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Review

The Influence of Polishing on the Mechanical Properties of Zirconia—A Systematic Review

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Abstract: Purpose: To systematically review studies that investigated the consequences of various polishing protocols on the mechanical properties of zirconia. The effects on the roughness and crystalline phase transformation were also evaluated. Materials and methods: The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) was followed. The electronic searches were conducted via OVID MEDLINE (R) and Scopus for publications between 1996 and August 2022. The search strategy was limited to full texts in the English language and in vitro studies. The influences on flexural strength, hardness, fracture strength, fracture toughness, wear resistance, roughness and phase transformation were collected. Various methodologies to measure these properties were also outlined and compared. The risk of bias for included studies was evaluated according to a modified Consolidated Standards of Reporting Trials (CONSORT) checklist. Results: After removing duplicates, the systematic search identified a total of 419 studies. Nineteen studies satisfied the inclusion criteria and were selected for final analysis. Fifteen of the included studies observed the changes in surface roughness along with the mechanical properties and ten studies detected the tetragonal (*T*) to monoclinic *(M)* phase transformation. Eight studies also investigated the change in properties after polishing the ground surface. Testing parameters were not consistent among studies due to the varying methods. Conclusions: To a certain extent, polishing influences the strength, hardness, toughness and wear resistance. The damage in some mechanical properties, as well as the roughened surface, from grinding can be restored via an appropriate polishing treatment. The polishing process itself barely induces the transition from the tetragonal to monoclinic phase of zirconia, while this commonly occurs after grinding. If the subsequent polishing is adequate, the transformed monoclinic phase can be eliminated with the removal of the outermost surface layer. In dentistry, polishing is an imperative step to maintain the superior functions and service life of zirconia for patients.

Keywords: intraoral polishing; zirconia; dental ceramic; mechanical properties; systematic review

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1. Introduction

Since 1965, there have been several types of all-ceramic systems developed after the first attempt of adding aluminum oxide into feldspathic porcelain [1,2]. The acceptance of dental all-ceramic restorations has been increasing along with the increasing aesthetic demands from patients, as well as the development in ceramic technologies. From a restorative dentistry point of view, ceramic includes three major groups: glass materials (castable, machinable and pressable glass infiltrated), particle-filled glass (leucite) and polycrystalline ceramics (zirconia) [3]. In order to improve the poor mechanical properties of feldspathic porcelain and overcome the limitation of their clinical use, tetragonal zirconia polycrystal (TZP), commonly known as 'zirconia', was utilized as a dental material in the early 1990s [2]. Zirconia application in the field of dentistry has been widespread due to its good mechanical characteristics, namely, superior strength and fracture toughness. Zirconia's superior mechanical performance is reflected in its increased survival rate and the reduced chipping and fracturing of zirconia restorations [4]. Yttria (Y_2O_3) is added to stabilize TZP at room temperature and enhance its strength and toughness at the different concentrations of 3 mol% (3Y-TZP), 4 mol% (4Y-TZP) and 5 mol% (5Y-TZP), which represent the three generations of zirconia [5]. The greater the yttria concentration, the more translucent but the weaker the final zirconia restoration will be. Despite such variation, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) meets the demands of patients with its excellent properties and aesthetics.

The continuous development of zirconia aims to find a phase containing both superior translucency and aging resistance by experimenting with varied dopants and sintering strategies. The current generation of monolithic Y-TZP, where no porcelain veneering occurs, is favored in the posterior region as it allows for the reduction of the occlusal thickness to 0.5 mm, even though the recommended value is over 1.0 mm [6,7]. Its fracture strength is reported to be still sufficient for the posterior regions.

Computer-aided design and computer-aided manufacturing (CAD/CAM) are widely utilized alongside the new additive manufacturing systems (3D printing) [8]. Carbide cutters used in the CAD/CAM are known to produce flaws and microchips, lowering the strength of pre-sintered zirconia; therefore, the polishing of the milled restoration is an indispensable process and cannot be replaced by a subsequent sintering operation [9,10]. Despite the accuracy of CAD/CAM restorations, additional chairside adjustments may be required, such as intraoral polishing. This additional step would be conducted to smooth adjusted surfaces, thus decreasing the possibility of plaque accumulation and fracture caused by defects as well as reducing the antagonistic wear [11–13].

