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Surface area coverage of four extra-oral 3D scanning strategies for edentulous arches

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ABSTRACT

Aim The aim of this study was to assess the surface area coverage of four different extra-oral scanning strategies for edentulous arches.

Materials and methods Impressions were taken of six different edentulous models. Gypsum casts were poured from the impressions. The impressions and/or casts were scanned using four different scanning protocols. Three of the protocols used a custom-built 5-axis laboratory scanner; the final protocol used a commercially available 2-axis laboratory scanner (Rexcan DS2). Group imp-5Ax consisted of the scanned impressions, Group cast-5Ax, the scanned casts, the third group used a "hybrid" method and cast-2Ax consisted of scans of casts scanned in the laboratory scanner. All scans were repeated five times each to ensure consistency in the data. All scans were uniformly cropped using custom software. Meshlab was used to calculate the surface area coverage obtained from each scanning protocol. Results were compared using ranked ANCOVA and Friedmans test.

Results Overall, there was no significant difference across scanning methods from the ranked ANCOVA test. However, individual nonparametric testing with Bonferroni correction revealed one model differed significantly in surface area ($p=0.006$) with the hybrid group producing the greatest surface area. The trend showed the hybrid group produced the largest surface area, indicating fewer holes, more frequently than any of the other groups. The commercial 2-axis laboratory scanner was found to produce the smallest surface area most frequently of the four groups, despite being the only group which had undergone hole-filling prior to analysis.

Conclusion Overall, there was no statistical significance between scanning methods, but this does not rule out clinically significant differences in the surface coverage of each scan method. Further studies with a larger sample size would be required to overcome the limitations within this study, but findings indicate a tendency for the hybrid method to produce scans with a larger surface area than all other scan methods investigated.

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INTRODUCTION

Precise dental impressions are critical for fabricating dental restorations and prostheses with an accurate fit and good retention. Inaccuracy in the impression may cause inadequate fitting of the dental prostheses, which brings about financial and biological complications (1). Recent developments in the field of digital dentistry have led to increasing interest in digitizing complete dentures and producing high-quality 3D printed dentures (2). However, challenges remain in using extra-oral scanners and the digital workflow to scan edentulous models due to insufficient evidence to show that extra-oral scanners would provide sufficient surface area coverage of edentulous areas and undercuts, which might affect the clinical success of prostheses.

Recent innovations in computer-aided design (CAD) and computer-aided manufacture (CAM) have enabled the digitization of what traditionally have been conventional manufacturing methods for dental restorations such as removable dentures (2). This technology has been found to improve the clinical outcomes, reduced the number of appointments needed and provided better material properties and biocompatibility (2).

The workflow for fabricating digital dentures includes three main stages: surface scanning, design stage, and construction (3). On many occasions, the workflow encompasses both conventional and digitally supported stages, including primary and secondary impressions, casting, bite registration, scanning casts or impression then uploading data into a software for the design and finally production of the dentures (4). A study by Russo and Salamini (2) developed a workflow that combined much of the conventional techniques into the digital approach in order to facilitate easier transition to the digital approach. This would help clinicians to use familiar, clinically proven techniques and then incorporate the new digital aspects into the production process. This would reduce financial and practical burdens while utilising clinical expertise and equipment (2).

Primary input data for the digital workflow is obtained from digital scans. Dental scanners exist in two main types, namely, intra-oral scanners and extra-oral scanners (3). In theory, the elimination of conventional impressions in a completely digital workflow would have many advantages (5). It would reduce the cost of trays, impression materials, disinfection, packaging and shipping. In addition, digital impressions only require virtual storage, unlike conventional impressions which need a significant storage space for materials and equipment (5). However, the use of intra-oral scanners to obtain digital scans of edentulous ridges is difficult because of the absence of any clear anatomical landmarks which can be used for the alignment of the multiple views required for any scan, and the inability to border mould or apply muco-compressive impression techniques (6).

Alternatively, extra-oral scanning can be used to capture the input data required. This can be done by scanning conventional impressions and/or gypsum models. These techniques may offer a better strategy for capturing accurate input data by eliminating the issues associated with intra-oral scanning (7). Digital dentures require accurate models in order to adequately record the functional depth and width of sulcus; this can be achieved using an extra-oral scan of impressions or casts. Studies have demonstrated the effectiveness and efficacy of extra-oral scanning with digital systems in fabricating well-fitting restorations and implants (8). However, extra-oral scanners may also suffer from limited line-of-sight when scanning dental models or impressions. In particular, the degrees of freedom of the scanner (i.e. number of axes of motion), and the configuration of the scanning head, may affect the ability of the scanner to 'see' the entire surface, resulting in unscanned areas.

