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Original Article

Effects of polishing press-on force on surface roughness and gloss of CAD-CAM composites

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Abstract

Purpose: The aim of this study was to determine the effect of polishing press-on force on surface roughness and gloss of computer-aided design-computer-aided manufacturing (CAD-CAM) composites.
Methods: The materials evaluated included a CAD-CAM ceramic, a polymer-infiltrated ceramic, and three filler-based CAD-CAM composites. The CAD-CAM blocks were sectioned, embedded in self-cured resin, finished with abrasive papers and ultrasonically cleaned. Specimens were subsequently polished using the Sof-Lex disk system with 0.5, 1.0, 1.5, and 2.0 N press-on force by means of a custom-made apparatus. Contour arithmetic mean deviation (Ra) and gloss value (GU) data were acquired with a profilometer and glossmeter, respectively, and analyzed using ANOVA/Bonferroni *post hoc* test and Pearson's correlation ($\alpha = 0.05$). Representative samples of the various materials at baseline and after each polishing step were examined under scanning electron microscope.
Results: Mean Ra and GU values ranged from 0.096 ± 0.004 μm to 0.295 ± 0.045 μm and 13.4 ± 1.9 to 67.6 ± 11.3 correspondingly for the various material-force combinations. Surface roughness and gloss were found to be press-on force and material dependent. A moderately strong and negative correlation ($r_s = -0.69$) existed between Ra and GU values.
Conclusion: For optimal smoothness and gloss, ceramic and polymer-infiltrated ceramic CAD-CAM materials must be polished with a 2.0 N force, while filler-based CAD-CAM composites should, in general, be polished using a 1.0 to 1.5 N force.

Keywords: CAD-CAM, gloss, polishing, press-on force, surface roughness

Introduction

Computer-aided design-computer-aided manufacturing (CAD-CAM) technology is widely used in digital dentistry and enables indirect restorations to be delivered in a single visit. A wide variety of CAD-CAM restorative materials are available for producing restorations, including ceramics and composites. Rough restoration surfaces may be created during milling and chairside adjustments, which might lead to patient discomfort, esthetic imperfections, bacterial accumulation, and abrasion of opposing teeth [1-4]. Finishing (gross shaping and polishing to achieve anatomical contours) and polishing (step after finishing to attain high surface smoothness and luster) of CAD-CAM restorations must thus be performed.

Conventional ceramic restorations are usually glazed in the laboratory after finishing/polishing by firing in a furnace to obtain smooth and glossy surfaces. As dental furnaces are not available in most clinics, chairside polishing procedures are routinely employed by the majority of clinicians if restoration adjustments are required. Polishing instruments for ceramic as well as resin-based composite (RBC) materials include abrasive disks, rubber points, cups, lenses and polishing pastes [5].

Abrasive disks have produced excellent results for polishing feldspathic glass ceramics and RBCs when applied to the labial surfaces of anterior and buccal/proximal surfaces of posterior restorations [6-9]. Nonetheless, no consistent protocol has been established for the use of abrasive polishing disks. This could be attributed in part to variance in the abrasive disk system applied, and the press-on force among operators [10].

The influence of press-on force on surface roughness and gloss of RBCs was found to vary between materials [11]. While surface roughness specifies the micro-irregularity and unevenness of surfaces, gloss denotes the shine or luster of smooth surfaces. Surface roughness and gloss have been reported to be closely connected [12]. Smooth (low surface roughness) and glossy restorations increase patient comfort, enhance aesthetics, reduce plaque adhesion and are more maintainable [2,5,8]. Optimal press-on forces for polishing RBCs were 0.2 N to 0.3 N for aluminum-coated disks and 2.0 N with rubber cups [12,13]. In most previous studies, the press-on force was calibrated only before/during the polishing procedure and was not constantly monitored [7,14]. This may inadvertently result in some inconsistency and inaccuracy [7,14]. Moreover, the press-on force has been found to exceed 2.0 N, which is the highest recommended force by most manufacturers, during a quarter of the polishing time [10].

