using poured stone models. A high articulation error will affect the contact points, and thus, the overall comfort and effectiveness of the dental restoration. The clinical effect error is defined as a multitude of errors regarding the midline, vertical dimension, smile line, occlusal plane and the incisal edge. A high clinical effect error will cause discomfort and reduce the effectiveness of the restoration, which may require chairside alteration. Together, these three error objectives describe the accuracy of a scanner and alignment software in greater detail than other methodologies in the literature, while pertaining to a clinical application.

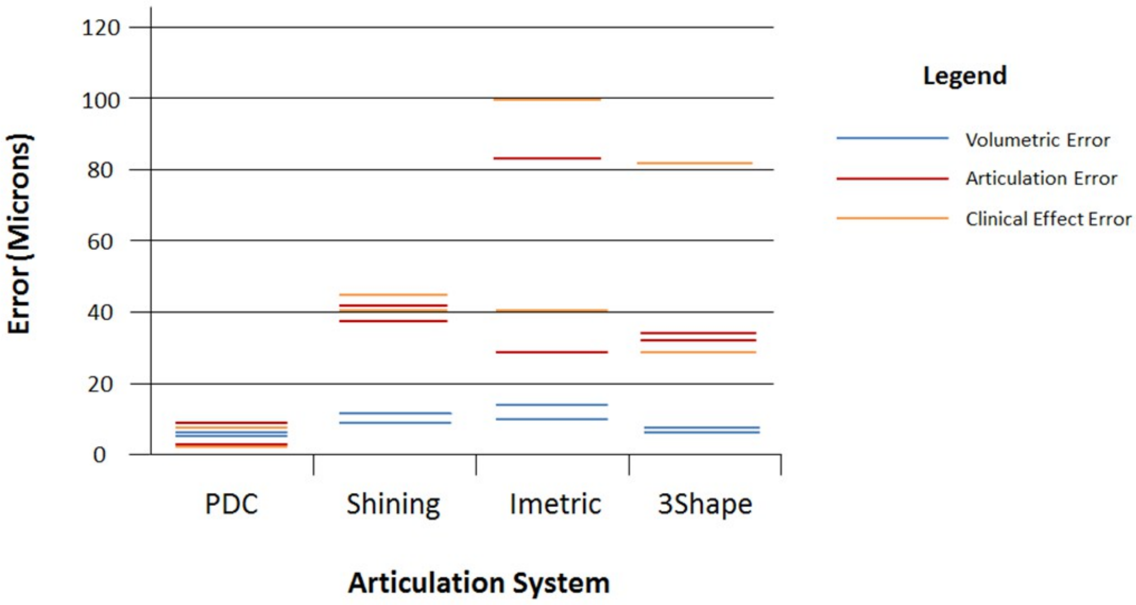

Figure 8: Average error of each digital articulation system across both scans

Table 1. Measurements and errors of each scan (millimetres) compared to CMM Reference results