The integrated software of most current scanners compensate for scan holes that are created during the scanning process by inserting a flat, or arbitrarily curved, patch to cover the holes in the scans (9). Such software-generated patches could affect the comfort, stability and the retention of the denture. Data is not published by scanner manufacturers on the size of the holes that are automatically patched. In most instances, the patched holes (or at least, small holes) cannot be detected by the operator, but incorrectly closed holes may be clinically relevant. Even small, auto-filled holes in digital scans may have a clinical effect on the comfort and stability of the final prosthesis. However, current standard methods of analysing digital accuracy in the dental literature focus on mean surface deviations over the entire mesh. This blunt analysis has been shown to drown out potential clinically relevant scan errors (10). The University of Leeds has developed a 5-axis scanner with a greater degree of motion, and a greater ability to capture challenging scan area than most commercial scanners due to the configuration of its optical acquisition unit. The new scanner was designed to produce scans with better surface coverage compared to conventional 2-axis scanners. In doing so, it may reduce the number of holes in the scans. Further, the software of the Leeds scanner detects and highlights holes in the scan but does not insert patches. Holes are defined as regions of missing data of radius 0.15 mm or more. Note that this threshold is empirically far smaller than the presumed threshold for automatic hole-filling used in current dental scanners (which is suspected to be closer to 1 mm).

Despite having 5 degrees of freedom, data may still be missing, even in a scan of a simple shape such as an edentulous arch. In order to avoid hole-filling, an approach called "Hybrid scanning" has been developed. This process involves two stages. Firstly, an "honest" scan must serve as the input data. By this, we mean a scan, which has undergone little, or no hole-filling. Next, the regions of missing data are identified, and a second scan (typically derived from the inverse of the first, so for example an impression scan may serve as the first input, and the poured model scan as the second) acts as a donor. Crucially, only those regions that were holes in the first scan are used from the second scan. Furthermore, the alignment of each patch is individually refined to compensate for the small dimensional changes of dental stone when setting (11).

The aim of this study was to examine the surface coverage of captured data for digital dentures obtained from four different scanning protocols for edentulous scanning. This was to be assessed by comparing the surface area of the scanned models produced by the following four scanning protocols.

- Method 1: Scans of impressions in custom made 5-axis scanner, referred to as Group imp-5Ax.
- Method 2: Scans of casts in custom made 5-axis scanner, referred to as Group cast-5Ax.
- Method 3: Creating a hybrid scan, using 'Flexible Scan Patching' software that combines scans of impressions and casts captured by the 5-axis scanner, referred to as the Hybrid group.
- Method 4: Scans of casts in a standard 2-axis scanner (Rexcan DS2, Solutionix, Seoul, Korea), referred to as Group cast-2Ax.

The null hypothesis states that there is no difference in the surface area of the scans covered by the four scanning methods.

MATERIALS AND METHODS

Three individual sets of edentulous acrylic reference models, A, B and C were made by the laboratory at Leeds Dental institute, which simulated three widely divergent edentulous clinical conditions. The anatomies of the three sets were created using dental models available in the teaching facilities at Leeds University (Fig. 1).

Silicon impressions of the upper and lower acrylic models were taken. The impressions were scanned in the Leeds scanner (Group imp-5Ax), then cast in gypsum. The casts were then scanned in the Leeds scanner (Group cast-5Ax) and in the Rexcan DS2 laboratory scanner (Group: cast-2Ax). The scanning process of each impression/model was repeated five times. For the Hybrid scan group the information captured from the Leeds scanner impression scans were used as the primary scans for the hybrid method. The corresponding cast scans produced by the Leeds scanner were used as "donor scans" to correct any holes present in the impression scans. The areas which had holes in the impression scan were most often found in undercut areas. The corresponding area on the cast will be the negative of the impression, and thus easily scanned. The hybrid software automatically identified areas which were missing on the impression, and patched and selectively aligned small donor sections from the cast scans into these missing areas, producing a hole-free "hybrid scan".

Since casting any impression produces well-known minor distortions due the expansion of the setting gypsum, this hybrid methodology uses the impression scan as the primary data source then adds small patches 'flexibly' from the scan of the casts to minimise the holes in the virtual models. Fine alignment of the cast patches to the impression reduces any "steps" or distortions where the two scans are merged (see Fig 2 for an illustration of the experiment protocol and Fig 3 for an illustration of the four scanning groups).

