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Qualitative aspects and minimum requirements of milling machines in digital dentistry: A narrative review

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ABSTRACT

Objectives: This review focused on key outcome variables, including materials used with milling machines, accuracy, machine specifications, efficiency, automation and workflow integration, as well as maintenance and reliability.

Data/sources: A comprehensive literature search was conducted across multiple databases, including PubMed/Medline, Scopus, Embase, Google Scholar, Dynamed, and Open Grey. To expand the search, the "snowballing" technique was also applied, identifying additional studies from the reference lists of relevant papers. The review focused on key outcome variables, including materials used with milling machines, accuracy, machine specifications, efficiency, automation and workflow integration, as well as maintenance and reliability.

Study selection: The search strategy yielded 2811 records. After removing duplicates and excluding papers that did not meet the inclusion criteria, 94 papers were selected for inclusion.

Conclusions: The properties of dental materials significantly influence the requirements of milling machines in prosthodontics, impacting the milling process and performance in fabricating dental restorations. CAD-CAM technology achieves satisfactory marginal fit values, though its superiority over conventional methods remains unclear. Regular calibration and quality assurance are crucial for maintaining accuracy, with specifications like spindle speed and toolpath accuracy affecting efficiency and quality. Software and connectivity improvements in dental milling expand customization options. Regular maintenance ensures consistent performance, reducing noise, predicting tool wear, and minimizing downtime. Addressing challenges and future directions will further enhance CAD-CAM milling machines in dentistry.

Clinical significance: By comprehending the characteristics of materials, accuracy factors, maintenance requirements, and operational parameters, dental practitioners can optimize the utilization of milling machines, thereby achieving superior outcomes.

1. Introduction

Dentistry has undergone a transformative journey fueled by technological advancements, with milling machines emerging as useful tools in prosthetic fabrication, in particular, the integration of milling machines into dentistry's workflow traces back to the latter half of the 20th century, characterized by a shift from traditional methods to computer-aided manufacturing (CAM) technologies [1–4]. This transition was driven by the quest for enhanced precision and efficiency in prosthetic fabrication, leading to the convergence of computer-aided design (CAD) and CAM methodologies [4].

Dental milling machines encompass a broad range of types, from compact benchtop units suitable for small clinics to industrial-grade systems used in large-scale dental laboratories [2,3,5]. Utilizing milling burs, milling machines carve restorations from solid blocks of materials like ceramics, metals, and polymers [2,3,5].

Two primary methodologies exist for milling operations: dry and wet milling, each distinguished by their unique processes and applications. Dry

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milling utilizes a milling machine that operates without the addition of coolant, resulting in a dry operational environment. This method is particularly suitable for processing materials such as zirconia, as it can yield high precision in producing restorations from presintered zirconia blocks. The efficiency of the milling operation is increased in the absence of cooling fluids, although this may lead to a higher wear rate on tools, necessitating frequent maintenance and replacement of milling instruments [6,7]. Conversely, wet milling involves the application of liquid coolants such as water or, in the case of metal materials, refrigerant oils. The introduction of a coolant reduces the temperature and friction during the milling process, which can improve the lifespan of the milling tools and the quality of the machined products. Wet milling is particularly advantageous when working with heat-sensitive materials or when achieving a superior surface finish is critical [8,9]. The choice between wet and dry milling often hinges on the specific properties of the material being milled, alongside the desired characteristics of the final restoration [10,11].

Also, milling machines used in dentistry can be broadly categorized into laboratory machines that mill disks and chairside machines that mill blocks. Laboratory machines are typically more sophisticated, often using 5-axis milling technology. This capability allows for the creation of complex geometries and intricate detailing, which are critical in fabricating high-quality dental restorations [6,12]. These machines are equipped to handle larger volumes, making them ideal for dental laboratories requiring efficiency and precision. In contrast, chairside milling machines are designed for use directly in the clinical setting, enabling dentists to fabricate restorations in a single visit. These machines usually employ 3-axis or 4-axis technology, allowing for more straightforward operations that facilitate immediate patient treatment [6,13]. The workflow is significantly expedited; however, the complexity of the restorations that can be fabricated may be somewhat limited compared to those created with laboratory machines [14].

The integration of milling machines into dentistry has significantly impacted the materials used for fabricating restorations. Commonly milled materials include lithium disilicate, zirconia, PMMA, cobalt-chromium alloys, titanium, polymer-infiltrated ceramics, and hybrid nanocomposites [15–24]. Material properties influence machining performance, affecting tool wear, surface texture, and energy consumption [25–28]. Novel approaches like ultrasonic-assisted milling address machining challenges [29,30]. The machinability of ceramics depends on mechanical properties and instrument characteristics [31], with studies highlighting the importance of the brittleness index [32].

