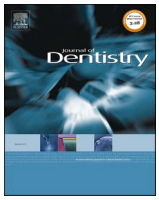
Journal of Dentistry 153 (2025) 105505

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent



Digital vs. conventional removable complete dentures: A retrospective study on clinical effectiveness and cost-efficiency in edentulous patients Clinical effectiveness and cost-efficiency analysis of digital dentures

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ARTICLE INFO

Keywords:
Edentulism
Digital dentures
CAD/CAM dentures
3D Printing
Cost-efficiency
Chair-side time

ABSTRACT

Objectives: This study aimed to compare the clinical effectiveness and cost-efficiency of conventional and digital prosthodontic protocols, with a specific focus on milled and 3D-printed digital removable complete dentures.
Methods: This retrospective clinical study was conducted at the Removable Prosthodontics Department of the University of Siena. 60 patients were divided into two groups: 30 received conventional complete dentures, while the remaining 30 received digital complete dentures (15 milled and 15 3D-printed). Clinical outcomes were assessed using OHIP-14, bite force measurements, and masticatory performance tests before and six months after treatment. Treatment-related metrics, including chairside time, follow-up time, and laboratory costs, were recorded and compared across the groups. Statistical analysis was performed to determine the significance of differences between conventional and digital complete dentures, as well as between milled and 3D-printed digital complete dentures.
Results: The study revealed that digital complete dentures significantly reduced chairside time compared to conventional dentures, with average times of 154.31 ± 13.19 min for digital dentures and 218.00 ± 20.75 min for conventional dentures ($p < 0.0001$). Laboratory costs were found to be statistically lower for digital dentures, (€378.79 ± 137.46 vs. €459.15 ± 63.72, $p = 0.0059$) compared to conventional dentures. No statistically significant differences were observed in bite force or masticatory performance between the groups. OHIP-14 scores indicated slightly lower patient satisfaction with digital dentures, but the difference was not clinically significant.
Conclusion: Digital removable dentures, including both milled and 3D-printed models, offer a practical and efficient alternative to conventional dentures, particularly in terms of reducing chairside time and laboratory costs.
Clinical significance: Digital removable dentures offer a practical and efficient alternative to conventional dentures, particularly in terms of reducing chairside time and costs. These simplified digital protocols could be applied in residential facilities or within national healthcare programs, improving access to prosthetic care for a larger number of patients.

1. Introduction

The edentulous condition significantly impacts not only the functional abilities of individuals—such as chewing and speaking—but also their social interactions, psychological well-being, and overall quality of life [1]. For many edentulous patients, particularly those with limited financial resources, finding effective and affordable prosthetic solutions is crucial for restoring dignity and enhancing quality of life [2].

Traditionally, conventional complete dentures (CD) have been the standard treatment for edentulous patients. Although they have provided reliable solutions for decades [3], the fabrication process is labor-intensive, requiring multiple clinical appointments and extensive laboratory work [4]. Additionally, complete dentures can sometimes lack the precision and fit that modern patients expect, particularly as demands for comfort and functionality have increased [5].

Recent advancements in digital dentistry, especially the introduction

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https://doi.org/10.1016/j.jdent.2024.105505
Received 26 September 2024; Received in revised form 26 November 2024; Accepted 1 December 2024
Available online 5 December 2024

of CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) technologies, have transformed the fabrication of complete dentures [6]. Digital complete dentures (DDs) offer advantages such as improved accuracy in fit, enhanced mechanical properties, and greater reproducibility [7]. Among these digital options, milled complete DDs are widely used for their durability and precision [8], while newer 3D-printed DDs are emerging as cost-effective alternatives, although their long-term clinical performance is still being evaluated [9, 10].

Various clinical measures can assess the effectiveness of these prosthodontic treatments. The Oral Health Impact Profile (OHIP-14) is a widely used questionnaire that measures the impact of oral health on quality of life, focusing on functional, psychological, and social aspects [11]. Bite Force (BF) serves as an indicator of masticatory efficiency, reflecting the maximum force exerted during biting [12], while Masticatory Performance (MP), measured with the VOH index, evaluates the ability to mix and grind food, crucial for proper digestion and nutrition [13].