All scans within a group were aligned to the first impression scan within its group. To achieve this, the clinically relevant denture bearing area of the first scan within each group was outlined. In order to obtain exactly the same outline for each scan, this outline was used to identically crop all scans within the group. This process used custom-made 'cookie cutting' software from Leeds Digital Dentistry (Leeds, UK) (10). This resulted in impression, cast and hybrid scans that were identically cropped.

The Leeds scanner highlights any residual scan holes in red. The red patches were removed from the impression scans, cast model scans and hybrid scans using an automated MeshLab script prior to cropping. Another

FIG. 1 Three different sets of edentulous acrylic reference models with their corresponding silicone impressions.

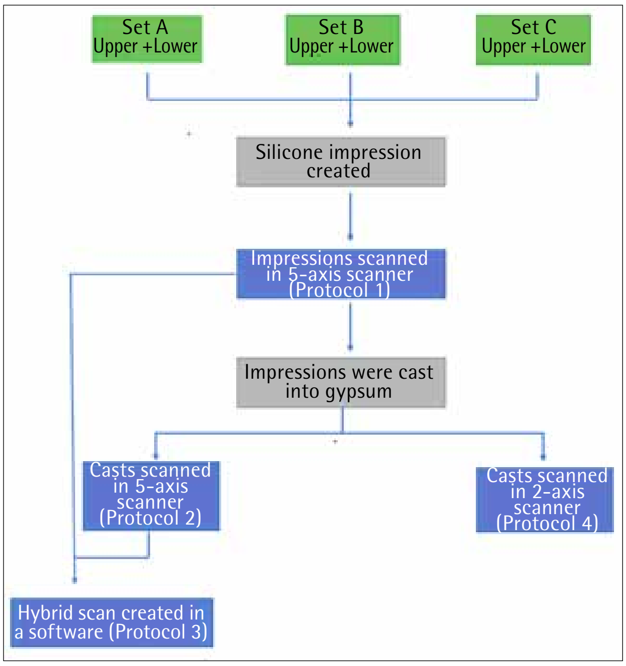

FIG. 2 A diagram of the methodology.

MeshLab script was used to record the surface area of each mesh individually (12). The six edentulous arch forms were anatomically diverse, therefore, each arch was separately compared across the four scanning methods.

The data were statistically analysed using IBM SPSS statistics 26 to explore the difference in the surface area of the scans captured by the four methods. Statistical significance was defined as $p < 0.05$ in all cases. Non-parametric covariance analysis (ranked analysis of covariance method) was performed to account for the variations from different models and jaws. Bonferroni correction was applied to post hoc multiple pairwise comparisons (adjusted p-value = 0.05/6 = 0.008).

RESULTS

The surface area of each group of scans of the six models was recorded in mm^2. Processing errors in arch Upper A meant only 3 of the scans were valid. All 5 repeat scans were valid across all test groups for the remaining arches. Table 1 shows the mean surface area covered by the four methods. The difference in the surface areas covered by the four scanning methods was assessed using Friedman test. The results of Friedman test shows that there was a statistically significant difference in the surface areas in Lower A (P= 0.006), and Lower B (P=0.011) (Table 1). Post hoc analysis with Wilcoxon signed rank test was conducted with a Bonferroni correction applied, resulting in a significance level set at p<0.008, meaning only Lower A remained statistically significant (full results in Table 2).

