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Trueness, 3D Deviation, Time and Cost Comparisons Between Milled and 3D-Printed Resin Single Crowns

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ABSTRACT

The purpose of this in-vitro study was to compare trueness, 3D deviation, production time and costs of milled and 3D-printed resin single crowns. A total of 20 CAD-CAM resin single crowns were fabricated from 10 digital wax patterns designed on 10 tooth preparations available in a reference model. Standardized control linear measurements were performed with a CAD software. Each STL file was then used to fabricate two resins crowns – one milled and one 3D-printed. All crowns underwent physical linear measurements using a digital caliper. The crowns were then scanned using an intraoral scanner for assessing 3D deviation. Finally, time to produce a single crown, as well as costs and production rates of both methods were also compared. Both CAM methods did not present statistically significant differences in linear measurements, as compared to controls (P>.05). Furthermore, 3D-printed crowns had significantly greater deviations in cervical margins (P=.032) and occlusal surfaces (P=.041), as compared with milled crowns. Finally, 3D-printing took significantly longer to produce one single crown (P=.001), but with a cheaper and higher production rate than milling. These findings suggest that milling devices produce resin single crowns with smaller 3D deviations but more expensive costs, as compared with low-cost 3D printers.

INTRODUCTION

Computer-aided design and computer-aided manufacturing (CAD-CAM) systems are experiencing a rapid growth in dentistry. The development of CAD-CAM tools and devices has led to the establishment of chairside digital workflows in oral rehabilitation.[1,2] In prosthodontics, CAD-CAM crowns were found to provide better marginal and internal adaptation, as compared to crowns performed with conventional workflow.[3,4] However, the aforementioned and most the available studies in the literature assess CAD-CAM crowns milled from zirconia and ceramic materials.

Outcomes of CAD-CAM crowns might be influenced by several factors related to CAD or CAM procedures. Among the factors affecting CAD, are conditions of tooth preparations,[5] as well as different intraoral scanners,[6,7] scanning techniques,[8] software programs used during digital waxing and levels of expertise of software operators.[9] Factors affecting CAM include different devices,[10] and manufacturing materials.[11]

Dental materials used for CAD-CAM single crowns can be milled or three-dimensionally (3D) printed. Among the most commonly used CAM materials in oral rehabilitations are ceramics and resins. Unlike ceramic materials, resins can be 3D printed and are inexpensive, which may be of relevance from a public dental health perspective.[12] In this context, 3D-printed resins can be used to produce reliable interim single-crown restorations and short-span fixed prostheses.[13]

Among other materials, CAD-CAM resin single crowns can be manufactured either from resin blocks using milling devices or from light-curing resins by means of 3D-printing. Both techniques have been described to lead to better crown adaptation and mechanical outcomes, as compared to acrylic resin crowns performed with conventional workflow.[14,15] Nevertheless, little is known on differences in trueness, precision, as well as production time and costs between milling and 3D-printing for manufacturing resin dental prostheses.

Thus, the aim of this preliminary study was to compare differences in accuracy, 3D deviation, as well as production time and costs of resin single crowns manufactured with milling and 3D-printing.

MATERIAL AND METHODS

This *in-vitro* study was conducted on 10 tooth preparations (5 mandibular posterior preparations and 5 maxillary posterior preparations) that were performed with 1 mm supragingival shoulder finish lines on a resin dental study model *(Figure 1)* by an experienced prosthodontist. All 10 preparations were scanned using the same intraoral scanner (Trios III, 3Shape). The resulting images were saved as Standard Tesselation Language (STL) files and imported into a CAD software (DentalCAD, Exocad GmbH).