			Shining 1 Reference		Imetric 1 Reference		PDC Imetric 1		PDC Imetric 2		Shining 1		Shining 2		Imetric 1		Imetric 2		3Shape 1		3Shape 2	
		Reference	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error	Meas-ure	Error
Volumetric Error Measurement	A	51.5062	51.5173	0.0111	51.5060	0.0002	51.5104	0.0042	51.5106	0.0044	51.5126	0.0064	51.5157	0.0095	51.5058	0.0004	51.5074	0.0012	51.5061	0.0001	51.5092	0.0030
	B	42.7400	42.7504	0.0104	42.7403	0.0003	42.7474	0.0074	42.7477	0.0078	42.7500	0.0100	42.7489	0.0089	42.7471	0.0072	42.7478	0.0078	42.7329	0.0070	42.7350	0.0050
	C	38.9993	39.0095	0.0102	38.9976	0.0017	38.9963	0.0030	38.9977	0.0016	39.0122	0.0129	39.0106	0.0113	39.0000	0.0007	39.0098	0.0105	38.9966	0.0027	38.9957	0.0036
	D	45.6224	45.6282	0.0059	45.6235	0.0012	45.6260	0.0037	45.6239	0.0016	45.6373	0.0150	45.6340	0.0117	45.6380	0.0157	45.6381	0.0158	45.6227	0.0004	45.6257	0.0034
	E	47.7460	47.7576	0.0116	47.7478	0.0018	47.7497	0.0037	47.7521	0.0061	47.7634	0.0174	47.7586	0.0126	47.7758	0.0298	47.7633	0.0173	47.7146	0.0314	47.7279	0.0181
	F	51.3345	51.3374	0.0029	51.3411	0.0066	51.3427	0.0082	51.3407	0.0062	51.3525	0.0180	51.3449	0.0104	51.3690	0.0345	51.3566	0.0221	51.3432	0.0087	51.3338	0.0007
	AVERAGE			0.0087		0.0020		0.0050		0.0046		0.0133		0.0107		0.0147		0.0125		0.0084		0.0056
	STD DEV			0.0032		0.0032		0.0026		0.0031		0.0058		0.0018		0.0170		0.0105		0.0157		0.0087
Articulation Accuracy Measurements	G	27.9389	27.9405	0.0016	27.9401	0.0012	27.9401	0.0012	27.9458	0.0069	27.9324	0.0065	27.9320	0.0069	27.9369	0.0020	27.9307	0.0082	28.0017	0.0628	27.9825	0.0436
	H	23.4058	23.4183	0.0126	23.4097	0.0040	23.4130	0.0073	23.4222	0.0165	23.2987	0.1070	23.2898	0.1159	23.1210	0.2847	23.3330	0.0727	23.4059	0.0002	23.4127	0.0070
	I	26.0522	26.0535	0.0013	26.0532	0.0010	26.0530	0.0008	26.0621	0.0099	26.0389	0.0133	26.0838	0.0316	26.0840	0.0318	26.0444	0.0078	26.1296	0.0774	26.1321	0.0799
	J	54.8231	54.8305	0.0074	54.8235	0.0004	54.8264	0.0033	54.8176	0.0055	54.8655	0.0424	54.8750	0.0519	54.8583	0.0352	54.8504	0.0273	54.8821	0.0590	54.8888	0.0657
	K	56.0648	56.0723	0.0075	56.0652	0.0004	56.0683	0.0035	56.0817	0.0169	56.0362	0.0286	56.0470	0.0178	56.0623	0.0025	56.0501	0.0147	56.0756	0.0108	56.0681	0.0033
	*L**	*49.1767*	*49.2019*	*0.0252*	*49.1952*	*0.0185*	*49.2004*	*0.0237*	*49.2073*	*0.0306*	*49.1604*	*0.0163*	*49.1587*	*0.0180*	*49.1814*	*0.0047*	*49.1701*	*0.0066*	*49.1831*	*0.0064*	*49.1891*	*0.0124*
	M	52.6843	52.6964	0.0121	52.6856	0.0013	52.6890	0.0047	52.6957	0.0114	52.6492	0.0351	52.6529	0.0314	52.5333	0.1510	52.6511	0.0332	52.6743	0.0100	52.6760	0.0083
	AVERAGE			0.0071		0.0014		0.0035		0.0112		0.0388		0.0426		0.0845		0.0273		0.0367		0.0346
	STD DEV			0.0045		0.0012		0.0022		0.0043		0.0329		0.0356		0.1027		0.0224		0.0304		0.0304

* This result was not able to be measured reliably on the CMM, therefore was omitted from comparison of results

table 1 continued overleaf...

...table 1 continued

Table 1. Measurements and errors of each scan (millimetres) compared to CMM Reference results