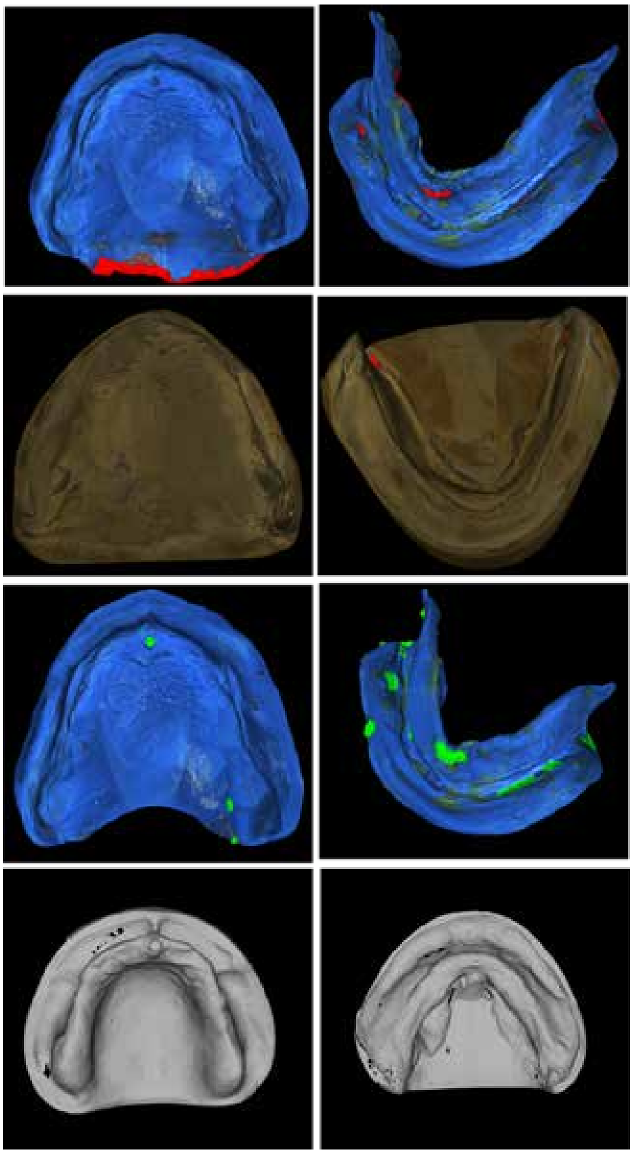

FIG. 3 The first row depicts an upper and lower impression (imp-5Ax), with red marks indicating the areas that could not be scanned, and are "holes". The second row shows an upper and lower scan of the gypsum casts (cast-5Ax), again using the 5-axis scanner which shows that the areas that were not detected on the impression scan became visible on the gypsum cast scan and vice versa. The third row shows the Hybrid Scan. The missing areas on the impression scan were patched with an area of digital data from the scan of the same area on the corresponding cast, these patches are colored green. Lastly, screen shots of upper and lower cast scans produced by the Solutonix scanner (cast-2Ax). This scanner does not capture color.

Ranked ANCOVA showed that there was no overall significant difference among scanning methods after adjusting for scanning models and jaws (p-value = 0.598).

The frequency with which each scan group produced the greatest, and smallest, surface area across the four methods is presented in Figure 4.

Model	Jaw	Impression 5-axis (imp-5Ax)	Cast 5-axis (cast-5Ax)	Hybrid 5-axis (Hybrid)	Cast 2-axis (cast-2Ax)	P-value by Friedman test
A	Upper (n=3)	4134.43 (113.24)	4138.89 (35.41)	4333.55 (88.99)	4310.64 (65.08)	0.060
A	Lower (n=5)	3442.14 (30.17)	3368.42 (16.12)	3442.69 (14.59)	3405.54 (23.76)	0.006 *
B	Upper (n=5)	3802.36 (91.60)	3816.16 (23.05)	3810.52 (95.08)	3790.28 (22.00)	0.564
B	Lower (n=5)	2740.50 (19.62)	2696.47 (0.66)	2753.32 (25.26)	2748.96 (11.45)	0.011 *
C	Upper (n=5)	3617.06 (58.07)	3586.14 (53.56)	3620.73 (64.56)	3555.32 (12.37)	0.323
C	Lower (n=5)	2291.41 (6.93)	2284.69 (6.91)	2290.78 (12.60)	2283.71 (1.69)	0.178

TABLE 1: Mean surface areas (standard deviation) in mm^2, by scanning methods and Friedman test.
* denotes a statistically significant difference. Green indicates largest surface area, light green = 2nd largest, peach = 3rd largest, and red = smallest surface area.

Model	Jaw	P-value by Wilcoxon signed rank test (Asymp. Sig.)					
		c-5Ax - i-5Ax	Hybrid -i-5Ax	c-2Ax - i-5Ax	Hybrid -c-5Ax	c-2Ax-c-5Ax	c-2Ax - Hybrid
A	Upper	0.556	0.343	0.096	0.190	0.024	1.000
A	Lower	0.024	0.690	0.056	0.024	0.096	0.048
B	Upper	0.690	0.548	0.690	0.548	0.095	0.841
B	Lower	0.024	0.310	0.548	0.024	0.024	0.690
C	Upper	0.548	0.841	0.151	0.548	0.310	0.151
C	Lower	0.151	0.690	0.056	1.0 00	0.151	0.690

TABLE 2 Demonstrates the Pairwise comparison for mean surface areas using Wilcoxon signed rank test between scanning methods Model Jaw P-value by Wilcoxon signed rank test (Asymp. Sig.).