Other treatment-related metrics, such as chairside time and laboratory costs, are also critical for determining the feasibility of treatment protocols [14]. Assessing chairside time involves evaluating the total time required for various clinical procedures, from preliminary impressions to complete denture delivery [15]. Laboratory costs represent the expenses incurred in the fabrication of complete dentures, excluding the dentist's profit margin, and are essential for understanding the economic impact of different prosthodontic solutions [16]. In fact, digital technologies allow the production of DDs with shorten protocols, thanks to the use of Intraoral scanners that can be used to acquire the final impression starting from a preexisting CDs without the need for a duplicate. This shortened digital protocols are particularly useful in elderly patients to reduce the number of appointments [17]. Despite numerous studies on the clinical effectiveness of various prosthodontic approaches, there is a lack of comprehensive articles that integrate patient-reported outcomes with practical aspects like construction time and costs as highlighted by Srinivan et all. [18–21]. Addressing this gap is vital, as treatment choices must meet clinical needs while also considering economic sustainability.

Our study aims to fill this gap by examining the clinical effectiveness of conventional and digital complete denture protocols alongside their impact on treatment-related metrics such as chairside time and laboratory costs. We hope to provide valuable insights for clinicians to choose the most appropriate and sustainable prosthodontic solutions.

The following null hypotheses were tested:

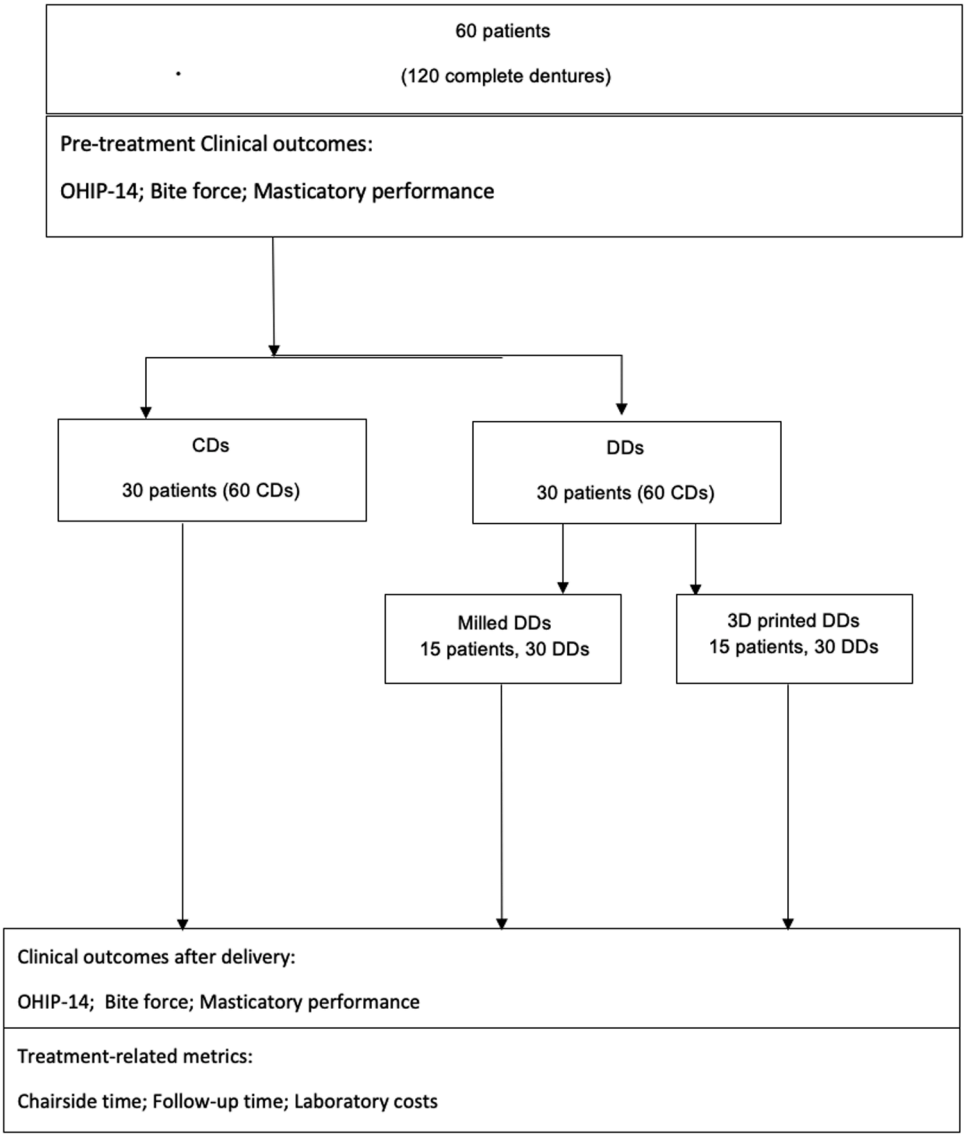

Fig. 1. Schematic diagram of the study design.

1. There is no significant difference in post-treatment outcomes between the complete CDs and DDs groups regarding clinical outcomes (OHIP-14, BF, and VOH) and Treatment-Related metrics (chairside time, follow up time and laboratory costs)
2. There is no significant difference in post-treatment outcomes between milled and 3D-printed digital complete denture groups regarding clinical outcomes (OHIP-14, BF, and VOH) and Treatment-Related metrics (chairside time, follow up time and laboratory costs)

2. Materials and methods

This retrospective clinical study was conducted at the Removable Prosthodontics Department of the University of Siena. The study received approval from the local ethics committee (No. 22,686, 18/07/2022), and all participants provided written informed consent. Sixty edentulous patients wearing complete removable dentures for both maxillary and mandibular arches were selected for new treatment from September 2022 to September 2023. The patients were divided into two groups as reported in Fig. 1:

Group 1: 30 patients treated with conventional dentures (CD).
Group 2: 30 patients treated with digital dentures (DDs), with 30 dentures fabricated by milling and 30 by 3D printing.

Inclusion criteria: patients included both genders, a minimum age of 45 years, at least three years of experience wearing CDs for both arches, signing informed consent, and having at least a secondary level of education to ensure uniform understanding of the questionnaire. Exclusion criteria included inflammatory changes in the oral cavity, candidiasis, hyperplasia, acrylic resin allergies, neurological disorders, and malignancies.

Patients were examined by two expert removable prosthodontists to evaluate the need for renewal of existing dentures. Participants were subsequently included in one of the two groups (CD or DD) based on the possibility of using the existing denture as an individual tray for closed-mouth impressions.

For the patients assigned to Group 2 (DD), the subdivision between milled and 3D-printed dentures was performed using a stratified randomization method via Microsoft Excel. Each patient in the group was assigned a sequential number, and a random number was generated for each using Excel's =RAND() function. The patients were then sorted according to the random numbers. The first 15 patients in the sorted list were allocated to the milled dentures group, while the remaining 15 were allocated to the 3D-printed dentures group.

2.1. Conventional treatment

The conventional treatment required four main appointments, including the taking of preliminary and definitive impressions, centric registration, the try-in of prototypes, and the insertion of the final dentures [22]. All clinical procedures were carried out by the same experienced prosthodontist. Preliminary impressions were taken with Schreinemaker-design stock trays (Clan Dental BV, Rotterdam, Netherlands). and hydrocolloid impression material (Neocolloid, Zermack, Rovigo, Italy). During the same appointment, the Rest Vertical Dimension (RVD) and Occlusal Vertical Dimension (OVD) were determined using the Niswonger method [23]. A preliminary maxillo-mandibular relationship was also recorded using a Centric Tray (Ivoclar Vivadent AG) at the OVD using polyvinyl siloxane-based material (Virtual, Ivoclar Vivadent AG). Maxillary and mandibular casts were poured from the preliminary impressions and mounted in an articulator (Stratos 100, Ivoclar Vivadent AG) using the preliminary centric record. Individual tray bases were fabricated using a self-curing resin tray material (Ivolen, Ivoclar Vivadent AG) with wax rims (Solidus 84, Yeti, Engen, Germany). At the second appointment, maxillary wax rim was individualized according to the bipupillary line in the frontal view, Camper plane in the sagittal aspect and carved according to lip support and phonetics. The OVD was established using esthetic and phonetic evaluations. Once both wax rims were individualized, the definitive impressions were taken, first by border molding using thermoplastic compound (Isofunctional, GC). The trays were subsequently loaded with a zinc oxide-eugenol-based impression paste (Cavex, Haarlem, Netherlands), and the impressions were taken with a closed-mouth technique. The final centric intermaxillary position was manually recorded with poly (vinyl siloxane)-based material (Futar D, Kettenbach LP, California, USA). The impressions were poured in class IV stone and mounted in the articulator (Condylator Vario 6, Candulor) using the intermaxillary relationship. The teeth arrangement was performed using Ivoclar SPE artificial teeth (Ivoclar Vivadent AG) that were adapted to the Gerber occlusal scheme [24]. All laboratory procedures were carried out by the same highly trained dental technician. Once the try-in was validated by both the clinician and the participant, the prostheses were fabricated using the flasking procedure. Then the prostheses were refined and polished with pumice (Pomice X-fine, Larident srl, Italy) and paste (KMG PASTE, Candulor) and the final prosthesis are shown in Fig. 2c.

2.2. Digital treatment

The digital denture protocol used was based on a patient's existing denture as a reference for creating a new digital denture. The process began by assessing the patient's current denture for parameters such as occlusal vertical dimension (OVD), centric relation, esthetics, and phonetics. If the denture met basic acceptable criteria, it was used directly. Minor adjustments, such as correcting overextended borders or adjusting the centric position, were made if necessary. The patient's existing denture was used to take a closed-mouth reline impression, with or without border molding, to capture the tissue surface accurately.

The border molding, if necessary, was registered with heavy body polyvinyl siloxane (PVS) material (Virtual Heavy body, Ivoclar Vivadent AG) and the final closed mouth impressions were registered using light body poly(vinyl siloxane)-based material (Virtual light body, Ivoclar Vivadent AG). The final centric intermaxillary position was manually recorded with wax in case of a rinse of VDO was required and a PVS material (Futar D, Kettenbach LP, California, USA). After the reline impression, the dentures and the bite block were scanned using an intraoral scanner (Trios 3, 3Shape A/S,Copenhagen, Denmark). The scanner captured a 360-degree view of the relined denture, including the intaglio surface, cameo surface, and occlusal surfaces. This digital model served as the basis for designing the new denture.

The scanned data were processed using specialized CAD software (Dental System, 3Shape,A/S, Copenhagen, Denmark) to create a digital model of the new dentures as shown in Fig. 3. The software allowed for adjustments to the design, such as modifying tooth position, shape, and shade, based on patient preferences or clinical requirements. The teeth arrangement was performed following the same Gerber occlusal concepts used for CD [24]. The finalized digital design was used to print prototypes (Temp Print, GC Japan). After their validation by the patient and the dentist, the DDs were finalized through either milling or 3D printing.

2.3. Milling procedure

A universally applicable 5-axis milling unit (PM7, Ivoclar Vivadent) was employed for the fabrication of 30 polymethyl methacrylate (PMMA) resin denture bases using Ivotion base disks (Ivoclar Vivadent). The teeth were milled in one monolithic block from multilayer disks (Ivotion Dent Multi, Ivoclar Vivadent). The milling procedure was performed following the manufacturer's instructions.

Fig. 2. Analogic workflow: (A) Closed mouth impression, the corresponding (B) teeth arrangement positioned in the articulator, and (C) finished *CDs*.

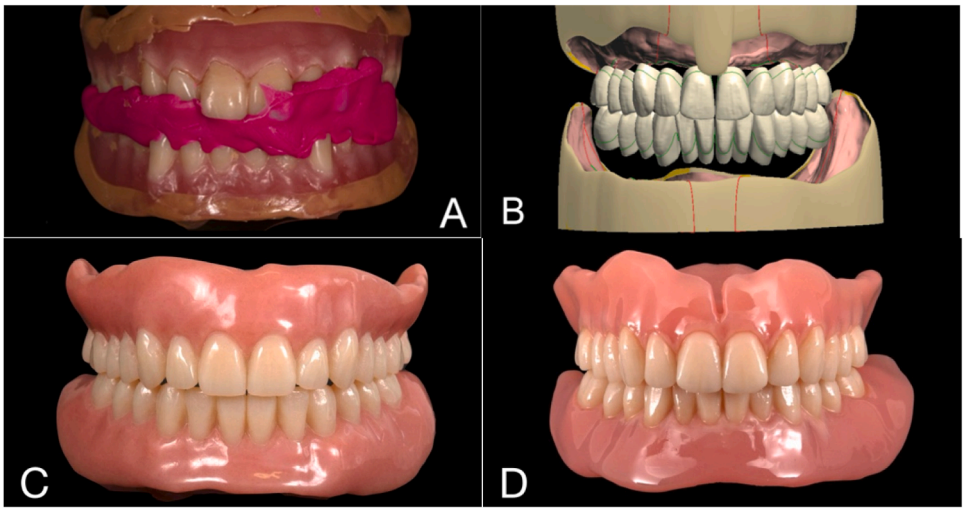

Fig. 3. Digital workflow for DDs : (A) Existing denture relined, (B) digital design and (C) milled DDs denture (D) 3Dprinted DDs.

2.4. 3D printing procedure

The denture bases were printed with V-Print Dentbase (Voco GmbH, Germany) and teeth were printed with V-Print DT (Voco GmbH, Germany). The denture bases and teeth files were positioned at a 45° angle to the build plate, and the supports were arranged using Asiga Composer software (Sydney, Australia). The denture bases and teeth were produced using a DLP 3D printer, (Asiga V MAX 3D Sydney, Australia), with a wavelength of 385 nm and a pixel resolution of 62 μm, featuring a UV light-emitting diode with a wavelength of 405 nm and a printing layer thickness set at 100 μm. All components were printed at a resolution of 50 μm. After printing, the support structures were removed, and the 3D-printed CD bases and teeth were rinsed for 10 min in an ultrasonic bath containing isopropyl alcohol and polymerized for 15 min using an ultraviolet polymerizer (HiLite Power 3D, Kulzer, Hanau, Germany) according to the manufacturer's instructions. The bases and corresponding teeth were luted using the same light-curing resin used for the 3D printing of the bases (V-Print Dentbase, Voco). Before polishing, teeth were customized with stains (Line Art, Scofu). All dentures, after processing, were refined and polished with pumice (Pomice X-fine, Larident srl, Italy) and paste (KMG PASTE, Candulor).

2.5. Outcome measures and treatment-related metrics

The patient's maximum bite force (BT) was recorded. The BF was analyzed using Innobyte (Kube Innovation, Montreal, Canada) with three 3-second measurements, asking the patient to bite on the support. The final reported value was calculated as the average of the three measurements. Masticatory function was assessed through the Masticatory Performance Test (MP), where individuals chewed a standardized portion of test gum (Hue-Check Gum®). The participants were instructed to chew five samples of gum on their preferred chewing side for 20 chewing cycles. The chewed gum was flattened to 1 mm thickness, as shown in Fig. 4, and scanned with an ADS-2800 W (Brother, Nagoya, Japan). These images were analyzed using free software (ViewGum, dHAL Software, Kifissia, Greece). An oral health–related quality of life (OHRQoL) test, OHIP-14 in Italian version, was administered to all the participants. The outcome measures were assessed according to predetermined time points: before treatment and at 6 months after delivery.

In addition to clinical outcomes, this study evaluated treatment-related metrics at 6 months after delivery.

Chairside time was measured as the total duration (in minutes) spent by the clinician with the patient from the initial consultation to the final delivery of the removable dentures.

Follow-up time refers to the total duration (in minutes) of all post-delivery appointments needed to adjust the dentures. Laboratory costs were calculated based on the expenses incurred during the fabrication of the dentures, included material costs, technician time, and overheads.

2.6. Statistical analysis

The Kolmogorov-Smirnov test was employed to assess the normality of Bite Force (BF), Masticatory Performance (MP), and OHIP-14 scores pre- and post-treatment. With normal distribution confirmed, paired *t*-tests compared pre- and post-treatment measurements, while independent samples *t*-tests were used to compare outcomes between conventional and digital prostheses, as well as between milled and 3D-printed dentures. For treatment-related metrics—chairside time, laboratory costs, follow-up time, and the number of follow-ups—independent samples *t*-tests were similarly applied to evaluate potential advantages of digital protocols. A p-value of <0.05 was deemed statistically significant, indicating meaningful differences related to treatment type. All statistical analyses were performed using SPSS software (version 26, IBM Corp., Armonk, NY, USA)

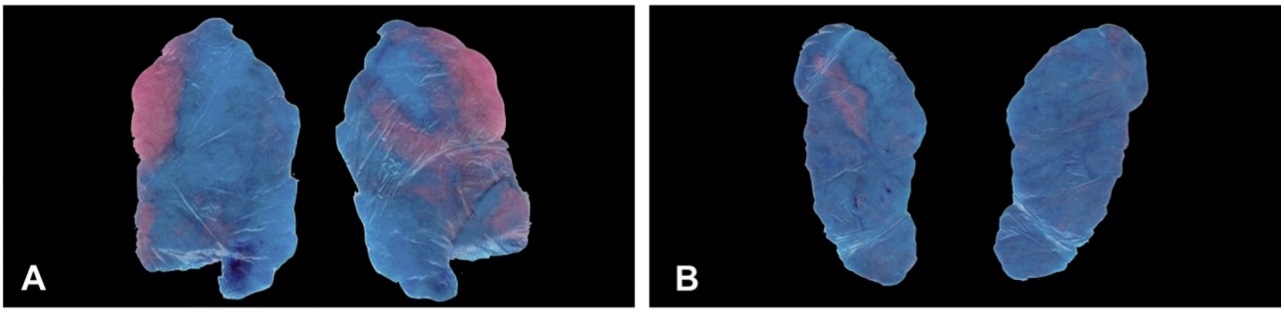

Fig. 4. Two-colored mixed gums (A)pre-treatment (B)post-treatment.

3. Results

The mean age of the patients was 74.46 ± 8.03 years, and the sample was composed of 27 males and 33 females. There was no significant difference in BT between CDs and DDs ($p = 0.963$). The difference in MP between the two groups was not statistically significant ($p = 0.403$). A statistically significant difference was observed in OHIP-14 scores ($p = 0.0016$), with the DDs group reporting worse patient-reported outcomes compared to the conventional group as reported in Table 1.

The difference in chairside time between CDs and DDs was highly statistically significant ($p < 0.0001$), with the latter requiring significantly less time at the chair The difference in laboratory costs between the two groups was statistically significant ($p < 0.0001$), with CDs incurring significantly higher laboratory costs. No significant differences were found between the groups in follow-up time ($p = 0.587$) or the number of follow-ups required ($p = 0.694$), suggesting similar post-treatment follow-up needs as reported in Table 2.

The difference in all the patient related outcomes were not statistically significant, indicating similar performance in these parameters between DDs produced through milling or 3D printing as reported in Table 3.

Treatment related metrics for milled and 3D printed DDs are reported in Table 4. The chairside time was similar between the two groups, with no statistically significant differences ($p = 0.6089$). Similarly, there were no significant differences in the number of follow-ups required ($p = 0.4725$). The average follow-up times were similar for both groups, with a slight trend towards longer follow-up times for printed prostheses as shown in Table 4.

Laboratory costs showed a significant difference between the two groups ($p = 0.0496$), with milled prostheses incurring higher average costs compared to printed ones.

4. Discussion

The results obtained in the present study partially reject the null hypotheses since significant differences were observed in OHIP-14 scores between CDs and DDs, with the latter reporting slightly lower patient satisfaction. Therefore, the null hypothesis regarding OHIP-14 was rejected. However, no significant differences were found in bite force and masticatory performance between CDs and DDs, leading to a failure to reject the null hypotheses related to these measures. Despite the slight differences in OHIP-14 scores, both types of dentures demonstrated effectiveness in improving the OHIP-14 and functional outcomes for the patients, as evidenced by the clinical values obtained. This suggests that the treatment with new prostheses, whether conventional or with shorten digital protocol, is effective in achieving the desired clinical outcomes.

Digital dentures significantly reduced chairside time compared to conventional dentures, leading to the rejection of the null hypothesis on this parameter (154.31 ± 13.19 min vs. 218.00 ± 20.75 min, $p = 1.09E-19$). For elderly or less independent patients, reducing the number of visits can have a significant impact on their quality of life [25]. In this context, digital protocols, particularly those using 3D printing, offer a tangible advantage by potentially reducing not only overall chairside time but also the number of appointments required. This is particularly important for patients living in residential facilities or those with limited access to dental clinics. As reported by Srinivasan M et al. the 3D-printed dentures required more clinical time for adjustments and consequently more cost than the milled dentures [26]. In the present study, no significant differences were found in follow-up time and the number of follow-ups required, suggesting that the null hypotheses for these metrics cannot be rejected. These results are in accord to the ones of other

Table 1
Outcome Measures in CDs and DDs.

	CD Mean ± Std	DD Mean ± Std	T-Statistic	P-Value
BF (N)	273,68 ± 44,38	273,15 ± 43,84	0,46	0,963
MP	0,46 ± 0,06	0,48 ± 0,05	−0,843	0,403
OHIP-14	16,63 ± 3,37	16,53 ± 3,96	1,05	0,916

Table 2
Treatment-Related Metrics in CDs and DDs.

	CD Mean ± Std	DD Mean ± Std	T-Statistic	P-Value
Chairside Time	218,00 ± 20,75	154,31 ± 13,19	13,59	1,09E-19
Follow-up Time	26,94 ± 12,13	28,13 ± 15,37	−0,546	0,587
Number of Follow-ups	1,70 ± 0,47	1,77 ± 0,43	−0,396	0,694
Laboratory Costs	459,15 ± 63,72	378,79 ±137,46	2,91	0,0059

Table 3
Outcome measures in milled and printed DDs.

	Milled Mean ± Std	Printed Mean ± Std	T-Statistic	P-Value
BF (N)	269,77 ± 47,39	274,87 ± 43,24	0,294	0,771
MP	0,47 ± 0,06	0,48 ± 0,06	0,393	0,697
OHIP-14	15,93 ± 4,08	17,13 ± 3,89	−0,825	0,417

Table 4
Treatment-Related Metrics in milled and printed DDs.

	Milled Mean ± Std	Printed Mean ± Std	t-value	p-value
Chairside Time (min)	108,33 ± 18,67	111,80 ± 20,54	−0,52	0,6089
Follow-up (min)	22,80 ± 7,93	24,87 ± 10,51	−0,67	0,5077
N follow-ups (min)	1,86 ± 0,69	1,67 ± 0,80	0,73	0,4725
Lab costs (Euro)	435,16 ± 143,90	322,42 ± 131,02	2,05	0,0496

authors reporting no significant differences in the number of unscheduled post-insertion visits for participants whose dentures were fabricated following injection-molding or milled protocols [27–29]. Additionally, it should be considered that, given that successful CDs therapy is often built on a positive relationship between patient and clinician [30], as reported by the Sririvasan et al. [21] there is an extremely small number of clinical studies which have utilized validated PROMs to evaluate the outcomes of conventional versus 3D printed or milled complete dentures. In this study Quality of Life measures were analyzed in edentate older adults and only a slightly lower patient satisfaction was found in patients treated with DDs.

Lastly, laboratory costs were significantly lower for DDs compared to CDs ones (€378.79 ± 137.46 vs. €459.15 ± 63.72, $p = 0.0059$), resulting in the rejection of the null hypothesis for this aspect in accord with previous studies such as Peroz et al. [17] have reported a 25–30 % reduction in chairside time with the use of DDs compared to CDs [1]. Our results are consistent with studies by Hassel et al. [31], which demonstrated that CAD/CAM-fabricated dentures require less time for adaptation compared to conventional methods and Saponaro et al. [16] where CAD-CAM fabricated dentures performed similarly to CDs in terms of clinical outcomes. Further studies support the effectiveness of DDs in clinical practice [6,26,32,33]. Studies such as those by Goodacre et al. [8] and Bidra et al. [34] support the integration of CAD/CAM technologies into clinical workflows, suggesting that DDs can streamline the fabrication process while maintaining high clinical standards.

Regarding the comparison between milled and 3D-printed dentures, our study found no significant differences in clinical outcomes between the two fabrication methods. Specifically, the mean BF was 26.977 ± 4.739 N for milled dentures and 27.487 ± 4.324 N for 3D-printed ones ($p = 0.771$), suggesting that both manufacturing process offer equivalent performance as supported by other studies [20,35,36].It should be considered that 3D printing allows a substantial reduction in costs compared to the milling fabrication methods (322.42 ± 131.02 vs 435.16 ± 143.90) allowing to make prosthetic rehabilitation more accessible to a larger number of patients, overcoming economic barriers that often limit access to high-quality care.

The environmental sustainability of digital technologies is another point of interest. The use of 3D printing could reduce material waste and improve energy efficiency compared to traditional denture fabrication methods or milling procedure [37].

Finally, although laboratory costs were found to be lower for DDs, it is important to consider the long-term economic implications and evaluate the long-term economic aspect warrants in future studies.

In summary, DDs offer significant advantages in terms of reducing chairside time and the number of appointments required, along with lower laboratory costs compared to CDs. 3D printed dentures have a lower laboratory cost compared to milled ones, but with comparable patients' outcomes. These simplified digital protocols improve access to prosthetic care for a larger number of patients with a positive impact of DDs on patients' satisfaction and oral health-related quality of life [38,39].

However, this study has some limitations that must be considered when interpreting the results. First, it is a retrospective study, which may introduce selection bias and data collection issues. Moreover, the follow-up was limited to one year, which may not be sufficient to fully evaluate the long-term durability and performance of digital dentures, particularly those that are 3D-printed. Future studies with prospective designs and longer follow-ups would be useful to confirm the results and provide a more comprehensive understanding of the effectiveness of different prosthetic technologies. Additionally, it should be considered that in this study a shorten digital protocol, where the old CDs were used to take the final impressions, was compared to the conventional full protocol starting without any references to evaluate the outcomes of a reduced chairside time compared to the gold standard of treatment and correlate the time reduction with standard clinical outcomes. Since the high effectiveness of the shorten digital protocol comparable to the traditional one, it can be concluded that DDs can be considered an effective alternative reducing time and costs. In fact, thanks to the use of Intraoral scanners, it is possible to use the preexisting dentures to obtain the final impression for the new prosthesis in the same appointment, while in a traditional reduced protocol it would have been necessary to duplicate the prosthesis of the patients, increasing laboratory time and costs, or to keep the patient's denture increasing patients' discomfort.

5. Conclusions

Digital dentures, both milled and 3D-printed, are effective alternatives to conventional dentures, reducing chairside time while offering comparable clinical outcomes. Our study and existing research found no significant differences between these digital options, confirming their equivalent performance. Their lower laboratory costs make them viable for broader use, especially in cost-sensitive environments. As digital technologies advance, they will become central in prosthodontics, though ongoing skill development is crucial. Future research should explore their long-term durability, cost-effectiveness, and environmental impact.

CRediT authorship contribution statement

Alessio Casucci: Writing – original draft, Project administration. **Edoardo Ferrari Cagidiaco:** Writing – review & editing, Methodology, Investigation, Data curation. **Giulia Verniani:** Writing – original draft, Validation. **Marco Ferrari:** Writing – review & editing, Validation, Conceptualization. **Andrea Borracchini:** Validation, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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