An experienced CAD and dental technician performed a digital wax pattern on each tooth preparation following the same steps in the CAD software (DentalCAD, Exocad GmbH). Briefly, the finish line of each digital wax pattern was initially outlined in the crown margin. Crown shapes were then chosen from the software library before adjusting their dimensions and positions in the dental arch of the study model. Such adjustments were conducted by taking into consideration interproximal contacts with adjacent teeth and occlusal contacts with the antagonist arch. Next, a digital small mark with 1 mm in diameter was added to the midpoint of the occlusal third of each of the 4 vertical surfaces (i.e. buccal, lingual, mesial and distal) of the crowns. Such marks were used to ensure reproducibility of the linear measurements to be performed for trueness analysis. Accordingly, the two control linear measurements between opposing marks were performed on each digital wax pattern by two trained observers using the same CAD software, and recorded in millimeters. Both observers performed their measurements twice, at intervals of two weeks in order to eliminate the memory bias *(Figure 2A)*.

The resulting digitally designed crowns were exported to STL files, and then imported into a 5-axis milling machine (Ceramill Motion 2, Amann Girrbach AG) and a low-cost liquid crystal display (LCD) 3D printer (Photon, Anycubic) to manufacture the resin single crowns, following the specifications of the respective manufacturers. For the milling machine, Polymethyl methacrylate (PMMA) resin blocks (Ceramill Temp A3, Amann Girrbach AG) were used, whereas for the 3D printer, a light-curing resin (Cosmos A3, Yller) composed mainly by monomers and oligomers was used. 3D-printed crowns were also washed and light-cured for 15 seconds in the UV light-curing chamber of the manufacturer.

The resulting manufactured crowns were initially measured for trueness. A digital caliper with precision of two decimal places was used to measure buccal-lingual and mesial-distal widths. For this purpose, the caliper tips were positioned in the crown points immediately above the marks designed on each pair of opposing vertical surfaces *(Figure 2B)*. These measurements were also performed twice by two trained observers at intervals of two weeks to eliminate the memory bias, recorded in millimeters and compared to the control measurements that were previously performed on digital wax patterns using the CAD software. Means and standard deviations were obtained for both CAM methods and compared in the statistical analysis.

The manufactured crowns were then individually scanned with an intraoral scanner to assess 3D precision. For this purpose, the STL files of the scanned crowns were aligned and superimposed with the STL files of their respective digital wax patterns in a CAD software dedicated for 3D mesh comparisons (GOM Inspect 2019, GOM GmbH). 3D mesh deviations between STLs at the cervical margin (coupling interface), distal, mesial and occlusal surfaces were automatically calculated. All measurements were obtained in millimeters within a 3D color map, following a previously described methodology.[9] Mean deviations were obtained from the software data and then used in the statistical analyses.

In addition to above-mentioned analyses, the mean times required by milling and 3D-printing to fabricate only one single crown were also recorded in minutes and compared. Finally, cost analysis was carried out for both methods, including their production rates (considering the prices available to run both methods in Malta). For this *in-vitro* study, only material and laboratory raw costs were evaluated considering an in-house production. Costs per unit (CPU) of each item was calculated by dividing the raw cost by the number of crowns produced during the item's lifespan. Direct costs included CAM devices and consumables, whereas indirect costs included maintenance, operator-related and software expenses. Hourly, daily, monthly and yearly production rates were assessed considering the in-house production at the institution of this study, with both devices operating 8 workings hours per day at full capacity (i.e. maximum level of output of the device) to manufacture resin single crowns.

For statistical analysis, sample size was estimated to work with a statistical power of 80% and a significance level of 5% using the Noether's formula. Normality of 3D deviation and cost measurements were assessed using the Shapiro-Wilk test. Intra- and interobserver agreements for all linear measurements were assessed with the Intraclass Correlation Coefficient (ICC). Trueness and precision of both methods at different surfaces were also compared with the paired T-test (for