DISCUSSION

This study investigated the recently proposed scanning strategy of hybrid scanning and compared it to three other extra-oral scanning strategies, measuring the surface area coverage of six edentulous models. Overall, there was no significant difference across scanning methods from ranked ANCOVA test, meaning that the null-hypothesis was accepted. However individual nonparametric test did show a statistically significant difference in the surface area between the scanning methods in arch form Lower A (p= 0.006). The general lack of significance may be partly explained by the small sample size that was used in this study. However, despite the small sample size, a clear trend emerged. The frequency with which each scan group produced the greatest, and smallest, surface area (Fig. 4) showed that the Hybrid group produced the largest surface area for over half of the scanned arches (4 out of 6), and the second largest surface area for the remaining two groups. The commercial 2-axis scanner produced the smallest surface area for half of the scan objects (3 out of 6) despite these scans already having undergone hole-filling prior to analysis.

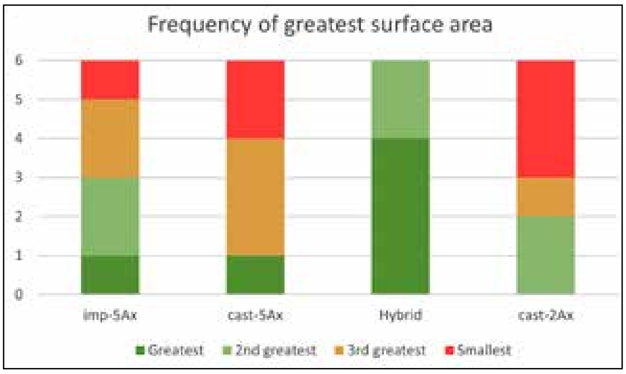

FIG. 4 Frequency with which each group produced the greatest and smallest surface area. A smaller surface area is likely to indicate holes and unscanned regions.

No statistically significant differences were found in the surface area coverage between the scans of casts produced by the 5-axis scanner and the 2-axis scanner. However, while the surface area of the 5-axis scanner will have been entirely "true data", the 2-axis scanner data will have undergone hole-filling prior to analysis. The current method had no means of identifying which areas of the scans produced by the 2-axis scanner were artificial, and what was genuine data. Thus, it may be postulated that in the two instances that larger surface areas (second largest overall) were produced by the 2-axis scanner, this does not necessarily indicate better scan coverage. This does, however, highlight the common issue within dentistry of "black-box" software obfuscating data upon presentation to the end user. A clinician would likely prefer to know which areas of a scan have been "modified" and repaired, and use this information while designing the prosthesis.

The current study was limited by a small sample size. A small sample size could increase the chance of having false positives and significant values, and this may explain having statistically insignificant values in the post hoc test (13). Further, issues with the custom cropping software reduced the sample group for Upper A scan to 3. However, statistical significance and clinical significance are not equal. A statistically small variation in surface area may yet have clinical implications, since an ulcer can be caused by just a small inaccuracy in a denture, often only 1-2 mm^2 in size. The Upper A model from which the original impressions were taken was found to have a deep labial undercut. This presented as substantial scan holes in all scan groups, but as indicated by the fact that the Hybrid group produced the largest surface area, the combined scanned impression and scanned cast may have produced better coverage than either scan on its own, or the 2-axis cast scan. The fact that the impression scan (see color coding in Table 1) reported the smallest surface area, may give some merit to the introduction of hybrid scanning as a method with which to improve scan-coverage in anatomically complex regions.

Another limitation is that it was only possible to use the hybrid scanning technique in software developed by the University of Leeds for their scanner. It was not possible to use scans of impressions from the 2-axis scanner in the hybrid technique since it was not possible to know where the software in the conventional laboratory scanner had artificially repaired scan holes. Additionally, the 2-axis scanner is not considered appropriate for impression scanning as it requires clamping of the scan-object, which is likely to result in distortion.

In relation to the current literature, many studies have demonstrated the efficacy and accuracy of extra-oral scanning in dentistry. A study conducted by Russo and Salamini (2) concluded that using extra-oral scanners to scan conventional stone casts could reduce the number of clinical sessions required for making complete dentures. Another study by Han et al. (14) demonstrated that the use of extra-oral scanning with CAD/CAM systems could result in a successful design and fabrication of complete dentures. This may support the concept of the present study that extra-oral scanning could provide reliable and accurate measurements of edentulous models.

CONCLUSION

This study assessed the difference in the surface area coverage of completely edentulous models between four different scanning techniques using two extra-oral scanners. No statistical difference was found overall, probably owing to the small sample size. However, the hybrid technique showed a clinically significant trend with superior surface area coverage, while 2-axis model scanning tended to produce poorer surface coverage. Due to the limitations of this study, definite conclusions regarding the scanning method cannot be drawn. Further research is essential with a suitable sample size to overcome the limitations of this study.

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Conflicts of interest

The authors declare there are no conflicts of interest.

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