Mechanical behavior is one of the major evaluation criteria for the clinical performance of dental materials. It shows how the materials respond to external forces or loads, as well as deformation or transformation [14]. Sufficient mechanical integrity of dental materials is necessary for long-term clinical success [15]. There are several common mechanical properties used to evaluate the functional ability of dental materials: strength, fracture toughness, elastic modulus and hardness. Zirconia has favorable mechanical properties and has the best performance when compared to other dental ceramic materials [2], as it has high corrosion and crack propagation resistance while being biocompatible and aesthetic compared to metallic materials [16]. Nevertheless, the high translucency level of zirconia is associated inversely proportional with the fracture toughness and flexural strength of the yttria content, which also could consequently influence the wear resistance [17,18].

Fixed dental restorations are required to contain sufficient mechanical properties to withstand continual bite forces of over 500 N [19]. Although numerous previous in vitro studies have investigated the influence of grinding or other surface treatments [20–23], the polishing procedure may also unduly compromise the mechanical integrity of zirconia. However, there are only limited systematic reviews focused on this topic, and, therefore, the purpose of this study was to systematically review studies on the effects of different polishing systems on the mechanical properties.

2. Methodology

2.1. Search Strategy

This systematic review was developed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISM) [24]. The present study was conducted to answer the following question: how could polishing influence the mechanical properties (strength, hardness, toughness and wear resistance) of zirconia? An electronic search was performed using two databases, OVID MEDLINE (R) and Scopus, based on the PICO (S) (Patient or population, Intervention, Control or Comparison, Outcome and Study) strategy (Table 1).

Table 1. Systematic search strategy.

Search Strategy	
Population	Zirconia (Zirconium; Yttrium-stabilized tetragonal zirconia)
Intervention	Zirconia samples received polishing
Comparison	Untreated zirconia samples
Outcome	Mechanical properties (Strength; Toughness; Hardness; Wear resistance)
Study type	Quantitative study

The following MeSH (Medical Subject Headings) terms were carried out in OVID (the syntax was modified to adapt to the other respective database):

(polishing OR dental polishing OR polish)

AND

(mechanical properties OR mechanical property OR flexural strength OR compressive strength OR tensile strength OR shear strength OR biaxial strength OR wear resistance OR elastic modulus OR fracture toughness OR hardness OR Vickers hardness)

AND

(zirconium OR zirconia OR Y-TZP OR zirconium dioxide)

2.2. Eligibility Criteria

The inclusion criteria for this systematic review were as follows: (1) in vitro studies, (2) English language, (3) full-text studies and (4) from 1996 to August 2022. Studies were excluded if they were (1) in a non-English language, (2) in vivo, (3) reviews or protocols, (4) abstracts only, (5) irrelevant to the focus question, (6) not about zirconia or Y-TZP, (7) without the evaluations of mechanical properties, (8) not evaluating the effect from polishing or (9) polishing by grinding papers.

2.3. Study Selection and Data Extraction

The search steps, including screening, are illustrated in Figure 1 (flow chart). Titles and abstracts were firstly screened by two independent reviewers (X.L and J.C) and the selection was completed according to the inclusion and exclusion criteria. All disagreements were analyzed and discussed by the two reviewers to reach consensus; if consensus was not achievable, other reviewers (J.M.A and S.M) were utilized. After assessing the selected full-text studies, studies that did not meet the inclusion criteria were further eliminated. The following information was collected from the final list of included studies: authors, year, title, experimental groups, polishing protocol, measured mechanical properties, post-test analytic methods and main findings. The data regarding roughness and phase transformation from some studies were also extracted.

2.4. Risk of Bias Evaluation

The risk of bias assessment in this systematic review was based on the modified Consolidated Standards of Reporting Trials (CONSORT) checklist [25]. Two authors (X.L and J.C) evaluated and categorized each item as “yes” or “no”. The overall risks of bias for the studies were judged at the end as “low”, “moderate” or “high”. Any disagreements were discussed to reach consensus.