Accuracy is paramount in dental prosthetics fabrication to ensure optimal fit, function, and aesthetics [33]. Modern milling machines are equipped with advanced technologies, including high-resolution optical scanners and multi-axis milling units, capable of achieving micron-level trueness [34]. Key factors influencing accuracy include tool diameter, spindle speed, feed rate, and material properties, necessitating meticulous calibration and adherence to manufacturer-recommended parameters [35,36]. Moreover, the successful integration of milling machines into dental workflows requires adherence to established parameters and guidelines [33,37]. Dental practitioners and technicians must carefully select materials, milling strategies, and machining parameters tailored to each clinical scenario [38]. Furthermore, regular maintenance and calibration of milling machines are imperative to maintain performance consistency and prolong equipment lifespan [39].

The present paper highlights the pivotal role of milling machines in modern dentistry and outlines the minimum requirements and qualitative aspects for their efficiency in clinical applications. In particular, this review analyzes key outcome variables, including the materials used with milling machines, accuracy, milling machine specifications, efficiency, automation and workflow integration, maintenance and reliability, as well as challenges and future directions in digital dentistry. These factors were extracted and analyzed from studies that met specific inclusion criteria, ensuring a focused and relevant discussion on CAD-CAM milling in dentistry. To achieve these objectives, a comprehensive literature search was conducted across multiple databases, including PubMed/Medline, Scopus, Embase, Google Scholar, Dynamed, and Open Grey.

2. Methods

2.1. Search strategy

A comprehensive literature search was conducted across several databases, including PubMed/Medline, Scopus, Embase, Google Scholar, Dynamed, and Open Grey, to find papers related to milling machines. Additionally, the "snowballing" method was used to locate papers within the reference lists of previously identified records. The search employed combinations of the keywords "milling machines" AND "dentistry".

The literature search was completed in July 2024 and the included studies were published between 1987 and 2024.

The queries used for each database were as follows:

- PubMed (Medline), Google Scholar, and Open Grey = "(milling machine) and (dentistry)" were added to each query box.
- Dynamed = milling machine; dentistry.
- Scopus = (TITLE-ABS-KEY (milling AND machine AND dentistry) AND TITLE-ABS-KEY (milling machine dentistry)).
- Embase = ‘milling machine dentistry’ OR ('milling’AND (machine) AND (dentistry)).

To exclude duplicates, the references of the identified records were uploaded as a Research Information Systems file into Mendeley (Mendeley Ltd., London, UK).

2.2. Inclusion and exclusion criteria

Studies were deemed appropriate if they met the following inclusion criteria:

1. Addressed at least one of the following outcome variables related to milling machines in dentistry:
   - Materials used with milling machines
   - Accuracy
   - Milling machine specifications (spindle speed, toolpath precision, axis number).
   - Milling efficiency (speed, power consumption, noise levels).
   - Automation and workflow integration
   - Maintenance and reliability
2. Studies conducted in vitro, in silico, or in vivo
3. Systematic reviews

The exclusion criteria were:

1. Studies conducted on non-human animals
2. Case reports

There were no restrictions on the publication date or language of the papers.

2.3. Data extraction

According to the inclusion criteria, 3 calibrated researchers independently selected the articles by reading the titles, abstracts, and keywords. The full text of each identified article was read to determine whether it was suitable for inclusion. In case of disagreement among the investigators, a majority criterion was used (i.e., 2 out of 3).

2.4. Calibration process

To conduct pilot calibration exercises on the collected titles and abstracts, the three reviewers used a common and randomly selected set of 20 references, applying the inclusion and exclusion criteria. Following this exercise, the reviewers discussed which references were included or excluded. This procedure would be repeated until they reached a pre-determined level of agreement before screening the entire set of recorded titles and abstracts. Additionally, the calibration system was applied to a random selection of 10 papers for full-text screening of the included papers, maintaining the same agreement level. After just one calibration exercise, the reviewers achieved an agreement level of over 90 % for title and abstract screening and 100 % for full-text article screening.

3. Results

3.1. Data synthesis

The search strategy yielded 2811 records, many of which were duplicates: 452 from PubMed/Medline, 717 from Scopus, 225 from Embase, 1258 from Google Scholar, 134 from Dynamed, 13 from Open Grey, and 12 using the “snowballing” approach. After removing duplicates, 881 records remained. Reviewers then examined titles, abstracts, and keywords, excluding 723 records for not meeting the inclusion criteria. Of the remaining 158 records, an additional 64 were excluded after a full-text analysis because they did not provide significant information on milling machines for dental research and clinical practice. The final 94 articles were included in this review (Fig. 1). There was no disagreement among the search investigators. Table 1 provides an overview of the reviewed studies, summarizing the study types and major conclusions regarding CAD-CAM milling technology in Dentistry. A summary of the key studies with findings and clinical implications is shown in Table 2.

3.2. Limitations of the search methodology

This paper is a literature review, meaning it summarizes current literature rather than synthesizing findings or addressing a specific question. Unlike systematic reviews, it does not include statements on formal synthesis or the quality of evidence. Additionally, literature reviews can be biased due to the lack of critical bias assessment. Therefore, this paper does not present statistically validated findings like a systematic review or meta-analysis would. Instead, it qualitatively summarizes evidence related to the materials used with milling machines, focusing on aspects such as accuracy, efficiency, workflow integration, and reliability in dental applications.

4. Discussion

The integration of milling machines into dentistry has had a significant impact on the range of materials utilized for fabricating dental

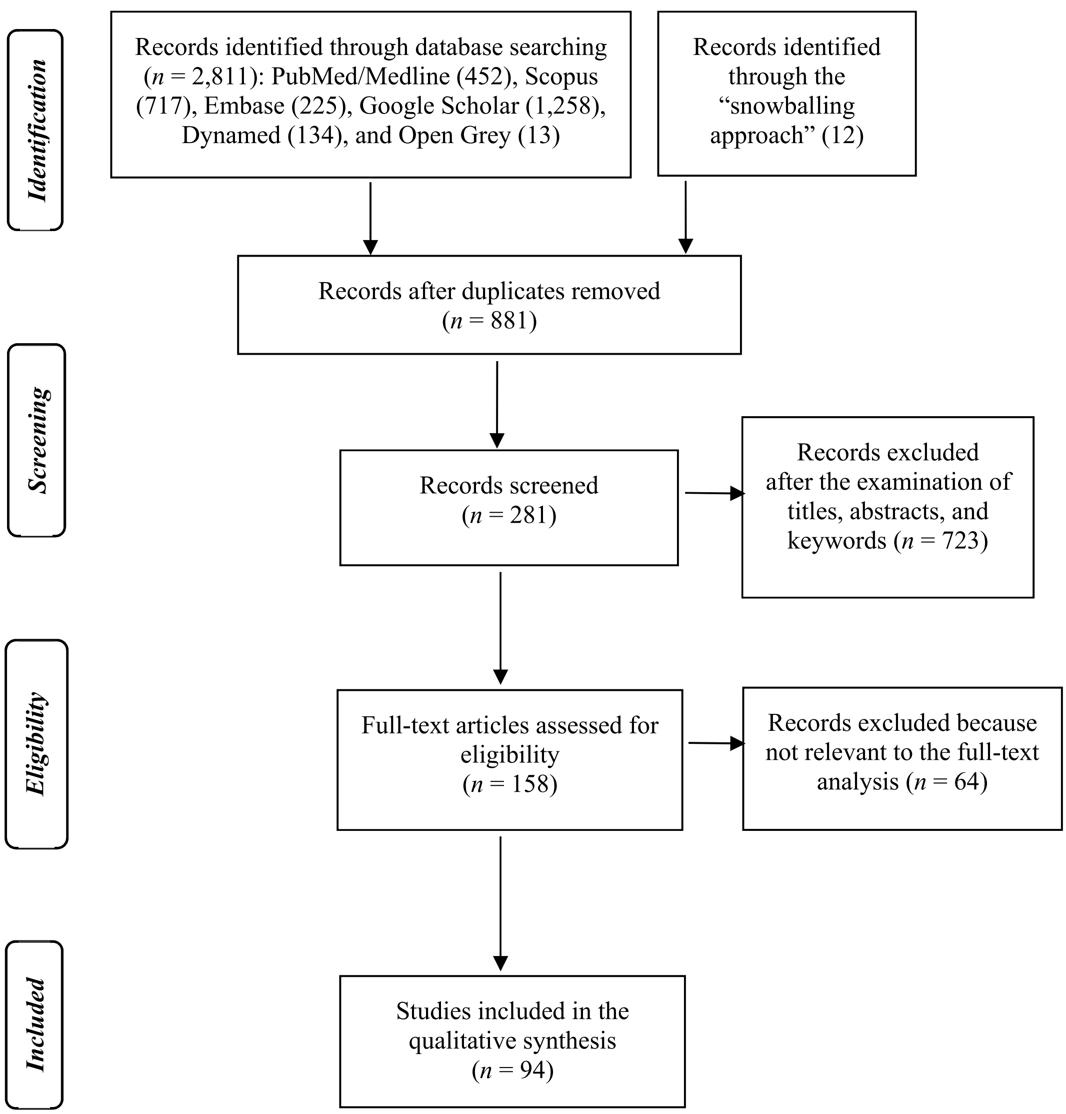

Fig. 1. Title: Search flowchart as described in the PRISMA guidelines. Caption: (n = number of records).

Table 1
Overview of the included studies, summarizing the types and major conclusions regarding CAD-CAM milling technology in dentistry.