Literature pertaining to the impact of press-on force on the surface roughness and gloss of RBCs is still limited, while that for CAD-CAM composites is unavailable. CAD-CAM composites are thought to behave differently from light-cured RBCs in view of their standardized and controlled production involving high temperature and/or high-pressure polymerization that results in higher polymer cross-linking. Therefore, the objectives of this study were to compare the effect of press-on force during polishing on the surface roughness and gloss of CAD-CAM composites and to establish the optimal press-on force for the various materials. In addition, differences in surface roughness and gloss between CAD-CAM materials were also compared. The null hypotheses were as follows: (a) press-on force during polishing does not influence surface roughness and gloss of CAD-CAM composites, (b) there is no optimal press-on force for CAD-CAM composites, and (c) there is no difference in surface roughness and gloss between the various CAD-CAM materials.

Materials and Methods

Specimen preparation

The materials selected for this study included a CAD-CAM feldspathic ceramic (Vita Mark II [VM], Vita Zahnfabrik, Bad Sachingen, Germany) and four CAD-CAM composite blocks. Based on their microstructure, the CAD-CAM composites can be sub-categorized into polymer-infiltrated ceramic network (Vita Enamic [VE], Vita Zahnfabrik) and dispersed fillers (Lava Ultimate [LU], 3M ESPE, St Paul, MN, USA), (Shofu Block HC [SB], Shofu Inc., Kyoto, Japan), and (Brilliant Crios [BC], Coltène AG, Altstätten, Switzerland). The technical profiles and manufacturers of the various CAD-CAM materials are shown in Table 1. The sample size for each material and press-on force combination ($n = 6$) was determined using the G*Power Software version 3.1.9.3 based on an ANOVA test with an effect size of 0.4, alpha error of 0.05 and power of 80% for five materials

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Table 1 CAD-CAM materials evaluated

Materials	Manufacturer	Type	Main composition
Vita Mark II (VM)	Vita Zahnfabrik (Bad Sachingen, Germany)	CAD-CAM ceramic	feldspar glass ceramic, SiO_2, Al_2O_3, Na_2O, K_2O, CaO and TiO_2
Vita Enamic (VE)	Vita Zahnfabrik	CAD-CAM polymer-infiltrated ceramic	polymer (UDMA and TEGDMA) network infiltrated into feldspar based ceramic network
Lava Ultimate (LU)	3M ESPE (St Paul, MN, USA)	nanofill CAD-CAM composite	Bis-GMA, UDMA, Bis-EMA, TEGDMA, non-agglomerated SiO_2 (20 nm) and ZrO_2 (4-11 nm), and SiO_2/ZrO_2 nano-agglomerates.
Shofu Block HC (SB)	Shofu Inc. (Kyoto, Japan)	microhybrid CAD-CAM composite	polyurethane resin matrix and zirconium silicate micro ceramic filler
Brilliant Crios (BC)	Coltène AG (Altstätten, Switzerland)	microhybrid CAD-CAM composite	Bis-MEPP, UDMA, DMA, silica (20 nm), barium glass (300 nm)

and four different press-on forces.

CAD-CAM blocks (12 × 14 mm) of the various materials were sectioned into 1.5 mm thick specimens using a low-speed diamond saw under water coolant (SYJ-150, MTI Corp., Richmond, CA, USA). The CAD-CAM sections were examined for surface defects and embedded in cylindrical self-cured resin holders (30 mm diameter and 15 mm height) to facilitate subsequent polishing procedures.

To simulate milled surfaces, the CAD-CAM specimens were roughened with 240-grit and 400-grit silicon carbide abrasive papers under water coolant using a grinding machine (AutoMet250 Grinder-Polisher, Buehler, IL, USA) operated at a rotation speed of 300 r/min. The specimens were then ultrasonically cleaned for 10 min in distilled water and air-dried.

Polishing procedures

Baseline surface roughness and gloss were assessed prior to polishing. The specimens were polished with an alumina disk polishing system (Sof-Lex, 3M ESPE) using a low-speed handpiece (NM-EC, NSK, Tokyo, Japan) set at 10,000 rpm. The polishing sequence consisted of three grades of polishing disks, namely, medium (4931M), fine (4931F), and superfine (4931SF), with each disk grade being applied for 30 s [13]. After each polishing step, the polishing disk was replaced. The specimens were ultrasonically cleaned in distilled water, air-dried and re-evaluated for surface roughness and gloss.