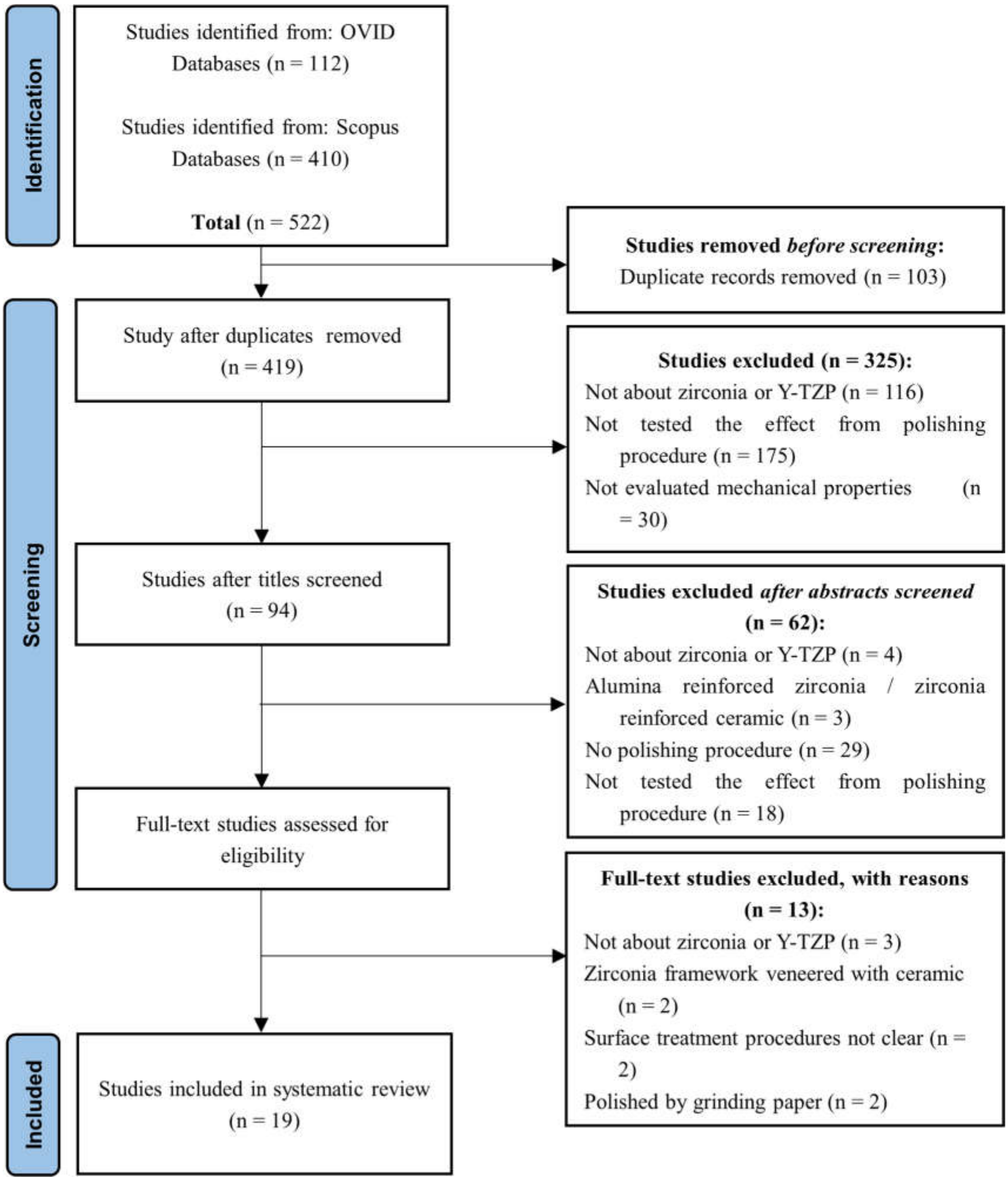

Figure 1. PRISMA flow diagram of study identification.

3. Results

3.1. Search and Selection

Five hundred and twenty-two papers were initially identified using the databases. After removing duplicates, 419 papers were screened and evaluated using their titles and abstracts, leading to the exclusion of 387 papers. The 32 remaining studies were subjected to a full-text assessment. Among them, 13 publications were excluded and 19 studies were finally selected for further analysis in this systematic review (Figure 1).

3.2. Risk of Bias in Individual Studies

The assessment of risk of bias for the 19 included studies is shown in Table 2. Almost all of them showed a low overall risk of bias with only five studies fulfilling all requisites. One study [26] was graded as moderate due to missing information from the abstract, sample size, statistical methods, outcomes and limitations. Most studies (n = 14) did not present a clear explanation on how the sample size was determined, as shown in Table 2. Project funding and support was not clearly stated within five studies (Table 2). Pittayachawan et al. (2009) [27] was the only study that did not report the detailed methodology for experimental groups.

3.3. Study Characteristics

The 19 reviewed studies were analyzed and divided into different categories based on their tested material, intervention, polishing protocol and measured mechanical properties (Table 3). The material types were divided into three subgroups: (1) zirconia, (2) polycrystalline tetragonal zirconia partially stabilized by yttria Y-PSZ and (3) yttrium-stabilized tetragonal zirconia polycrystal Y-TZP. The material types are classified by yttria content: (1) 3 mol% (3Y-TZP), (2) 4 mol% (4Y-TZP) and (3) 5 mol% (5Y-TZP). The mechanical properties chosen for testing contained the following categories: (1) flexural strength, (2) fracture strength, (3) fracture toughness, (4) hardness and (5) wear resistance.

Except for mechanical properties, the changes in roughness and phase transformation were also observed in most of the studies. Roughness or superficial structures were measured in 15 studies and crystalline phases of zirconia were assessed in ten studies (Table 4).

Table 2. Assessment of risk of bias.

Author (Year)	Items	de Carvalho et al. (2021) [28]	Lu et al. (2020) [26]	Vila-Nova et al. (2020) [29]	Wang et al. (2020) [20]	Pfefferle et al. (2019) [10]	Yin et al. (2019) [30]	Khayat et al. (2018) [31]	Buciumeanu et al. (2017) [32]	Mohammadi-Bassir et al. (2017) [33]	Bai et al. (2016) [34]
Abstract	Abstract 1	Yes	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes
Introduction	Background and objectives 2a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Background and objectives 2b	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Method	Intervention 3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Outcomes 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Sample size 5	No	No	No	Yes	No	No	Yes	No	No	No
	Statistical methods 10	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Results	Outcomes and estimation 11	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Discussion	Limitations 12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other information	Funding 13	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Overall risk of bias		**Low**	**Moderate**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**

Author (Year)	Items	Hjerppe et al. (2016) [35]	Schatz et al. (2016) [36]	Chong et al. (2015) [37]	Traini et al. (2013) [38]	Preis et al. (2012) [39]	Aboushelib and Wang (2010) [40]	Pittayachawan et al. (2009) [27]	Papanagiotou et al. (2006) [41]	Guazzato et al. (2005) [21]
Abstract	Abstract 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Introduction	Background and objectives 2a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Background and objectives 2b	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Method	Intervention 3	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
	Outcomes 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Sample size 5	No	Yes	No	Yes	No	Yes	No	No	No
	Statistical methods 10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Results	Outcomes and estimation 11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Discussion	Limitations 12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other information	Funding 13	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Overall risk of bias		Low	Low	Low	Low	Low	Low	Low	Low	Low

Table 3. Summary of the polishing protocol and mechanical properties measurement in the included studies.

Authors (Year)	Material(s)	Experimental Group (s) (Group Code)	Polishing Protocol	Measured Mechanical Property	Results
Pfefferle et al. (2019)	Zirconia (Ceramill Zolid HT+, XY406339G, Amann Girrbach, Koblach, Austria)	• Positive polishing control group (PLK) • Negative control group (NP): No treatment • Felt wheel (Komet) (FW) • Felt wheel combined with a polishing paste (Komet; YETI dental) (FWP) • Goat hair brush (Komet) (GB) • Goat hair brush combined with a polishing paste (Komet; YETI dental) (GBP) • Green-state finishing kit (Amann Girrbach) (FK) • Universal polisher (Amann Girrbach) (UP) • SiC polishing paper (PP)	• PLK: Polish lab kit (Amann Girrbach, Lot. No. 409177) for 15 min in a two-step polishing protocol with 10,000 min^{-1} • All experimental groups (excluding PLK and NP) were employed for 3 min at 5000 min^{-1} and further divided into two subgroups: (1) Fine polisher (Post Wheel "fine", Amann Girrbach, Koblach, Austria) and,(2) Rough and fine polisher (Post Wheel "medium" and Post Wheel "fine", Amann Girrbach, Koblach, Austria) at 10,000 min^{-1} for 4 min	• Biaxial flexural strength (FS)	• All experimental groups had higher FS than the negative control group NP • Two-step polishing showed an increase compared to one-step polishing for all groups
Aboushelib and Wang (2010)	CAD/CAM zirconia milling blocks (Procera Zirconia; Nobel Biocare AB, Göteborg, Sweden)	• Polishing • Airborne-particle abrasion • Grinding with a diamond point Three surface restoration methods: (1) Polishing (2) Glazing (3) Bonding agent	• Customized rotating metallographic polishing device (EcoMet; Buehler Ltd., Lake Bluff, IL, USA) • Restoration method: polishing with fine aluminum oxide diamond point (Dura-White Stones; Shofu Dental Corp, Kyoto, Japan) and a 0.5 µm diamond polishing paste (EcoMet; Bue- hler Ltd.) at 10,000 rpm for 30 s	• 4-point flexural strength	• Compared with polished specimens, grinding and airborne-particle abrasion significantly reduced the flexural strength • Among all restoration methods, polishing resulted in a significant regain in the strength of ground specimens, which is the most effective strategy
Schatz et al. (2016)	Three pre-sintered monolithic zirconia: • Ceramill Zolid (Amann Girrbach, Koblach, Austria) • Zenostar ZrTranslucent (Wieland Dental, Pforzheim, Germany) • DD Bio zx2 (Dental Direkt, Spenge, Germany)	• Manual dry polishing before sintering • Machine wet polishing after sintering	• Dry-polishing: SiC discs for 5 s per specimen side • Wet polishing: Water-cooled polishing machine (Struers Abramin, Struers, Ballerup, Denmark) with coarse grinding with diamond pads at 150 rpm for 6 min, fine polishing with subsequent polishing solutions and a polishing plate for 6 min, and high polishing at 150 rpm for 30 s	• Biaxial flexural strength • 3-point flexural strength • 4-point flexural strength	• Different polishing protocols impacted the flexural strength • Flexural strengths showed the lowest value in 4-point flexural strength tests and the highest value in biaxial flexural strength tests • Wet polished specimens had significantly higher flexural strength

Table 3. *Cont.*

Authors (Year)	Material(s)	Experimental Group (s) (Group Code)	Polishing Protocol	Measured Mechanical Property	Results
Yin et al. (2019)	Pre-sintered zirconia (A3 12T, Liaoning Upcera, Benxi, China)	• Control group (Group 0): Grinding without polishing • Grinding + Extra-coarse polishing (Group 1) • Grinding + Medium polishing (Group 2) • Grinding + Fine polishing (Group 3) • Grinding + 3-step polishing (Group 4) • 1.0 mm Occlusal thickness + Grinding + 3-step polishing (Group A) • 1.0 mm Occlusal thickness + Grinding (Group B) • 0.5 mm Occlusal thickness + Grinding + 3-step polishing (Group C) • 0.5 mm Occlusal thickness + Grinding (Group D)	• Extra-coarse polish: green polishing bur (ZIRCO MASTER, SEICHONG, Seoul, Korea) • Medium polishing: red polishing bur (ZIRCO MASTER, SEICHONG, Seoul, Korea) • Fine polishing: yellow polishing bur (ZIRCO MASTER, SEICHONG, Seoul, Korea)	• Fracture strength (cycling and fracture tests)	• Polished occlusal contact and larger occlusal thickness increased fracture strengths • There were no significant differences
Bai et al. (2016)	Pure white zirconia and pre-colored A2 zirconia (Upcera)	• Control (C): No treatment • Polishing system 1 (K) • Polishing system 2 (B)	• K: ZrO_2 2-step polishing (Komet Dental) at 6000 rpm • B: Robinson brush and Zenostar paste (Wieland Dental)	• 2-body wear resistance (confocal microscopy; light microscopy; SEM)	• Polished specimens showed significantly less wear depth than untreated groups and smaller wear area on antagonists than glazed or stained groups • Group B showed no measurable wear on specimens and smallest wear area on antagonists
de Carvalho et al. (2021)	Ultra-translucent Y-PSZ (Prettau Anterior, