

An Investigation into the Trueness and Precision of Copy Denture Templates Produced by Rapid Prototyping and Conventional Means

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Authors

Dr. Krishan Davda *
(BChD)

Cecilie Osnes *
(BA (Hons) MSc)

Sean Dillon *
(BSc (Hons) PGCE)

Dr. Jianhua Wu *
(BSc (Hons) PhD)

Dr. Paul Hyde *
(BChD PhD MGDS RCS(Eng))

Dr. Andrew Keeling *
(BDS BSc(Hons) PhD MFGDP RCS (Eng))

Address for Correspondence

Dr. Andrew Keeling *

Email: a.j.keeling@leeds.ac.uk

* Leeds School of Dentistry

ABSTRACT

Objective. To assess the trueness and precision of copy denture templates produced using traditional methods and 3D printing. *Material and methods.* Six copies of a denture were made using: 1. Conventional technique with silicone putty in an impression tray (CT). 2. Conventional technique with no impression tray (CNT). 3. 3D scanning and printing (3D). Scan trueness and precision was investigated by scanning a denture six times and comparing five scans to the sixth. Then the scans of the six CT, CNT and 3D dentures were compared by aligning, in turn, the copies of each denture to the scanned original. *Outcome measures* were the mean surface-to-surface distance, standard deviation of that distance and the maximum distance. Student's unpaired t-tests with Bonferroni correction were used to analyse the results. *Results.* The repeated scans of the original denture showed a scan trueness of 0.013mm (SD 0.002) and precision of 0.013mm (SD 0.002). *Trueness:* CT templates, 0.168mm (0.047), CNT templates 0.195mm (0.034) and 3D 0.103mm (0.021). *Precision:* CT templates 0.158mm (0.037), CNT 0.233mm (0.073), 3D 0.090mm (0.017). For each outcome measure the 3D templates demonstrated an improvement which was statistically significant ($p < 0.05$). *Conclusions.* 3D printed copy denture templates reproduced the original with greater trueness and precision than conventional techniques.

INTRODUCTION

Conceived and developed in the latter half of the last century¹⁻¹³, the 'copy denture technique' continues to be advocated and used in current dental practice¹⁴⁻¹⁸ to provide cost effective replacement dentures. The templates for the copy denture technique have been produced in a number of ways^{8,10,12,15}. All these traditional ways of producing the copy denture template involved a physical impression of the denture to produce a mould and a subsequent pouring of a cast or template in wax or acrylic of the patient's denture. Recently, new technology has enabled these templates to be produced by optical scanning of the patient's denture and 3D printing the shape of the original denture.

The main advantage of using a copy denture technique is the potential for rapid adaptation by the patient to the familiar shape of their original denture. However, the work of Kippax¹⁹ and Polyzois²⁰ has shown that the traditional techniques of producing the copy denture template produce in-

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herent inaccuracies. This is primarily due to setting contraction of the materials used.²⁰ Polyzois²⁰ states "In making dentures by the duplicating technique, the dimensional accuracy of the replicas is of the utmost importance". Optical scanning and 3D printing has been advocated as an alternative technique to produce the copy denture template and it holds the possibility of being more accurate.²¹ Other digital manufacturing methods using both additive and subtractive processing have been reviewed in detail elsewhere.²²

The aim of this research is to investigate and compare the accuracy of traditional copy denture techniques with the relatively new technology of scanning and 3D printing a copy denture template. Accuracy is defined in terms of 'trueness' and 'precision'. The null hypotheses for this research is that there is no difference in trueness and precision between traditional manufacture and digital manufacture. Trueness indicates how closely a measure reflects the real value. Precision indicates the similarity of multiple repeated measures. It is important to remember that a single comparison between two dentures entails sampling many thousands of points on each surface. These measurements allow for a calculation of mean trueness (the mean deviation of one surface from the other) and mean precision (the standard deviation of the trueness). In this sense, "trueness" is only a comparison between the two 3D scanned dentures, and there exists the potential, for example, for an undetected systematic scanning error.

MATERIALS AND METHODS

Six copies of a single upper complete denture were reproduced by the three methods (two conventional and one digital) under investigation. The first method used a traditional 'copy denture technique' including the use of impression trays to provide support for the material. The second method used unsupported impression material. In both conventional methods, impressions of the polished surface of the denture were recorded using a laboratory silicone putty which is condensation-cured. Petroleum jelly was applied to the surface of the set putty, and a second mix of putty was applied to the fitting surface to obtain a complete impression of the denture. The original denture was removed, and a template created using a self-curing acrylic.

The digital method reproduced the denture using 3D scanning and printing as follows. Firstly, the denture was scanned in a structured light scanner. To accomplish this, the denture was lightly powdered to prevent reflection artefacts. The fitting surface and polished surface were scanned separately, and the two scans aligned and merged.

A 3D-printable file (STL file format) was then created by re-sampling the surface using Poisson surface reconstruction in Meshlab software. To print the denture template, structural supports were digitally added using Nauta software before the file was imported into Fictor software which controlled the stereolithographic 3D printer. The printer supported a minimum slice thickness of 10 microns, an x-y resolution of 50 microns. The build angle was kept off the long axis, typically

by 20 degrees. The printer resin used was DS3000, which is bio-compatible and carries a CE mark (which permits intraoral use of the resin for temporary medical devices in human subjects). This entire process was repeated using the same methodology in the same environment to produce six printed copy denture templates.

To validate the measurement protocol, the trueness and precision of the scanning process was investigated by scanning the same denture six times. The first scan was designated as the 'baseline scan'. Each of the subsequent five scans was compared to the baseline. The scan of each of the five dentures was digitally measured against the scan of the original denture by using the Hausdorff distance filter in Meshlab. This method sampled >500,000 points over the surface of each denture, measuring the unsigned distance to the closest point on the surface of the original denture scan. The mean unsigned distance between each denture template to the original was calculated; this mean was used as the outcome measure for the 'trueness' of the scan. The standard deviation of the unsigned mean distance for each comparison was calculated; this standard deviation was used as the outcome measure for the 'precision' of the scan. The maximum distance between each pair of scans was also recorded. These 3 outcome measures (mean unsigned distance, standard deviation of that mean and the maximum distance) together allow a clinically relevant assessment of trueness and precision.

After the validation of the measurement protocol, the accuracy of all the copy dentures were assessed using the outcome measures described for 'trueness', 'precision' and 'maximum error' (the latter being the true Hausdorff distance – the largest deviation between the two surfaces). Six dentures produced by each construction method (3D, CT and CNT) were investigated by comparing scans of templates to the original denture scan.

The analysis of the trueness and precision of the new dentures was restricted to the analysis of the teeth and polished surfaces; the fitting surface was ignored. This is because in all clinical techniques for new dentures, the fitting surface is redefined by a new impression (it is not copied). Therefore, a virtual template was used to specifically 'trim' the fit surfaces on each template and leave only the polished surfaces and teeth. Preparation and analysis of all scans was automated using batch scripts and MeshlabServer to ensure consistency and reduce human error.

The difference in 'trueness', 'precision' and 'maximum distance' between the test groups was assessed using Student's unpaired t-tests with Bonferroni correction, respectively.

To aid clinically relevant understanding, quantified colour maps of the dentures were produced which illustrated where, and by how much, each denture differed from the original. This enabled potential identification of the typical patterns in the distributions of errors over the denture surface for each type of denture.

An overview of the different methods for creating copy templates is shown Figure 1.

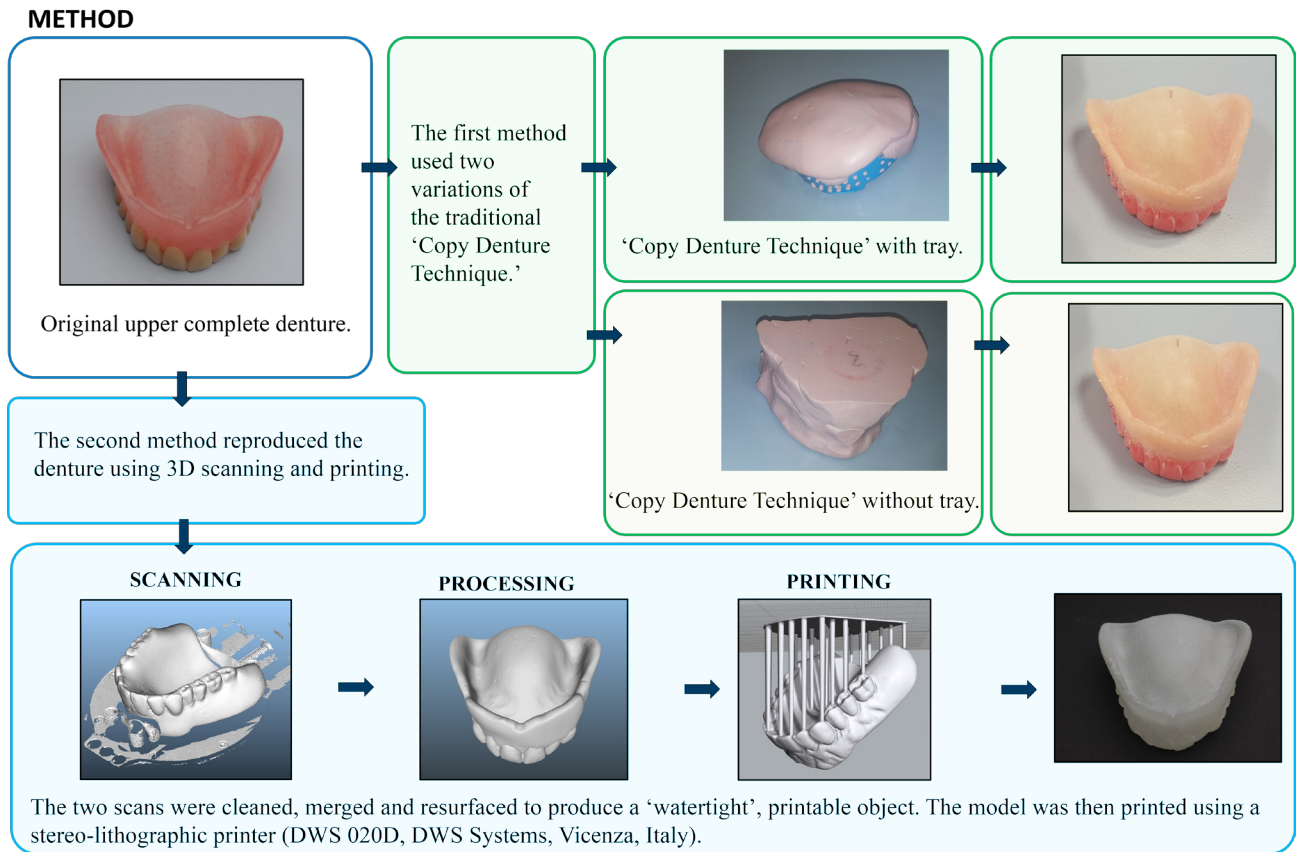


Figure 1: Overview of the methods for creating traditional, and 3D printed, copy denture templates.

RESULTS

SCANNER PRECISION

The five separate scans of the single upper complete denture are compared to a sixth scan in Table 1.

Table 1. The mean trueness, precision and maximum error of five scans of the same denture.

Validation of measurement protocol	
No. of copies	5
Trueness (mean (sd))	0.013 (0.002)
Precision (mean (sd))	0.013 (0.002)
Maximum Error (mean (sd))	0.421 (0.028)

TRUENESS AND PRECISION OF EACH METHOD OF DENTURE PRODUCTION

The trueness, precision and maximum error of each method of denture production compared to the scan of the original denture are shown in Table 2. The trueness, precision and

maximum error of each denture production method are statistically analysed against each other method and statistically significant results are highlighted in Table 2.

The overall mean of the unsigned error (trueness), mean of the standard deviation of the unsigned error (precision) and mean of the maximum error was significantly lower with the 3D printed templates compared to both methods of traditional copy production ($p < 0.05$). There were no statistically significant differences between the two traditional methods of denture production (see comments in discussion section).

COLOUR MAPPING OF THE RESULTS

Typical colour maps of the errors produced by each method of denture template production are shown in Figures 2-4. The visual comparisons of the colour maps showed distinctive distributions of error within the different groups. An upper limit of 0.5mm was set to highlight an obvious discrepancy in the copy template that may be picked up in a clinical setting. Both CT and CNT templates showed errors on polished surfaces, most noticeably in the palate (Figure 2) and heels of each template (Figures 2 and 3). The colour maps of the 3D printed templates illustrate high accuracy over the polished surfaces with the largest errors located on the teeth, usually in positions where printing supports had been placed (Figure 4).

Table 2. Trueness, precision and maximum error for each method of denture template production with statistical analysis: *represents significant difference at $p < 0.05$, ** represents significant difference at $p < 0.01$

Differences between the 3D printed copies and the traditional copies with tray, when each denture is compared to the original denture

	3D printed copy	Traditional copy with tray	Difference (95% CI)	P-value
No. of copies	6	6		
Trueness (mean (sd))	0.103 (0.021)	0.168 (0.047)	-0.065 (-0.116, -0.015)	0.036*
Precision (mean (sd))	0.090 (0.017)	0.158 (0.037)	-0.068 (-0.107, -0.028)	0.013*
Max Error (mean (sd))	0.669 (0.073)	1.212 (0.214)	-0.543 (-0.768, -0.319)	0.030*

Differences between the 3D printed copies and the traditional copies without tray, when each denture is compared to the original denture

	3D printed copy	Traditional copy without tray	Difference (95% CI)	P-value
No. of copies	6	6		
Trueness (mean (sd))	0.103 (0.021)	0.195 (0.034)	-0.092 (-0.129, -0.055)	0.001**
Precision (mean (sd))	0.090 (0.017)	0.233 (0.073)	-0.143 (-0.219, -0.066)	0.014*
Max Error (mean (sd))	0.669 (0.073)	2.139 (0.901)	-1.470 (-2.415, -0.525)	0.021*

Differences between the traditional copies with and without tray, when each denture is compared to the original denture

	Traditional copy with tray	Traditional copy without tray	Difference (95% CI)	P-value
No. of copies	6	6		
Trueness (mean (sd))	0.168 (0.047)	0.195 (0.034)	-0.027 (-0.080, 0.027)	0.298
Precision (mean (sd))	0.158 (0.037)	0.233 (0.073)	-0.075 (-0.154, 0.003)	0.058
Max Error (mean (sd))	1.212 (0.214)	2.139 (0.901)	-0.927 (-1.870, 0.017)	0.053

DISCUSSION

COMPARING THREE DIMENSIONAL SURFACES

There is currently no consensus in the dental literature over which method for comparing 3D surfaces yields the most clinically relevant information. When comparing over 500,000 points over two surfaces, the unsigned mean error gives an indication of how similar two surfaces are – a measure of trueness between the two virtual surfaces. The standard deviation of that unsigned mean error gives an indication of the variation in surface fit – an indication of the precision.

However, with closed-form surfaces, such as the dentures used here, the maximum error may be of more clinical relevance. For example, a localised over-extension may be clinically problematic; causing trauma. Where there is an overextension, a comparison using the means of absolute error or the standard deviation of the mean error might indicate an almost perfect copy. This is because the region of error is only a fraction of one percent of the entire surface of the denture, so its influence in the final comparison will be small; its significance will be lost in the 500,000+ points analysed. For this reason, we report the maximum error alongside the more traditional measures. Furthermore, these maximum errors are valid because they are not formed by stray scanning points or noise; the printable, surfaced 3D files constitute a fully processed dataset, with all noise removed, and all 3D processing completed.

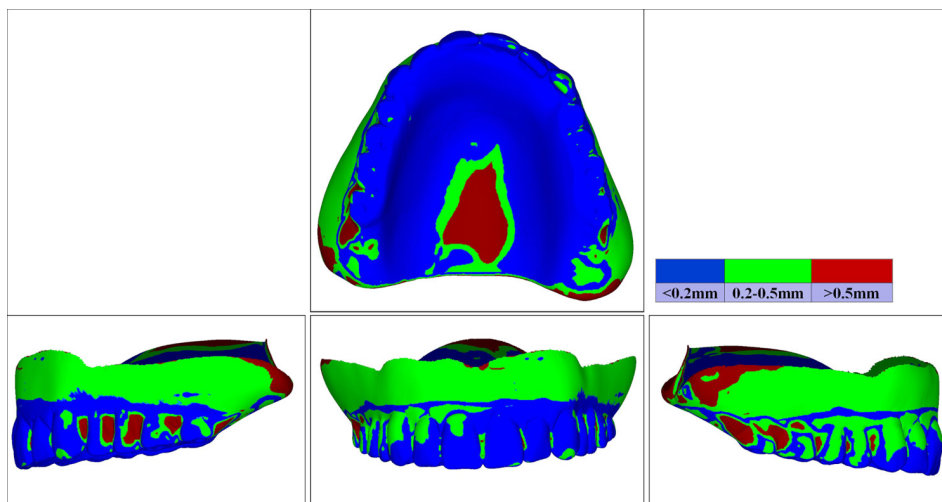


Figure 2: Typical reproduction errors for conventional copy denture technique without a supporting impression tray (CNT).

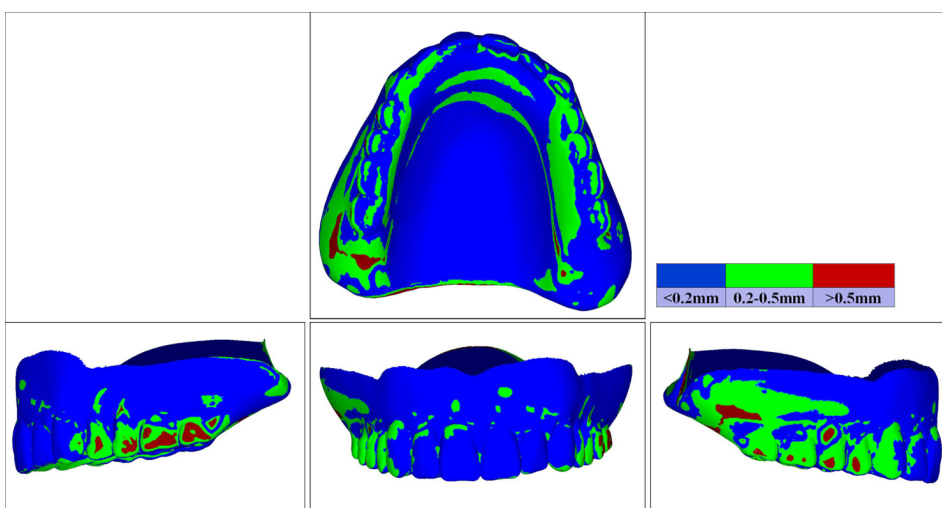


Figure 3: Typical reproduction errors for conventional copy denture technique with a supporting impression tray (CT).

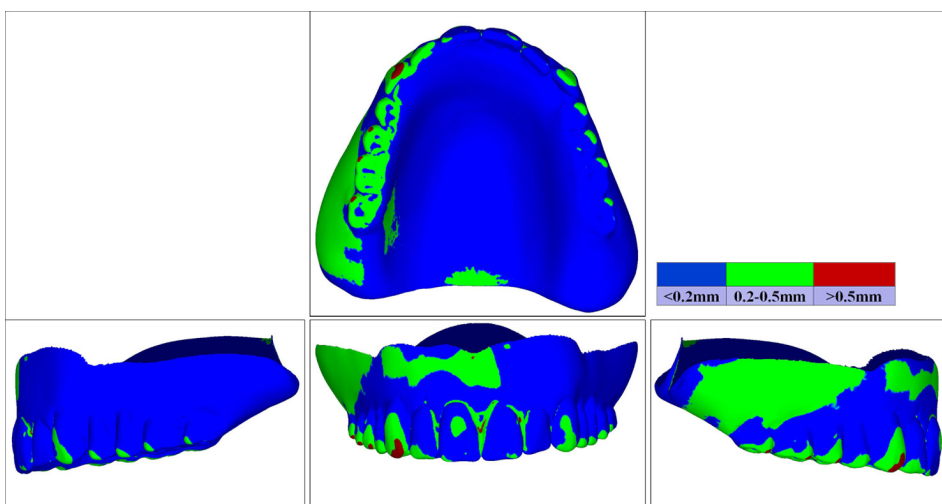


Figure 4: Typical reproduction errors for 3D printed copy templates.

For clinicians, looking at a scan of an individual denture and comparing it to the original, a simple colour coded 3D map (Figures 2, 3 and 4) may prove more useful because it illustrates the clinically relevant patterns of distortion. Whilst statistical analysis is difficult to perform on such colour maps, it is easier to observe patterns of distortion this way, and these colour maps are popular in the literature. However, these maps only form an indication of the accuracy of a reproduction, and should not be viewed as 'absolute'. This is because the alignment algorithms used to overlay the two, slightly different, surfaces do not have a perfect mathematical solution, instead relying on iterative 'best guesses'.²³ Often, as one region of the first scan is pulled towards a corresponding area on the second scan, the effective mathematical 'pull' of other regions can become decreased as they separate (much like gravity). For example, it is possible that the pattern of error shown in Figure 4 (3D template), which has a one-sided distribution (more error apparent on the right-hand side), is actually an artefact of the alignment process, attempting to align a slightly smaller 3D template to the original file. In such a case, the 3D template would be pulled to one side (in this case the left), minimising the error on this side, but causing the right side to pull away slightly. This seems more probable than an exactly asymmetric error in 3D printing, and the error in clinical fit of such a denture might be more evenly distributed.

There did appear to be a consistent error in the palate of copy denture templates produced without a supporting tray. Therefore it might be considered wise to employ support whenever possible if the clinician deems this significant. Some errors were also seen in tooth position in all 3 groups, but the standard clinical protocol of using the template to construct a wax trial should negate their effect, since small adjustments can be made at the clinical visit.

This caution in reading too much into colour maps (or indeed, any individual numbers arising from alignments) applies to all aspects of 'digital dentistry', and it is advisable to use several aspects of 3D analysis to add weight to a hypothesis, rather than assume any particular measure is perfect. In the same way that a clinician makes a diagnosis based on many signs and symptoms, comparisons of 3D data should employ different techniques, in order to point towards a trend.

The authors would encourage and recommend the reporting of 3 outcome measures alongside the illustrative colour maps in all clinical studies reporting precision and trueness ('accuracy') of dental prosthesis. They are:

- The unsigned mean surface deviation,
- The standard deviation of that mean and
- The maximum difference between the 2 surfaces.

The unsigned mean deviation indicates the magnitude of the error between two surfaces, the maximum distance indicates the height at which the 2 surface will first touch and the standard deviation (S.D.) of the unsigned mean deviation indicates the spread of the data (small S.D. means a small spread and an increased likelihood of an 'accurate' fit; the same mean with a large S.D. would be a large spread of data and potentially a less accurate fit).

SCANNING PRECISION

The process of scanning a denture involves multiple stages, and it is important to establish the precision with which repeated scans of a single denture will yield similar 3D data. The scanner used here has a quoted resolution of $<10\mu\text{m}$ when measured against the industry standard VDI 2634/2. This standard relates to the accuracy of individual scans. The complete denture scan involves many different scans from different viewpoints, all of which are aligned and merged to form the final denture scan; this alignment process incurs cumulative errors. Within this study, a custom scan program was used to provide optimal, full scan coverage of each denture whilst minimising the number of scan alignments required. The data was further processed by being resurfaced into a 3D-printable mesh. Because of these interventions, it was deemed necessary to investigate the trueness and precision of the scan-and-build process. It was found that the trueness of the entire denture scanning process was 0.013mm (0.002) and the precision was 0.013mm (0.002). This can be considered as equivalent to the sensitivity of the measuring equipment for the remainder of the experiment. However, our definition of trueness, in this sense, could be contested. We are comparing the scan-and-build process of a denture, to a second scan-and-build of the same denture. This process entails scanning, alignment and resurfacing – all of which will impart a degree of error. If, for example, our digital workflow caused a systematic error of 1% shrinkage (in the same way that the size of an extracted an iso-surface from a CT scan is dependent upon the user-defined threshold applied to the software), our results for trueness would not indicate this shrinkage. One might argue that we are only measuring the precision of the process, not the trueness. In fact, our later results on 3D printed templates lend an argument against this uncertainty. If the scan/build process caused a systematic shrinkage, then the file being printed would already be small, and would furthermore be shrunk again during the second scan/build process (of the 3D-printed template). Another potential source of error is the variation in the position of the supports during printing. We would expect the 3D printed templates to fare poorly against conventional means. Since we have not found this, by any method of assessment, we assume that the process of scanning and building a digital denture incurs mean trueness and precision errors in no more than the 10-15 micron range – at least 7 times lower than the effects of the copy techniques under investigation. Our method would seem suitably sensitive to quantify these errors. Conversely, it is interesting to note the maximum error for the scan-and-build process (0.421mm) may account for a large proportion of the maximum error observed for the 3D printed templates (0.669mm). This is due to the difficulty in scanning certain areas (such as embrasure spaces, where stereo vision is not possible), and the subsequent hole-filling performed by the surfacing algorithm. Newer 5-axis scanners are beginning to appear on the market and these may offer better scan coverage of convoluted surfaces. Perhaps a future focus should be on assessing such scanners abilities to record these crevices, in preference to trying to improve the 3D printing process.

TRADITIONAL VS 3D COPY TEMPLATES

3D printed copy denture templates reproduced the original denture with significantly greater trueness and precision, regardless of which error metric was used. The metric of 'maximum surface deviation' may prove to be the most clinically relevant, as previously discussed. This maximum error was significantly lower with 3D printing, than with the traditional copy technique ($p < 0.05$).

The error patterns for both 3D and traditional techniques warrant further investigation, in particular to include lower dentures.

CONCLUSION

3D printed copy denture templates reproduced the original polished surfaces and occlusion with greater precision than either of the conventional techniques.

Further investigation is required into understanding the distribution of errors produced from the rapid prototyping process and how these errors will affect clinical management of a patient.

CLINICAL IMPLICATIONS

The primary advantage of the copy denture technique lies in its ability to accurately reproduce the polished surfaces of the patient's old denture and so allow the patient to adapt easily to their new denture. This research clearly shows 3D printing the copy denture template has the advantage of greater precision; this should allow easier adaptation by the patient.

This technology eliminates the need to take physical impressions for copy dentures. As the price and convenience of accurate chairside scanners reduces, it is anticipated the technique will slowly infiltrate primary care dental practices.

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- Manufacturers' Details
- Laboratory scanner; Rexcan DS2, Solutionix, Seoul, Korea.
- Scanner software: EzScan 7, Solutionix, Seoul, Korea.
- Scanner powder: CEREC Optispray, Sirona Dental Systems, Salzburg.
- Scan aligning software: Meshlab (<http://meshlab.sourceforge.net/>).
- Software to add printing support: Nauta, DWS Systems, Vicenza, Italy.
- 3D printer; DWS 020D, DWS Systems, Vicenza, Italy.
- 3D printer software: Fictor, DWS Systems, Vicenza, Italy,
- Printer resin: DS3000, DWS Systems, Vicenza, Italy
- Impression trays: Solo Impression Tray, J&S Davis, Stevenage, UK.
- Silicone putty: Lab-Putty, Coltene/Whaledent AG, Altstatten, CH. Petroleum jelly:

- Vaseline, Unilever UK Ltd, Leatherhead, UK.
- Self-curing acrylic: Medway Rapid Repair Liquid + Powder, MR. Dental, Surrey, UK.

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