	N	27.6180	27.6190	0.0010	27.6180	0.0000	27.6185	0.0005	27.6260	0.0080	27.5977	-0.0203	27.5968	-0.0212	27.5811	-0.0369	27.5987	-0.0193	27.6742	0.0562	27.6526	0.0346
	O	24.9850	24.9840	-0.0010	24.9850	0.0000	24.9845	-0.0005	24.9905	0.0055	24.9851	0.0001	25.0223	0.0373	24.9933	0.0083	24.9952	0.0102	25.0682	0.0832	25.0776	0.0926
	P	21.1650	21.1630	-0.0020	21.1650	0.0000	21.1661	0.0011	21.1761	0.0111	21.0374	-0.1276	21.0491	-0.1159	20.8726	-0.2924	21.0584	-0.1066	21.1623	-0.0027	21.1727	0.0077
	Q	24.3840	24.3900	0.0060	24.3840	0.0000	24.3861	0.0021	24.3731	-0.0109	24.4319	0.0479	24.4453	0.0613	24.4201	0.0361	24.4143	0.0303	24.4171	0.0331	24.4354	0.0514
	R	27.0100	27.0150	0.0050	27.0100	0.0000	27.0119	0.0019	27.0245	0.0145	26.9739	-0.0361	26.9635	-0.0465	26.9798	-0.0302	26.9873	-0.0227	26.9792	-0.0308	26.9667	-0.0433
	S	2.7120	2.7120	0.0000	2.7140	0.0020	2.7208	0.0088	2.7256	0.0136	2.7309	0.0189	2.6933	-0.0187	2.7387	0.0267	2.7576	0.0456	2.6935	-0.0185	2.7007	-0.0113
	T	3.9250	3.9250	0.0000	3.9250	0.0000	3.9235	-0.0015	3.9166	-0.0084	3.9981	0.0731	3.9952	0.0702	4.1465	0.2215	3.9864	0.0614	3.9567	0.0317	3.9648	0.0398
	U	6.0760	6.0800	0.0040	6.0630	-0.0130	6.0748	-0.0012	6.0796	0.0036	6.0419	-0.0341	6.0875	0.0115	6.1965	0.1205	6.0147	-0.0613	6.0802	0.0042	6.0616	-0.0144
	V	36.3420	36.3500	0.0080	36.3230	-0.0190	36.3414	-0.0006	36.3423	0.0003	36.3510	0.0090	36.3695	0.0275	36.4684	0.1264	36.3328	-0.0092	36.3405	-0.0015	36.3366	-0.0054
	AVERAGE			0.0023		-0.0033		0.0020		0.0084		0.0408		0.0456		0.0999		0.0407		0.0291		0.0334
	STD DEV			0.0033		0.0069		0.0025		0.0044		0.0369		0.0310		0.0941		0.0299		0.0256		0.0264
Clinical Effect Measurements	W	Mid Line Error (+ve = upper moved to patient left)						0.0002		-0.0140		0.0450		0.0390		0.0228		0.0290		0.0244		0.0340
	X	Mid Line Angle Shift						0.0030		0.0010		0.0334		0.0770		0.0730		0.0420		0.0372		0.0710
	Y	Anterior / Incisal Edge Vertical Dimension Error (+ve = upper raised)						0.0001		-0.0050		-0.0293		-0.0700		-0.0424		-0.0160		-0.1026		-0.1090
	Z	Smile Line / Incisal Plane Angle Shift (front view)						0.0037		0.0010		0.0330		0.0760		0.0722		0.0420		0.0372		0.0710
	AA	Posterior / Occlusion Vertical Dimension Error (+ve = upper raised)						0.0020		-0.0120		-0.1279		-0.1180		-0.2957		-0.1070		-0.0057		-0.0040
	BB	Occlusal Plane Angle shift (side view)						0.0030		0.0100		0.2126		0.2270		0.5098		0.1850		0.1359		0.1070
	CC	Incisal Edge Protrusive Error (+ve = upper moved distally)						0.0010		-0.000007		0.0390		0.0220		-0.0292		0.0500		0.0199		0.0170

* This result was not able to be measured reliably on the CMM, therefore was omitted from comparison of results

Table 2. Measurement errors means and standard deviations of the tested groups in the current study

	PDC Imetric		Shining System		Imetric System		3 Shape	
Type of Error	Scan 1 Errors	Scan 2 Errors	Scan 1 Errors	Scan 2 Errors	Scan 1 Errors	Scan 2 Errors	Scan 1 Errors	Scan 2 Errors
Volumetric Measurement errors	(0.0050 ± 0.0026)	(0.0045 ± 0.0031)	(0.0132 ± 0.0058)	(0.0107 ± 0.0018)	(0.0147 ± 0.0170)	(0.0124 ± 0.0104)	(0.0083 ± 0.0156)	(0.0056 ± 0.0087)
Articulation Accuracy Measurements errors	(0.0034 ± 0.0021)	(0.0111 ± 0.0043)	(0.0388 ± 0.0328)	(0.0425 ± 0.0355)	(0.0845 ± 0.1026)	(0.0273 ± 0.0223)	(0.0366 ± 0.0304)	(0.0346 ± 0.0303)
Clinical Effect Measurements errors	(0.0020 ± 0.0024)[a]	(0.0084 ± 0.0044)	(0.0407 ± 0.0369)	(0.0455 ± 0.0310)	(0.0998 ± 0.0940)[a]	(0.0407 ± 0.0298)	(0.0291 ± 0.0255)	(0.0333 ± 0.0263)

Groups in the same row with similar superscript letter are significantly different $p<0.05$

The novel methodology proposed in the current study determines the accuracy of various extraoral scanners and alignment processes by comparing the results to the reference measurements of a poured stone model created from a conventional bite impression of fully dentate male (fifty years old) participant, which was measured using a CMM. The model was modified to include recognisable geometry for accurate and reliable measurements, while still closely representing in-vivo conditions before measurements were taken.

The use of a single pair of poured stone model jaws allows for a valid experiment, whereby an identical model was scanned using each scanner within a short timeframe. Another advantage of this methodology is the use of CMM results for reference, rather than a die[4-8] or a master scan.[9,10] The spheres attached to each jaw act as a standard of measurement regardless of the geometry of the jaw, which validates the methodology as well as ensuring repeatability across experiments. This methodology has been developed to introduce the concept of metrology into dental research, and thus, deliver more accurate, repeatable and valid scientific results which will inform the efficacy of dental technologies. Metrology is defined as the science of measurement, which cover both experimental and theoretical variables and can confirm the measurement at any type of technology.[12]

Intraoral scanners were not used as they have been shown to be inaccurate for full arch scans.[13] Also, for the application of complete dentures, intraoral scanners are not effective for edentulous patients.[14] Recently, Rehmann *et al.*[15] investigated the need for calibration of intraoral scanners, which was not an included feature of the intraoral scanner software in their experiment. They found errors between intraoral scan results of the same model over 18 months with no calibration. This indicates poor repeatability which is an expected result as extraoral scanners must be calibrated each day to maintain accuracy and repeatability as an included software feature.

For measurements of error originating from the digital articulation, namely the articulation and clinical effect errors, the PDC system displayed the lowest observable error of the four digital articulation systems in the current study. This is most likely due to the creation of the upper and lower jaw axes, as well as the articulator axis playing a key role in this articulation system. The other alignment software packages in the current study may not include these factors and instead may rely on a purely best fit method using the scanned point cloud. The PDC system also displayed good repeatability overall, indicating that the results from the PDC system are repeatable and consistent.

Due to the high accuracy and repeatability of the PDC digital articulation system, the current study recommends PDC for digital articulation. This brings forth the argument that the data acquisition and data processing steps in the CAD/CAM process should rely on an analogue measurement from a CMM to create axes to align the data, rather than relying on a digital best fit. Analogue measurement also serves to increase the repeatability of the results obtained, as the alignment does not purely rely on point cloud data which varies greatly upon each scan.

Further, the minor effect of the scanning accuracy on the results of the articulation and clinical effect errors indicates that the current research priority should be placed upon digital articulation systems rather than scanner accuracy. Chang *et al*[16] have published one of the very few studies in this field and have provided two algorithms: one which transforms the upper and lower models from the scanner coordinate system to a singular coordinate system, and one which minimises the distance between the models to obtain maximal tooth contact without collision. However, these methods will not be effective for edentulous patients as it requires the location of tooth cusps for the final occlusion, and has also provided higher errors than the PDC system in the current study.

The clinical implications of a highly accurate scan and digital articulation system are patient comfort, restoration longevity and a reduction of chairside modifications. For the application of digital dentures, this can affect the masticatory performance of patients[17] and can cause destruction of the residual alveolar ridge as bone remodels to protect soft tissue from excess pressure originating from incorrect occlusion.[18] This highlights the importance of an accurate scan and digital articulation for all CAD/CAM dental restorations and especially digital dentures, as the quality of the milled denture rests on scanner and digital articulation accuracy.

A limitation of the current study is that the scans from the Shining 3D AutoScan-DS100 and 3Shape D800 scanners were not digitally articulated with the PDC system to examine whether the PDC system improved on the articulation of the models compared to the digital alignment software included with the Shining and 3Shape scanners. A minor limitation was the inability to accurately provide a reference measurement for dimension L due to physical inaccessibility when using the CMM.

Future research should incorporate this novel methodology to rigorously validate the accuracy of 3D scanning and digital articulation systems. The PDC articulation system should be further examined and compared to other digital alignment systems, to confirm the recommendations of the current study. A greater number of cases should also be compared to identify whether these results will vary across different models.

CONCLUSION

Within the limitation of the current study, the following can be concluded:

1. A novel methodology for validating the accuracy of 3D scanners and digital articulation systems was proposed.
2. The PDC digital articulation system using Imetric scans was recommended as it displayed the lowest articulation error and clinical effect error with good repeatability.
3. Scanning accuracy represented by volumetric error had a minor effect on the accuracy of the digital articulation, represented by articulation error and clinical effect error.

MANUFACTURERS' DETAILS

- **Alginoplast, regular set**

Heraeus Kulzer GmbH *Leipziger Straße 2 63450 Hanau, Germany*

- **Araldite**

Selleys Pty Ltd 1 *Gow St, Padstow NSW 2211 Australia*

- **Discovery II D-8**

Sheffield Measurement *Cedar House, 78 Portsmouth Rd, Cobham KT11 1AN, UK*

- **Splitex Key**

Amann Girrbach AG *Herrschaftswiesen 1 6842 Koblach, Austria*

- **Artex**

Amann Girrbach AG *Herrschaftswiesen 1 6842 Koblach, Austria*

- **PowerSHAPE**

Autodesk (previously Delcam Ltd.) *Small Heath Business Park, Talbot Way, Birmingham B10 OHJ, UK*

- **iScan d104i**

Imetric 3D SA *Le Bourg 9 2950 Courgenay, Switzerland*

- **AutoScan-DS100**

Shining 3D 1398 *Xiangbin Rd, Wenyan, Xioshan, Hangzhou, Zhejang, China*

- **D800**

3Shape A/S *Holmens Kanal 7 1060 Copenhagen, Denmark*

- **PDC**

Stoneglass Industries *Unit 26 11-21 Underwood Rd, Homebush NSW 2140 Australia*

- **CopyCAD**

Autodesk (previously Delcam Ltd.) *Small Heath Business Park, Talbot Way, Birmingham B10 OHJ, UK*

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