A custom-built apparatus was used to maintain constant press-on force and movement of the polishing disks (Fig. 1). The low-speed handpiece was fixed onto a jig linked to a sliding guide that provided reciprocating movements at a speed of 2.5 mm/s and a distance of 5 mm. The CAD-CAM specimens with their holders were mounted in a special receptacle that allowed for weights to be placed for simulating various press-on forces. A total of four different press-on forces (i.e., 0.5, 1.0, 1.5, and 2.0 N) were evaluated. The receptacle with specimen and holder weighed 50 g and gave a force of 0.5 N. Additional weights of 50 g to 150 g were added to vary the press-on force accordingly.

Measurement of surface roughness

Surface roughness (Ra value) was measured using a profilometer (Surftest SJ-410, Mitutoyo, Kawasaki, Japan) with a stress force of 0.75 mN, cutoff of 0.8 mm, transverse length of 3.2 mm, and stylus speed of 0.5 mm/s. Calibration was performed before each measurement with a standard plane (reference Ra value of 2.94 µm). For each specimen, four Ra readings were attained by rotating the specimen at an angle of 45° for each measurement. The numerical average of the readings was calculated and recorded as the Ra value for the specimen.

Measurement of gloss

Surface gloss was determined using a glossmeter (Novo-Curve, Rhopoint Instruments, Hastings, England) with an incident angle of 60°. Calibration was performed before each measurement via a standard plate with a reference value of 93.7 GU. The measurements were performed in a black container to minimize the influence of external light. Four GU readings were obtained at the center of each specimen by rotating the specimen at an angle of 90° for each measurement. The numerical average of the readings was calculated and recorded as the GU value for the specimen.

Scanning electron microscope (SEM) observation

Representative samples of the material at baseline and after polishing with medium, fine and superfine disks with a 1.0 N press-on force were subjected to SEM analysis. The specimens were fixed on an alumina stub, gold-sputtered, and observed under 2,000× magnification.

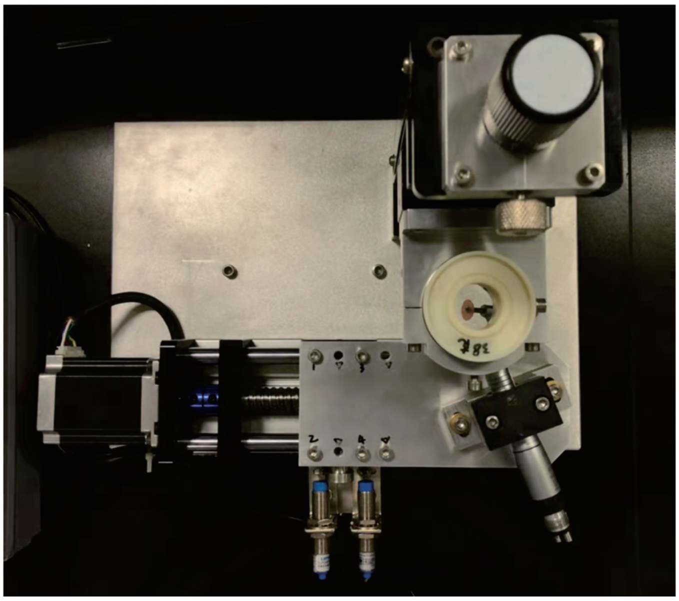

Fig. 1 Custom-built polishing apparatus

Statistical analysis

The SPSS 24.0 software (IBM, Chicago, IL, USA) was used for statistical analysis with the significance level set at 0.05 ($\alpha = 0.05$). Data were subjected to the Shapiro-Wilk test and Levene test to test the normality and equality of variance. Both Ra and GU data were found to be normally distributed having homogeneity of variance, and were analyzed using two-way ANOVA and Bonferroni *post hoc* test. Additionally, the association between surface gloss and roughness was examined using Pearson's correlation.

Results

The baseline and sequential surface roughness and gloss of the materials are shown in Tables 2 and 3, respectively. The data are also presented as line charts in Fig. 2. The results of two-way ANOVA indicated that both Ra and GU values were significantly influenced by press-on force and material ($P < 0.001$). The interaction between the two factors was also significant ($P < 0.001$), suggesting that the effect of press-on force during polishing on Ra and GU was material dependent.

Surface roughness

Regardless of the press-on force, surface roughness generally decreased with increasing fineness of the abrasive disks with the exception of VM. For VM, the smoothest surfaces were mostly observed after polishing with a medium grade disk. Subsequent polishing with finer disks with a force of 1.0 to 2.0 N resulted in rougher surfaces. Significant differences in Ra values between the various press-on forces were as follows: VM-0.5 N > 1.0 N, 1.5 N > 2.0 N; VE-0.5 N > 2.0 N; LU-0.5 N > 1.0 N; SB-2.0 N > 1.5 N; and BC - NS (where > indicates significantly higher Ra values, and NS

Table 2 Baseline and sequential surface roughness (Ra values) of the materials (μm)

Materials	Groups	Polishing sequence			
		baseline	medium	fine	superfine
VM	VM-0.5 N	0.638 ± 0.037	0.451 ± 0.028	0.311 ± 0.030	0.295 ± 0.045^{Aa}
	VM-1.0 N	0.661 ± 0.034	0.097 ± 0.017	0.138 ± 0.028	0.140 ± 0.039^{Ba}
	VM-1.5 N	0.661 ± 0.032	0.089 ± 0.018	0.149 ± 0.018	0.166 ± 0.020^{Ba}
	VM-2.0 N	0.615 ± 0.023	0.072 ± 0.009	0.102 ± 0.028	0.108 ± 0.034^{Cb}
VE	VE-0.5 N	0.620 ± 0.053	0.202 ± 0.040	0.158 ± 0.010	0.160 ± 0.017^{Ab}
	VE-1.0 N	0.660 ± 0.044	0.278 ± 0.013	0.185 ± 0.013	0.129 ± 0.013^{ABab}
	VE-1.5 N	0.655 ± 0.066	0.288 ± 0.014	0.188 ± 0.023	0.139 ± 0.007^{ABab}
	VE-2.0 N	0.595 ± 0.017	0.229 ± 0.022	0.142 ± 0.011	0.124 ± 0.009^{Bab}
LU	LU-0.5 N	0.708 ± 0.092	0.276 ± 0.054	0.170 ± 0.016	0.133 ± 0.013^{Ac}
	LU-1.0 N	0.706 ± 0.155	0.281 ± 0.045	0.142 ± 0.020	0.096 ± 0.004^{Bb}
	LU-1.5 N	0.713 ± 0.075	0.329 ± 0.028	0.170 ± 0.022	0.103 ± 0.011^{ABc}
	LU-2.0 N	0.708 ± 0.007	0.305 ± 0.009	0.176 ± 0.006	0.129 ± 0.006^{ABab}
SB	SB-0.5 N	0.622 ± 0.119	0.461 ± 0.080	0.195 ± 0.019	0.125 ± 0.009^{ABbc}
	SB-1.0 N	0.678 ± 0.058	0.504 ± 0.123	0.200 ± 0.016	0.123 ± 0.012^{ABab}
	SB-1.5 N	0.632 ± 0.048	0.499 ± 0.077	0.183 ± 0.019	0.106 ± 0.017^{Abc}
	SB-2.0 N	0.606 ± 0.078	0.467 ± 0.102	0.228 ± 0.009	0.143 ± 0.020^{Ba}
BC	BC-0.5 N	0.731 ± 0.047	0.216 ± 0.038	0.138 ± 0.019	0.111 ± 0.008^{Ac}
	BC-1.0 N	0.614 ± 0.110	0.297 ± 0.027	0.165 ± 0.023	0.104 ± 0.014^{Ab}
	BC-1.5 N	0.681 ± 0.057	0.332 ± 0.036	0.162 ± 0.011	0.116 ± 0.005^{Abc}
	BC-2.0 N	0.658 ± 0.097	0.431 ± 0.113	0.218 ± 0.050	0.132 ± 0.019^{Aab}

Statistically significant differences in Ra values after sequential polishing are presented in the superfine column. Different capital letters indicate significant differences among press-on forces for individual materials (P < 0.05), while different small letters indicate significant differences among materials for specific press-on forces (P < 0.05). VM, Vita Mark II; VE, Vita Enamic; LU, Lava Ultimate; SB, Shofu Block HC; BC, Brilliant Crios

Table 3 Baseline and sequential gloss (GU values) of the materials

Materials	Groups	Polishing sequence			
		baseline	medium	fine	superfine
VM	VM-0.5 N	7.7 ± 0.4	10.8 ± 2.0	12.2 ± 1.7	13.4 ± 1.9^{Ac}
	VM-1.0 N	8.8 ± 0.5	58.0 ± 6.8	57.9 ± 7.1	53.5 ± 6.3^{Ba}
	VM-1.5 N	8.6 ± 0.2	64.3 ± 5.2	55.8 ± 7.0	55.5 ± 3.4^{Ba}
	VM-2.0 N	9.9 ± 0.4	62.9 ± 6.5	67.3 ± 15.3	67.6 ± 11.3^{Ca}
VE	VE-0.5 N	8.2 ± 0.8	9.6 ± 1.8	9.6 ± 1.2	14.3 ± 1.8^{Ac}
	VE-1.0 N	7.9 ± 0.8	9.5 ± 1.1	14.6 ± 1.2	21.9 ± 4.0^{ABb}
	VE-1.5 N	7.7 ± 0.6	9.1 ± 1.3	17.6 ± 2.6	21.1 ± 4.0^{ABb}
	VE-2.0 N	5.8 ± 0.4	10.8 ± 2.2	18.1 ± 1.8	28.2 ± 3.1^{Bc}
LU	LU-0.5 N	12.2 ± 1.3	13.7 ± 3.5	25.5 ± 3.7	48.1 ± 9.9^{ABb}
	LU-1.0 N	8.0 ± 1.2	13.6 ± 3.7	28.0 ± 7.8	50.0 ± 7.4^{ABa}
	LU-1.5 N	10.0 ± 1.4	12.0 ± 1.8	23.3 ± 4.6	54.0 ± 3.5^{Aa}
	LU-2.0 N	9.9 ± 0.9	8.8 ± 0.4	21.1 ± 2.4	41.5 ± 3.4^{Bb}
SB	SB-0.5 N	7.7 ± 0.6	5.4 ± 1.8	20.6 ± 2.7	58.3 ± 7.8^{ABa}
	SB-1.0 N	7.3 ± 0.9	5.8 ± 1.8	18.7 ± 1.9	48.2 ± 3.7^{Ca}
	SB-1.5 N	7.4 ± 0.6	6.5 ± 0.6	21.5 ± 4.3	51.9 ± 3.5^{ABCa}
	SB-2.0 N	8.0 ± 1.4	9.0 ± 2.2	19.9 ± 2.0	59.8 ± 4.7^{Aa}
BC	BC-0.5 N	7.8 ± 0.5	23.9 ± 7.5	37.9 ± 4.8	50.0 ± 7.2^{Aab}
	BC-1.0 N	9.3 ± 2.2	9.3 ± 2.6	20.2 ± 5.5	54.2 ± 6.3^{ABa}
	BC-1.5 N	8.4 ± 2.3	9.3 ± 0.9	17.9 ± 2.8	60.2 ± 3.5^{Ba}
	BC-2.0 N	7.9 ± 1.1	8.5 ± 2.1	17.1 ± 1.7	47.6 ± 5.8^{Ab}

Statistically significant differences in GU values after sequential polishing are presented in the superfine column. Different capital letters indicate significant differences among press-on forces for individual materials (P < 0.05), while different small letters indicate significant differences among materials for specific press-on forces (P < 0.05).

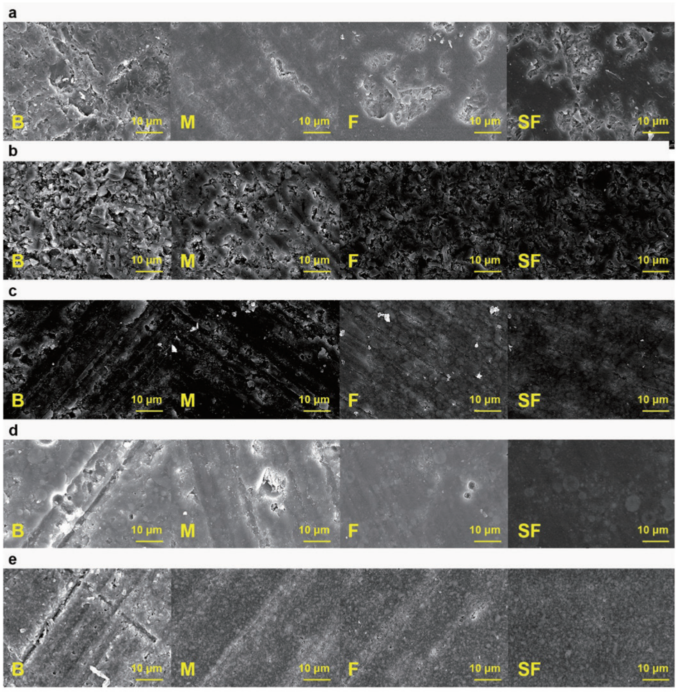

Fig. 2 SEM images of the various CAD-CAM materials ([a] VM; [b] VE; [c] LU; [d] SB; [e] BC) at baseline (B), and after polishing with medium (M), fine (F), and superfine (SF) abrasive discs

denotes no significant difference). The press-on force that offered the highest smoothness varied between materials in the following way: VM-2.0 N; VE-2.0 N; LU-1.0 N; SB-1.5 N; and BC-1.0 N.

Significant differences in Ra values between materials fluctuated with the press-on force during polishing as follows: 0.5 N-VM > VE > LU, BC, and VM > SB; 1.0 N-VM > BC, LU; 1.5 N-VM > BC, SB, LU, and VE > LU; 2.0 N-SB > VM (where > indicates statistically higher Ra values). When polished using 0.5 N to 1.5 N force, VM presented significantly rougher surfaces when compared to many of the CAD-CAM composites. However, VM was significantly smoother than SB when polished with a 2.0 N force.

Surface gloss

Apart from VM, surface gloss generally increased with increasing fineness of the abrasive disks for all press-on forces. Significant differences in GU values between the different press-on forces were as follows: VM-2.0 N > 1.5 N, 1.0 N > 0.5 N; VE-2.0 N > 0.5 N; LU-1.5 N > 2.0 N; SB-2.0 N, 0.5 N >1.0 N; and BC-1.5 N > 0.5 N, 2.0 N (where > indicates significantly higher GU values). The highest gloss was obtained when VM, VE, and SB were polished using 2.0 N, whilst LU and SB were treated with a 1.5 N press-on force.

Significant differences in GU values between materials for the various press-on forces were as follows: 0.5 N-SB > LU > VE, VM, and BC > VE, VM; 1.0 N-BC, VM, LU, SB > VE; 1.5 N-BC, VM, LU, and SB > VE; and 2.0 N-VM, SB > BC, LU > VE (where > indicates statistically higher GU values). Regardless of the polishing press-on force, VE generally presented the lowest surface gloss. VM required higher press-on forces of 1.0 to 2.0 N to achieve comparable gloss to the CAD-CAM composites. The correlation between GU and Ra values revealed a moderately strong negative association (correlation coefficient $r_s = -0.69$). Surface gloss thus increases with diminishing material roughness.

SEM observation

SEM images of the roughened and polished surfaces of the various CAD-CAM materials are presented in Fig. 2. For VM, large defects caused by crack propagation were observed at baseline. After polishing with a medium grade disk, most surface defects were eliminated and small areas of surface exfoliation were seen. The area of surface faults increased after polishing with fine and superfine disks. VE specimens were noted to have similar surface defects to VM at baseline. After sequential polishing, the regular ceramic network structure was gradually revealed with a few minute cracks and defects. For LU, deep furrows and delaminations were detected, and the microstructural components of LU were not discernible. The flaws were gradually eliminated after sequential polishing revealing evenly distributed nano-agglomerate fillers. For SB, large deep grooves were clearly visible with circular depressions caused by filler detachment. After polishing with a superfine disk, spherical ceramic fillers that were embedded in the resin matrix were discerned. For BC, the original deep troughs were also removed by the polishing procedure. Irregular shaped fillers and small depressions were noted after polishing.

Discussion

This study examined the effect of press-on force during polishing on the surface roughness and gloss of CAD-CAM composites. As both polishing press-on force and material significantly influenced surface roughness and gloss, and an optimal press-on force ensued for the CAD-CAM materials, all three null hypotheses were rejected.

A custom-built apparatus was used to regulate the press-on force of the polishing disks on the CAD-CAM specimens. Previous studies have demonstrated that polishing pressure varies between operators, and even in the same individual [10]. Furthermore, surface roughness of composites differed significantly among operators even when using the same instrument [15]. Only two studies employed the use of a specially designed apparatus to regulate the press-on forces applied. In the set-up by Heintze et al., the polishing device was placed vertically on the specimen using a constant press-on force to counterbalance the incoming air pressure that was measured with a manometer [12]. In contrast, Alawjali et al. utilized a paralleling device to fix the handpiece and standardize the pressure on the specimens [16]. The custom-built apparatus in this study combined the advantages of both devices, permitting press-on force measurement as well as consistent movement of the polishing disks.

The Sof-Lex abrasive disk system was selected as the polishing instrument due to its superior performance for both ceramic and composite materials. In-vitro studies demonstrated that the polishing of CAD-CAM ceramics with Sof-Lex disks produced smoother surfaces than even glazing [7,11]. A systematic review also concluded that smooth surfaces can be achieved on different types of RBCs by polishing with Sof-Lex disks [17]. Moreover, Sof-Lex disks were also found to produce smoother surfaces on hybrid materials than the manufacturers' recommended polishing protocols [14].

A critical threshold Ra value of above 0.2 μm has been shown to enhance bacterial adhesion, increasing the risk of caries and periodontal disease [18]. This critical threshold Ra value was achieved by all material and press-on force combinations apart from polishing of VM at 0.5 N. It was also attained by polishing with the fine grade disk for all materials with the exception of VM at 0.5 N, and SB/BC at 2.0 N.

Polishing could be considered a micro-grinding process on the material surface. Although the micro-mechanism of polishing varies, it generally involves material removal through abrasive wear, ductile flow and some degree of micro-fracturing [19]. The influence of polishing press-on force on surface roughness was thus anticipated. As the CAD-CAM ceramic (VM) and polymer-infiltrated ceramic (VE) were harder than filler-based CAD-CAM composites, higher press-on forces may be required during polishing [20]. As filler-based CAD-CAM composites are relatively softer, more material will be removed during polishing for a given press-on force. Greater depth of cuts and increased surface roughness may thus occur when they (LU, SB, and BC) were polished with a 2.0 N force.

In addition to the press-on force, the microstructure of the CAD-CAM materials also affects surface roughness. For filler-based composites, surface roughness is influenced by filler particle shape, size, and volume, as filler dislodgement during polishing leads to surface voids and dents [21]. The SEM images of SB revealed round voids where spherical fillers were displaced. Irregularly shaped cavities were also observed for BC due to the same reason. For LU, no surface voids were noted. This may be attributed to the blend of nano-sized ceramic particles (4-20 nm) and nano-agglomerate fillers employed which were substantially smaller in size than the hybrid fillers in SB and BC. Notwithstanding the variance in filler sizes, no significant differences in Ra were observed between the three filler-based CAD-CAM composites (i.e., LU, SB, and BC) regardless of press-on force.

VM and VE are ceramic and hybrid ceramic materials that are structurally different from the filler-based composites. VM has a heterogeneous microstructure composed of a glass matrix and discrete feldspar crystals [22]. Cracks generated during finishing propagate easily in the brittle glass matrix causing delamination and rough surfaces that were readily observed in the baseline SEM [22]. After polishing with medium grade disks, the large cracks and surface defects were eliminated, and micro-undulations appeared. As the depth of cuts was rather small, material removal may be achieved by ductile flow rather than cracks and fractures, resulting in less subsurface damage and smoother surfaces [19]. The increased surface roughness of VM with the use of fine and superfine grade disks was not anticipated. Although the exact mechanism is not known, it appears to involve a delamination process under SEM observation. For VE, the large surface irregularities at baseline were removed to reveal the fine ceramic network structure with sequential polishing.

Surface gloss is characterized by the amount of light reflected by a surface at the same angle as the incident light [23]. Although clinically acceptable gloss values have not been specified in the literature, Mörmmann et al. found that enamel had a GU value of 53 [24]. Based on a 10% variance as the benchmark, the following material and press-on force combinations did not achieve adequate gloss: VM polished at 0.5 N, VE polished at 0.5 to 2.0 N, and LU polished at 2.0 N. The highest and lowest surface glosses were attained with VM and VE, respectively. The findings were corroborated with those of previous studies by Koizumi et al. and Lawson et al [25,26]. For VM, higher press-on forces were needed to achieve satisfactory gloss. This may be attributed to its higher hardness when compared to the CAD-CAM composites. The surface gloss of VE was significantly lower than that of all other CAD-CAM materials when polished using 1.0 to 2.0 N force, and may be ascribed to its microstructure. In the present study, each disk grade was only applied for 30 s as proposed by Jones et al for RBCs [13]. As a hybrid ceramic material, VE may require longer polishing time due to its complex microstructure and greater hardness.

Gloss values among the filler-based CAD-CAM composites LU, SB and BC were largely comparable when polished using 1.0 to 2.0 N force. Theoretically, composites with smaller filler particles should present glossier surfaces on account of their lower degree of diffuse reflection [27]. The nanofilled LU should thus offer higher gloss than SB and BC. However, several studies reported no significant difference in gloss between composites with nano-sized and microhybrid fillers after polishing with Sof-Lex disks [28,29].

A moderately strong negative or inverse correlation between Ra and GU values was observed. This was foreseeable as the degree of diffuse reflection increases as light rays hit a rougher surface [27]. Nevertheless, this relationship was found to be less apparent in earlier studies. Antonson et al. noted significant differences in GU values between polishing systems despite comparable surface roughness [30]. In addition, Heintze et al. reported that while gloss increased consistently during polishing, GU values did not correspond with the reduction of surface roughness [10]. Extended polishing may thus be required after achieving clinically acceptable smoothness, to attain high gloss on CAD-CAM restorations.

The present study had several limitations. First, only one polishing system was evaluated. Further studies incorporating rubber points, cups, lenses as well as polishing pastes are warranted. They are pertinent especially for the occlusal surfaces of restorations where abrasive disks are not recommended as they are difficult to control and might result in uneven surfaces as well as loss of anatomy [12,29]. Furthermore, a combination of abrasive disks coupled with polishing pastes may enhance the results and needs to be investigated. Second, the polishing time and handpiece speed were set at 30 s and 10,000 rpm, respectively. These variables could significantly influence surface roughness and gloss of CAD-CAM materials, and require in-depth exploration. Lastly, additional CAD-CAM ceramic and composite materials, with different microstructures should also be investigated in future work.

Within the limitations of this study, the following conclusions can be made:

- The effect of press-on force on surface roughness and gloss of CAD-CAM composites was material dependent.
- To achieve optimal smoothness, ceramic and polymer-infiltrated ceramic CAD-CAM materials must be polished with a 2.0 N force, while filler-based CAD-CAM composites can be polished using a 1.0 to 1.5 N force.
- Smoother surfaces were glossier with a moderately strong negative correlation between Ra and GU values.
- The highest gloss was obtained when VM, VE, and SB were polished using a 2.0 N force, whilst LU and BC were treated with a 1.5 N force.
- The polymer-infiltrated ceramic (VE) presented significantly lower surface gloss when compared to filler-based CAD-CAM composite materials.

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Conflicts of interest
The authors declare that they do not have any conflict of interest related to this study.

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