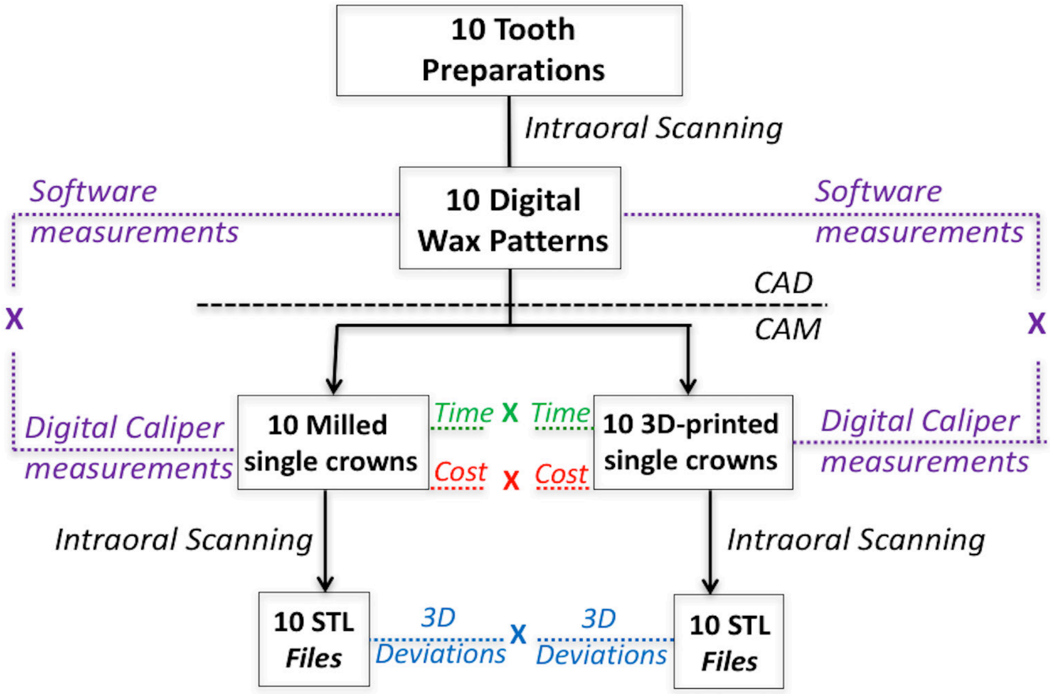

Figure 1: Flowchart of the study

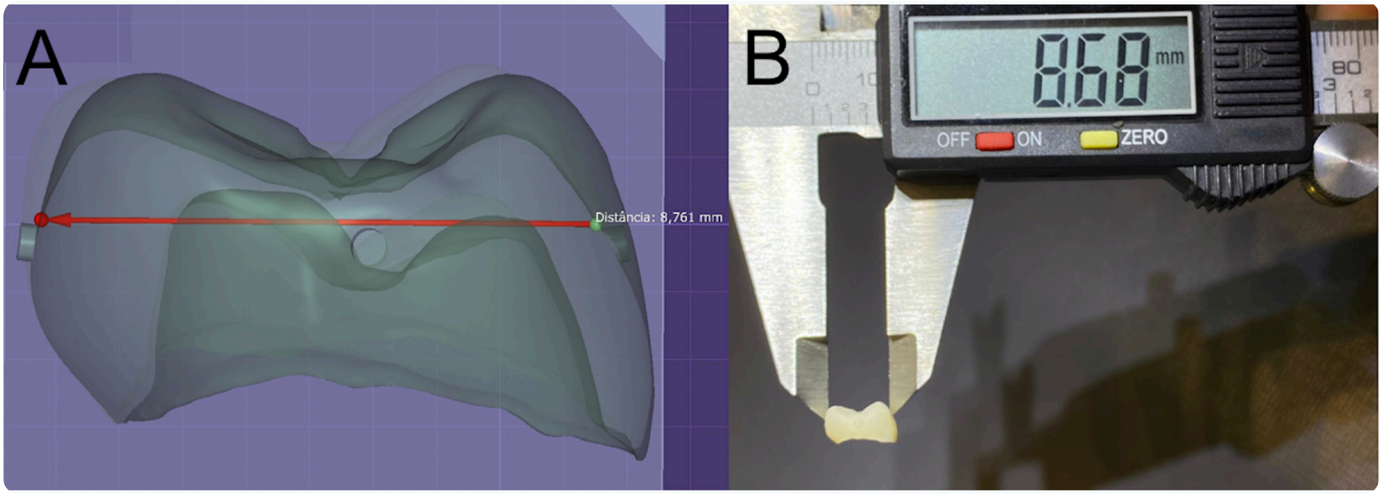

Figure 2: Methodology of the study. A) Digital control linear measurements performed in the CAD software. B) Physical linear measurements performed with the digital caliper with both tips positioned immediately above the marks.

parametric variables) and Wilcoxon Signed-Rank Test (for non-parametric variables). Furthermore, within group comparison among precision at the different surfaces (i.e. cervical, distal, mesial and occlusal) was carried out with the Kruskal-Wallis test. Finally, the mean time of each method to produce a single crown was compared with the Student T-test. All analyses were performed at a level of significance of 5%, using the IBM SPSS Statistics 26 software (SPSS Inc, Chicago, IL).

RESULTS

Regarding trueness analysis, normality was confirmed for all linear measurements (P<.05). Strong intra- and interobserver agreements were confirmed for all measurements, since ICC values ranged from 0.86 to 0.93 (P =.001). Mean control linear measurement performed on digital wax patterns using the software was 8.03 ± 1.34 mm. Mean physical linear measurements using the caliper were 8.17 ± 1.52 mm for milled crowns, and 8.37 ± 1.40 mm for the 3D-printed crowns. None of the aforementioned values presented statistically significant differences as compared to the mean control measurement (P>.05).

Regarding precision analysis, normality of 3D mesh deviation values was confirmed for cervical, distal and mesial deviations (P>.05), and rejected for occlusal deviations (P<.05). For 3D-printing, mean deviations were 0.20 ± 0.09 mm for cervical; 0.12 ± 0.04 mm for distal; and 0.14 ± 0.03 mm for mesial surfaces, whereas the median deviation for occlusal surfaces was 0.19 mm (range: 0.13 mm-0.73 mm). For milling, mean deviations were 0.10 ± 0.05 mm for cervical; 0.13 ± 0.04 mm for distal; and 0.09 ± 0.02 mm for mesial surfaces, whereas the median deviation for occlusal surfaces was 0.14 mm (range: 0.10 mm-0.16 mm). Paired t-test analysis revealed that the difference in cervical deviation observed between milling and 3D-printing was statistically significant (P=.032; *Figure 3*). On the other hand, there was no statistically significant differences between the two methods for distal and mesial deviations (P=.735 and P=.096, respectively). Wilcoxon test, in turn, also revealed a significant difference between the deviation values reported above for milling and 3D-printing (P=.041; *Figure 4*). Furthermore, within group comparison among the different surfaces (i.e. cervical, distal, mesial and occlusal) revealed statistically significant differences for both methods (P=.001; *Figure 5*).

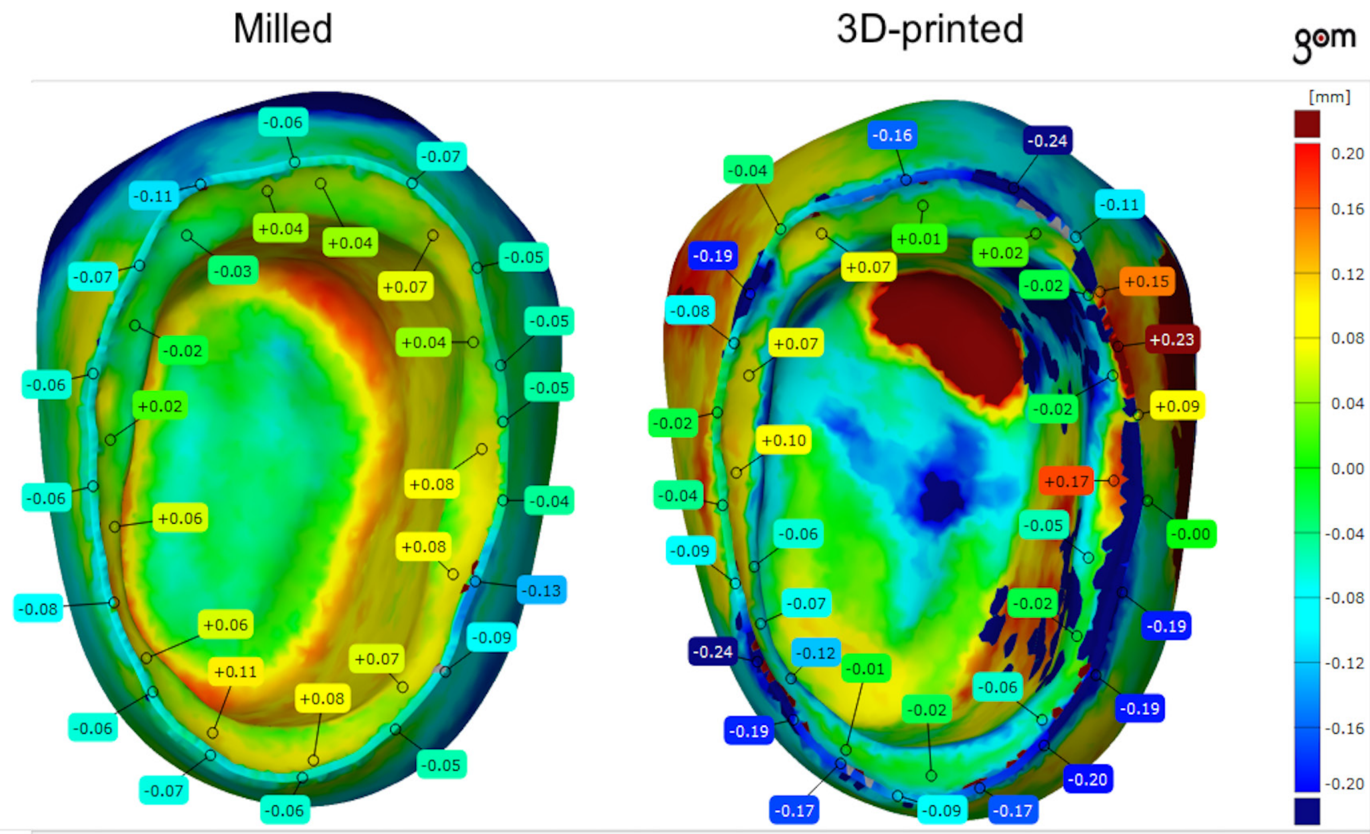

Figure 3: Comparison of precision of cervical margins between milling and 3D-printing (p=0.032).

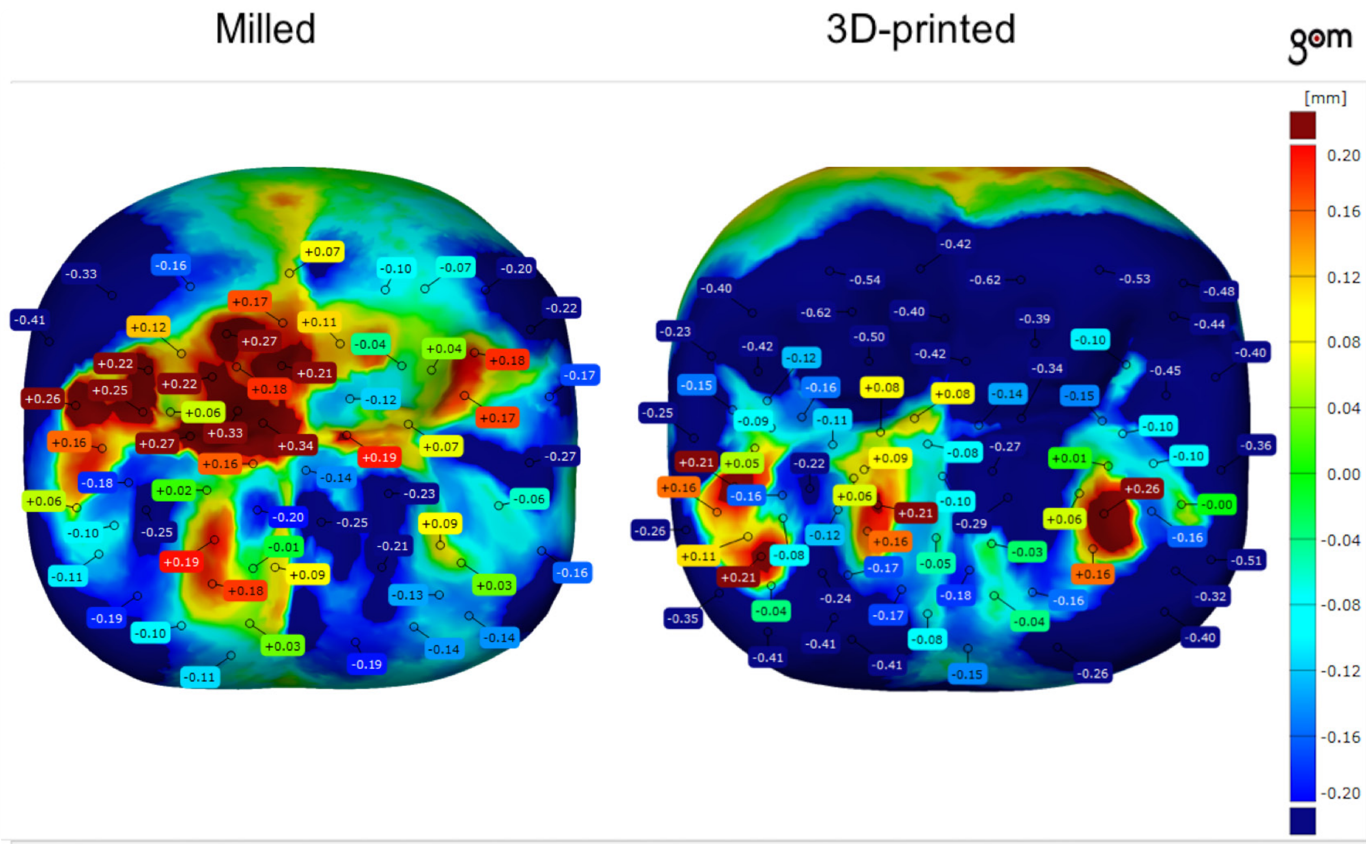

Figure 4: Comparison of precision of occlusal surfaces between milling and 3D-printing (p=0.041).

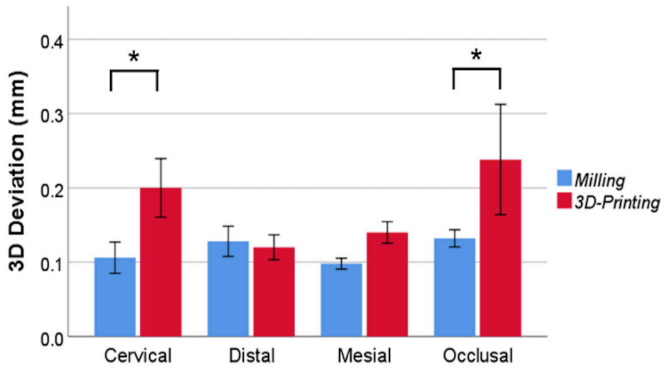

Figure 5: Within group comparison among the different surfaces (p=0.001). Asterisks depict statistically significant differences between groups shown in Figure 3 and in Figure 4.

Regarding time analysis, the mean times required by the milling device (12.5 ± 1.2 minutes) and by the 3D printer (41.5 ± 2.7 minutes) to produce only one single crown was statistically significantly different (P=.001). However, 3D-printing was found to have cheaper costs and greater production rate, as compared with milling *(Table 1)*. The milling device has a raw cost of 35,000.00 euros, and an average lifespan of 5 years producing approximately 7680 resin single crowns per year (totaling 38400 crowns during the lifespan). As a result, the cost per unit found for the milling device was 0.91 euros (35,000.00 euros divided by 38400 crowns). On the other hand, the 3D printer used herein has a raw cost of 252.00 euros, and an average lifespan of 5 years producing approximately 19200 crowns per year (totaling 96000 crowns during the lifespan). As a result, the cost per unit found for the 3D printer was 0.003 euros (252.00 euros divided by 96000 crowns).

DISCUSSION

This study aimed at comparing the two CAM methods used to perform CAD-CAM resin single crowns: milling and 3D-printing. For this purpose, trueness, precision, time and cost analyses were performed considering the milling and 3D-printing materials available in the dental clinic of this study. Those include two CAM devices commonly used in dental laboratories and clinics providing in-house production: a high-end 5-axis milling device and a low-cost desktop LCD 3D-printer. According to the present findings, milling showed significantly higher precision, but with higher costs and inferior production rate, as compared with 3D-printing. This the first *in-vitro* study to address the aforementioned differences between milling and 3D-printing to produce CAD-CAM resin single crowns. Nevertheless, the present findings contrast with a previous study that found better adaptation of 3D-printed resin crowns as compared with milled and conventional resin crowns.[16] Notwithstanding, the aforementioned study used a milled resin-based material different from PMMA, and found clinically acceptable results for the 3 methods analyzed (3D-printing, milling and conventional).

There is more controversy in the literature regarding outcome comparisons between 3D- printed or milled CAD-CAM single crowns. Studies reported contrasting results in fracture resistance for 3D printed or milled resin crowns.[17,18] On the other hand, several other studies confirmed that both CAM methodologies lead to clinically acceptable outcomes, which were better than those observed in conventional resin crowns.[4,15,19]

Table 1. Main Costs (For Malta) and production rate of both CAM methods used in this study

Method	Type of Cost	Item	Raw Cost (€)	CPU (€)	Production Rate (Number of Crowns) Hourly	Daily	Monthly	Yearly
Milling (Ceramill Motion 2)	Device	Milling Machine	35,000.00	0.91	4	32	640	7680
	Maintenance	Lubricant	300.00	0.04				
		Burs	150.00	3.00				
	Consumables	Resin Block	100.00	4.16				
	Operator	Hourly rate	10.00	2.50				
	Software	CAM software	890.00	0.03				
	Total	All above	35,560.00	10.64				
3D-printing (Anycubic Photon)	Device	LCD 3D-printer	252.00	0.003	10	80	1600	19200
		Curing station	230.00	0.002				
	Maintenance	UV Led	40.00	0.002				
		FEP Film	25.00	0.007				
	Consumables	1L Resin	215.00	0.535				
		1L IPA Alcohol	5.00	0.001				
	Operator	Hourly rate	10.00	1.00				
	Software	-	-	-				
	Total	All above	772.00	1.55				

Abbreviation: CPU, Cost per unit (i.e. single crown).

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This study also strove to perform 3D deviation comparisons among the different surfaces of the CAD-CAM resin crowns. According to the present findings, milling significantly outperformed 3D-printing in regards to 3D deviation at the cervical margin and at the occlusal surface. However, these results should be interpreted taking into consideration that a low cost LCD 3D-printer was used, whereas other 3D-printers used in dentistry have different resolutions and technologies.[20] On the other hand, there was no statistically significant differences between both methods for distal and mesial surfaces. This may be due to the lower resolution of the vertical axis, leading the multi-laminated milling burs to provide limited flatness of surfaces.[21]

One of the limitations of this *in-vitro* study performed on phantoms is that the impact of clinical factors commonly encountered in oral rehabilitations, such as subgingival finish lines or proximity of the preparation limits to adjacent teeth could not be addressed.[22] Furthermore, other variables that could affect 3D-printing outcomes such as orientation in the printing bed and shape of the object to be printed were not compared herein. Finally, only one 5-axis milling device and one low-cost LCD 3D-printer was assessed in this preliminary study. Therefore, future observational clinical studies would be recommended to address the impact of different CAM systems and materials on trueness, 3D-deviation and cost-effectiveness of CAD-CAM resin single crowns.

CONCLUSION

Within the limitations of this preliminary study, the present findings suggest that 5-axis milling devices produce resin single crowns with similar trueness but smaller 3D deviations than low-cost LCD 3D printers. Furthermore, 5-axis milling devices are faster to produce a single crown, which is clinically relevant for chairside digital workflow. On the other hand, LCD 3D printers offer lower costs and higher production rate, which is relevant to dental clinics with high demands for interim single crowns.

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