Category	Number of Studies	Study Type	Key Findings
Total Selected Studies	94	In vitro, in silico, in vivo, review	Various study methodologies analyzing CAD-CAM milling machines.
Materials Analyzed	25	In vitro, in silico, reviews	Zirconia, lithium disilicate, PMMA, cobalt-chromium alloys, titanium, hybrid nanocomposites.
Accuracy Studies	23	In vitro, in vivo, in silico	Milling accuracy varies with machine specifications; 5-axis machines provide superior marginal fit.
Efficiency	11	In vitro	Milling depth, spindle speed, and toolpath optimization influence processing time and energy efficiency.
Automation & Workflow Integration	15	In vitro, in vivo, review	CAD-CAM integration with intraoral scanners improves efficiency and customization.
Maintenance & Reliability	8	In vitro, In silico	Regular calibration and tool wear monitoring are essential for longevity and consistent performance.
Milling machine specifications	15	In vitro, reviews	spindle speed, toolpath accuracy, tolerance levels, and machine component rigidity, impact the efficiency and quality of milling operations.

restorations. The seminal work of Mörmann and Brandestini in computer-assisted dentistry played a pivotal role in laying the foundation for this evolution [40]. Among the commonly milled materials, there are lithium disilicate, zirconia, polymers such as the PMMA (polymethyl methacrylate), metals such as cobalt-chromium alloys or titanium, polymer-infiltrated ceramic network, and hybrid nanocomposites [15–24].

While significant strides have been made, challenges remain. Standardization of milling processes, material characterization, and the development of milling strategies for emerging materials are ongoing concerns.

The properties of the material being machined could play a crucial role in the performance and requirements of milling machines. Various factors, such as moisture content, brittleness, and energy consumption, have been identified as critical properties that impact the performance of hammer mills [25], posing challenges in conventional machining techniques and leading to the exploration of advanced processes like ultrasonic-assisted milling [26].

Moreover, the energy consumption during material fragmentation is dependent on factors like biomass type, moisture content, material properties, and machine parameters [27]. This highlights the intricate relationship between material properties and the energy requirements of milling machines.

Besides, the impact of material properties on the machining process extends to the selection of cutting parameters and conditions to reduce tool wear and achieve, at the same time, the desired surface texture [28]. The challenging nature of difficult-to-machine materials necessitates the exploration of novel machining approaches, such as vibration-assisted milling and ultrasonic-assisted machining, to address issues like delamination and surface roughness [29,30]. Therefore, it is clear that the material properties have a significant impact on the requirements of milling machines used in dentistry.

The machinability of dental ceramics is strongly dependent on their mechanical and physical properties, as well as on the characteristics of the machining instruments [31]. Additionally, the brittleness index of machinable dental materials and its relation to the marginal chipping factor has been studied, highlighting the importance of this physical parameter in the milling process [32].

In recent years, there has been extensive research on the milling characteristics of various dental materials. Studies have compared the accuracy of dental models manufactured using CAD-CAM milling and 3D printing methods, with results consistently indicating better accuracy in models produced by milling [41]. These findings highlight the superior precision and reliability of milling as a fabrication technique for dental models, although data are changing over time, due to the progress in 3D printing technologies.

Researchers have also focused on comparing different fabrication techniques for dental models with attachments for clear aligners, i.e. additive 3D printing versus subtractive milling [42]. Compared to milling, 3D printing was found to offer a more cost-effective and efficient method for fabricating clear aligner models with attachments, allowing for decreased time and material waste during the production process [42].

Moreover, there have been experimental investigations focusing on the behavior of Co-Cr alloys used in prosthetic restorations under different pH levels [43]. These studies have provided insights into the corrosion characteristics of these materials when produced through casting and milling processes [43]. The findings have significant implications for dental practitioners and researchers, as they enhance our understanding of the performance and durability of Co-Cr alloys in various environments [43].

Table 2
Summary of major studies on CAD-CAM milling in dentistry.

Category	Key Studies	Findings	Clinical Implications
Materials Used in Milling	Fasbinder (2006) [15]; Guess (2012) [17]; Dib Zakkour et al. (2023) [20]; Øilo et al. (2018) [23]; Prause et al. (2024) [24]; Jeong et al. (2018) [41]; Schmalz et al. (2018) [44]	Investigated machinability of zirconia, lithium disilicate, PMMA, and metal alloys, highlighting differences in precision, surface finish, and durability.	Material selection affects restoration longevity, adaptation, and patient outcomes.
Accuracy of Milling	Jeong et al. (2018) [41]; Sidhom et al. (2022) [45]; Papadiochou & Pissiotis (2018) [50]; Abduo et al. (2022) [62]; Alenezi& Yehya (2023) [63]	Reported clinically acceptable marginal fit ranges, with five-axis milling systems achieving higher precision than three-axis systems.	Improved marginal adaptation leads to better prosthetic fit and reduced complications.
Milling Machine Specifications	Kiswanto et al. (2014) [35]; Alenezi & Yehya (2023) [63]; Padrós et al. (2020) [64];	Identified spindle speed, toolpath planning, and milling depth as key parameters influencing quality and efficiency.	Optimized settings enhance restoration accuracy and production efficiency.
Efficiency	Li et al. (2023) [73]; Tang et al. (2016) [84]; Sedlecký et al. (2018) [85]	Demonstrated the role of spindle speed and milling depth in optimizing power consumption and reducing production time.	Faster production benefits high-volume dental practices and reduces patient waiting times.
Automation & Workflow Integration	Bernauer et al. (2023) [37]; Joda & Brägger (2015) [97]; Mangano et al. (2017) [99];	Showed that digital workflows improve fabrication speed, reduce manual errors, and enhance restoration accuracy.	Digital integration streamlines clinical workflows and enhances reproducibility.
Maintenance & Reliability	Ilie et al. (2022) [113]; Song et al. (2021) [114]; Markarian et al. (2018) [108]	Highlighted the importance of tool wear monitoring, predictive maintenance, and calibration for consistent performance.	Regular maintenance extends machine lifespan and ensures consistent milling precision.

The presence of nanoparticles in dental materials has also been a topic of scientific inquiry, particularly about their incorporation into milling-produced dental products. These studies have emphasized the inclusion of nanoparticles and their potential advantages in enhancing the properties of dental materials, indicating that, thanks to the milling processes, they may exhibit improved performance and enhanced functionalities [44].

Additionally, recently the effects of different CAD-CAM milling and 3D printing digital fabrication techniques have been investigated on the accuracy of PMMA working models and of the vertical marginal fit of PMMA provisional dental prostheses [45]. In this study, no significant differences were observed between the 2 methods, suggesting that both techniques can achieve similar levels of accuracy in producing dental working models and, similarly, that 3D printed prostheses exhibited comparable fit to those milled using CAD-CAM technology [45]. These findings highlight the potential of 3D printing as a viable alternative to CAD-CAM milling for fabricating working models and provisional dental prostheses. Additionally, a comparison between additive and subtractive CAD-CAM techniques for producing orthognathic surgical splints demonstrated the superior accuracy of milling technology over 3D printing [46]. This suggests that further advancements in 3D printing technology are needed to establish it as a valid alternative to milling in certain applications [46].

According to the literature, as to working models there is currently no consensus on the clinically acceptable value of accuracy. Some studies about working models fabricated by means of 3D printing defined the clinically acceptable error to be less than 500_μm [47,48]. In this regard, the study of Sidhom et al. reported 3D accuracy values of the milled models within this range (RMS mean = 288.8 ± 49_μm) [45]. The two digital working model fabrication techniques recorded comparable accuracy and, similarly, 3D-printed provisional prostheses showed comparable marginal fit to the CAD-CAM milled ones of Sidhom et al. [45]. Differently, Jeong et al. reported better results of the RMS value (152 ± 52_μm) by the milling method [41].

In prosthodontics, the accuracy requirements for dental models used in the fabrication of dental fixed restorations are considered to be higher, within the clinically accepted threshold of 120_μm, as reported in the classic literature [49]. In the systematic review by Papadiochou and Pissiotis [50], it was reported that the majority of dental restorations or structures generated through CAD-CAM technology exhibit marginal fit values within the clinically accepted range, typically up to 120_mm, as proposed in the staminal paper by McLean and von Fraunhofer [49,50].

In comparison to the slip-casting technique, single crowns produced using the CAD-CAM demonstrated comparable or worse marginal accuracy [51–53]. Besides, for lithium disilicate single crowns, the CAD-CAM systems showed comparable or worse marginal fit than heat-pressed ones [54–58].

As to the marginal fit of metals, both cobalt-chromium and titanium implant frameworks manufactured using CAD-CAM milling system showed better marginal fit values when compared to zirconia [59–61], although Abduo et al. (2012) reported similar vertical fit values for titanium (3.6 ± 0.9-mm) and zirconia Procera (3.7 ± 1.1-mm) 3-unit implant-retained fixed dental prostheses frameworks [62].

However, drawing definitive conclusions regarding the superiority of CAD-CAM milling technology over conventional casting and metal-laser sintering processes in terms of marginal adaptation is challenging.

As expected, the most recent studies focused on the accuracy of CAD CAM restorations report much more favorable results, confirming the advancement of technologies over the last few years. An article by Sidhom et al. showed highly accurate vertical marginal fit values of the milled fixed-dental prostheses [29.9 ± 4.3_μm], well within the clinical acceptance range of 120-μm, for a five-axis milling machine (CAM 5-S1) [45]. Similarly, with 5-axis milling machines, Alenezi and Yehya reported very good marginal fit mean values, respectively of 59 and 84-μm using the Dentsply Sirona inLab MC X5 and the KaVo Everest system [63].

In this context, laboratory milling machines are generally more advanced, often utilizing 5-axis technology. This enhanced capability enables the production of complex geometries and intricate details, which are crucial for high-quality dental restorations [6,12]. Moreover, these machines are designed to process larger volumes, making them highly suitable for dental laboratories that require both precision and efficiency. On the other hand, chairside milling machines are specifically developed for direct clinical use, allowing dentists to fabricate restorations in a single visit. These systems typically operate with 3-axis or 4-axis milling technology, providing a more simplified workflow that facilitates immediate patient treatment [12,13]. While this expedites the restoration process, the level of complexity achievable in chairside-fabricated restorations may be somewhat limited when compared to laboratory-milled restorations [14].

An important study conducted by Padrós et al. compared three-axis and five-axis milling machines, yielding significant findings [64]. The mean marginal gap values of Cr/Co restorations ranged from 92.38 ± 19.24-μm to 19.46 ± 10.20-μm for samples produced by three-axis and five-axis machines, respectively [64]. Additionally, the five-axis machine demonstrated lower roughness of the restoration, resulting in superior surface quality compared to the three-axis machine [64]. Regarding flexural strength, it fell within the range of 6500–7000-N, but no statistically significant differences were evidenced between the two systems [64]. These results suggest that an increase in the number of axes improves vertical fit and surface quality due to reduced roughness [64].

Furthermore, the use of five-axis milling machines has been associated with better marginal fit in restorations compared to four-axis milling machines, as highlighted by a study conducted by El-Mahdy et al. [65]. Additionally, it has been suggested that milling offers advantages over casting in terms of passive fit and accuracy of margins, as indicated by research by Abdelkader et al. [66].

These studies provide valuable insights into the benefits of using five-axis milling machines, including improved marginal fit, surface quality, and accuracy of margins. The findings support the preference for milling techniques over casting methods in achieving optimal results in dental restorations.

A potential drawback of milling with this material is a micro-crack formation during the procedure, which may compromise the mechanical durability of restorations, due to the high machinability index [3]. Additionally, the wear of burs used for chairside milling of ceramic crowns can affect internal fit and surface roughness, highlighting the importance of monitoring and maintaining the milling equipment [67]. However, the topic of hot-pressed vs. milled lithium disilicate has to be still considered somewhat controversial.

The specifications of milling machines play a critical role in determining the performance and accuracy of the production process. Several factors, including spindle speed, toolpath accuracy, tolerance levels, and machine component rigidity, significantly impact the efficiency and quality of milling operations.

The rigidity and strength of milling machine components, such as the milling machine beam, sliding saddle, and spindle sleeve, directly influence working accuracy and service life [68]. Additionally, variable spindle speed milling offers higher practical value and versatility across different machine tools [69]. Higher spindle speeds contribute to better milling surface quality [70,71]. The selection of spindle speed is vital for high-speed milling of specific materials, such as titanium alloy, to ensure effective processing and high-quality surface finish [72]. So, spindle speed is a key factor, with studies indicating that spindle speeds of 5650-min^{-1} [73], 21,400-rpm [74], and 2000-rpm or more are optimal for achieving high milling accuracy and efficiency [75]. Additionally, the influence of cutting parameters such as spindle speed, feed rate, and depth of cut on surface roughness has been extensively studied, with depth of cut identified as the main factor affecting surface roughness [76].

Besides, the rigidity and strength of key components such as the milling machine beam, sliding saddle, and spindle sleeve directly affect working accuracy and service life, highlighting the importance of structural design and finite element analysis in ensuring milling machine performance [68].

Furthermore, the milling depth also plays a crucial role in power consumption and efficiency during milling operations [73]. Moreover, specific toolpath planning and optimization are necessary to acquire smooth toolpaths and avoid interference [77,78]. Considering process vibration and stability in toolpath planning and machining operations is crucial, as the influence of vibration on machining performance in milling should not be overlooked [79].

Besides, the uneven features of dental restorations often require the use of milling machines equipped with burs of various sizes and shapes, generally, their diameter can vary from 0.3 to 2.5-mm for precise and efficient milling of different areas and contours of the restoration [80].

Finally, milling machines in the dental environment can generate excessive noise, which can be disruptive and unpleasant for both patients and dental professionals. To mitigate noise levels (variable from 45 to 70-dB during working time) and create a more comfortable working environment, it is important to utilize noise reduction techniques and soundproofing materials [81,82].

Nowadays, the use of advanced milling machines, such as the 6-axis machine, has been identified as a must for achieving accurate products in dental practice [83].

Several factors were found to significantly influence the milling process and production timelines. Li et al. highlighted that milling depth had the greatest impact on milling power and power efficiency, followed by spindle speed and helical angle [73]. Tang et al. found that the milling force increased with increasing milling speed until a certain point, beyond which it began to decline [84]. Additionally, the milling temperature increased with cutting speed. Sedlecký et al. investigated the effect of milling parameters and thermal modification on power input during wood milling, emphasizing the influence of cutting speeds, feed rates, and rake angles on the milling process [85]. Furthermore, Dharmalingam et al. optimized milling speed and time in mechanical alloying, demonstrating the importance of selecting appropriate milling parameters for the process [86].

To improve the efficiency of milling processes, various advancements have been made in recent years. One approach involves the use of external physical energy fields in combination with traditional mechanical energy in ball milling, which has shown promise in enhancing milling efficiency [84]. Additionally, optimization of milling conditions is crucial to address concerns about potential damage to materials, such as carbon nanotubes, under harsh milling conditions [87]. Furthermore, research on the relationship between milling parameters and energy consumption is essential for optimizing the energy efficiency of milling processes, particularly in industries such as furniture processing [73].

Moreover, advancements in modeling approaches have been identified as a growing need to predict particle size distribution during milling, thereby contributing to the enhancement of milling efficiency [88]. Additionally, micro-end-milling strategy and toolpath optimization have been developed to enhance the performance and capability of micro-end-milling processes, contributing to overall milling efficiency [89].

In practical milling processes, tool path generation has been a subject of study, indicating the importance of this aspect for further advancements in milling efficiency [90]. Furthermore, studies have shown that milling efficiency can be improved when cooling fluids are not used; however, this comes at the cost of increased tool wear, requiring more frequent maintenance and replacement of milling instruments [6,7].

Additionally, research has been conducted to improve computational efficiency for predicting vibration stability in milling, with a particular emphasis on spindle speed variation [91]. Furthermore, optimization and analysis for palm oil mill operations have been investigated to achieve higher economic performance, highlighting the importance of operational optimization in enhancing mill efficiency [92].

The integration of milling machines into digital workflows has brought about a revolution in various fields, particularly dentistry and manufacturing. In the fabrication of fixed adhesive dental prostheses, the use of intraoral scanners and CAD software, followed by mechanized prosthetic milling machines, enables a fully digital workflow [93]. Digital workflows, facilitated by CAD-CAM software, have streamlined processes, leading to improved efficiency and precision in dental prosthesis design and fabrication [94–97]. Studies in dentistry have supported the utility of CAD-CAM-based processes by demonstrating that crowns fabricated using digital workflows have smaller marginal gaps compared to those made using traditional techniques [98]. Furthermore, the use of intraoral scanners and CAD-CAM technologies allows for immediate restoration production, significantly reducing the time required for the entire workflow [99–102].

The automation of milling processes has been a subject of extensive research, aiming to optimize various parameters related to milling tools to maximize cutting depth for chatter-free machining [103]. Additionally, studies have focused on the automation and optimization of solid material grinding using ball mills, which has led to the establishment of relations between technological parameters and indirect indexes, contributing to improved automation systems [104]. Furthermore, research has addressed the dynamic response analysis of milling cutters and the optimization of machining parameters, emphasizing the significance of cutter displacements and deflections in achieving higher productivity in milling operations [105]. Moreover, the integration of toolpath and process parameter optimization has been developed to enhance the performance and capability of micro-milling processes, demonstrating the potential for automation in improving milling operations [89]. Additionally, the development of automated post-machining process planning methods for integrating additive manufacturing with rapid milling processes has been introduced, highlighting the potential for automation in hybrid manufacturing methods [106].

The maintenance requirements of dental milling machines are crucial for ensuring their optimal performance and longevity. Several studies have addressed different aspects related to the maintenance of these machines. For instance, Vera et al. proposed a hybrid intelligent system for optimizing dental milling parameters, which can be instrumental in streamlining maintenance processes by identifying and adjusting critical machine parameters to maintain optimal performance [107]. This approach aligns with the need for proactive maintenance strategies to prevent potential issues and ensure continuous operational efficiency.

Furthermore, Markarian et al. highlighted the challenges associated with manufacturing structures from fully sintered blocks of Co-Cr using CAD-CAM milling machines due to the hardness of the material, shedding light on the specific maintenance considerations for handling such materials and the associated machine wear [108].

Besides, a study on machine learning algorithms for smart manufacturing emphasizes the importance of predictive maintenance in tool wear prediction, which can be crucial for maintaining consistent milling machine performance [109]. Moreover, studies on machine maintenance planning using the Reliability Centered Maintenance (RCM) method emphasize the significance of scheduled maintenance intervals and maintenance strategies to reduce downtime and anticipate sudden machine failures [110]. The active prediction of milling force and the influence of milling kinematics on cutting force components and machined surface roughness further stress the importance of regular maintenance in preventing machining deformation and ensuring surface integrity [111,112].

The wear of dental milling cutters is worth noticing for the maintenance and reliability of milling machines. Remarkable is the data reported by Ilie et al. [113], which studied the wear behavior of dental milling cutters through in vitro experiments and statistical-mathematical modeling [113]. The experimental design was focused on measuring the mass lost by the active side of the cutters due to wear, with the rotation velocity identified as the primary factor influencing wear [113]. The research aimed to address practical issues related to dental milling cutter wear, such as determining replacement criteria, increasing cutter lifespan, optimizing operating conditions, and exploring potential design solutions [113]. The results showed that dental milling cutters undergo significant wear during the milling operation, with the highest mass losses occurring within the first 11 h of work, after which it is recommended to replace the cutters in order to maintain high standards of material processing [113].

The findings of Song et al. indicated that regularly replacing milling burs is crucial to uphold the accuracy of CAD-CAM manufacturing of metal dental prostheses [114]. Ensuring periodic changes in milling burs is essential for achieving optimal fit and consistent results in dental CAD-CAM prostheses [114]. Additionally, enhancing the longevity of milling bur cutting edges can lead to cost savings in fabricating dental prostheses with materials that are less easily machinable [114]. Integrating a drill compensation feature into dental CAD software can help mitigate inaccuracies in prosthesis milling caused by bur wear [114].

Understanding the wear patterns and optimizing cutter usage can help maximize their lifespan, so further studies will be necessary to get the best out of the milling technologies in Dentistry.

CAD-CAM milling machines have undeniably revolutionized the field of dentistry, however, as with any technology, they face challenges and present avenues for future growth and improvement within the dental industry.

One of the foremost challenges encountered by CAD-CAM systems is the limitation imposed by material selection and compatibility. These machines typically work within a predefined set of materials, therefore, expanding the repertoire of compatible materials to include a wider variety with diverse properties could significantly enhance the versatility and applicability of CAD-CAM milling machines, catering to a broader spectrum of clinical needs and patient preferences.

Another persistent challenge lies in the cutting speed and efficiency of the milling process, particularly concerning milling times. Despite significant advancements in technology, milling times can still be relatively long, posing practical limitations in busy dental practices. Balancing the need for expedited fabrication with the imperative to maintain high-quality outcomes remains a key challenge for manufacturers and developers of CAD-CAM systems.

Furthermore, the initial investment and ongoing maintenance costs associated with CAD-CAM systems can present barriers to adoption, particularly for smaller dental practices with limited financial resources. Reducing the upfront costs and simplifying maintenance requirements could democratize access to these transformative technologies, enabling a broader range of dental professionals to harness their benefits.

Integration with other digital technologies, such as intraoral scanners and 3D printers, represents another challenge and opportunity for CAD-CAM milling machines. Enhancing interoperability and seamless integration between these various digital tools can streamline the overall digital workflow in dentistry, enhancing efficiency, accuracy, and patient satisfaction. However, perhaps one of the most crucial challenges lies in user training and skill development. The complexity of CAD-CAM systems necessitates highly skilled operators proficient in both the hardware and software aspects of the technology. Comprehensive training programs and user-friendly interfaces are essential to facilitate the widespread adoption and effective utilization of CAD-CAM milling machines within the dental community.

Looking towards the future, several promising directions emerge for the advancement of CAD-CAM milling machines in dentistry. Research and development efforts focused on innovating new materials, such as high-strength ceramics or bioactive substances, could expand the range of applications and improve the longevity of dental restorations, further enhancing patient outcomes. Additionally, the integration of smart algorithms powered by artificial intelligence (AI) holds great promise for optimizing restoration designs based on patient-specific data, leading to greater precision and efficiency in fabrication. Moreover, the realization of fully automated workflows through robotics integration could further streamline the milling process, reducing the need for human intervention and minimizing errors.

Improvements in scanning technologies, particularly intraoral scanning, are also anticipated to contribute to more accurate digital impressions, ensuring better-fitting restorations and enhancing overall treatment outcomes. Moreover, tailoring CAD-CAM solutions to individual patient needs, considering factors like biomechanics and tissue compatibility represents a patient-centric approach that can improve treatment success and patient satisfaction.

5. Conclusions

This review highlights the essential factors influencing the performance and clinical application of CAD-CAM milling machines in dentistry. The analysis of existing literature reveals that material properties play a crucial role in determining milling accuracy, surface quality, and overall restoration fit. While CAD-CAM technology generally achieves satisfactory marginal adaptation, its superiority over traditional methods varies depending on the material and specific milling parameters.

Machine specifications, such as spindle speed, toolpath accuracy, and milling strategies, directly impact efficiency and precision. The integration of five-axis milling systems has demonstrated improved accuracy and surface smoothness compared to three-axis systems. However, ongoing maintenance, including regular calibration and tool wear monitoring, remains critical to sustaining long-term performance.

Automation and digital workflow integration have streamlined prosthetic fabrication, reducing manual intervention and improving efficiency. However, challenges persist, including the high initial cost of milling machines, material limitations, and the need for further advancements in software and process optimization.

Future research should focus on refining milling strategies, expanding the range of machinable materials, and enhancing digital workflow compatibility. By addressing these challenges, CAD-CAM milling technology can continue to evolve, improving precision, efficiency, and overall clinical outcomes in digital dentistry.

CRediT authorship contribution statement

Gennaro Ruggiero: Writing – review & editing, Methodology, Conceptualization. **Roberto Sorrentino:** Writing – original draft, Visualization, Data curation. **Pietro Venezia:** Methodology, Formal analysis. **Giuseppe Luongo:** Supervision, Formal analysis. **Fernando Zarone:** Writing – review & editing, Project administration, Formal analysis.

Patient consent

I confirm that we have received a complete written informed consent from the patient for the publication of this study and accompanying images. A copy of the written consent is available for review by the Editor-in-Chief of the journal upon request.

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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Data availability

Data will be made available on request.

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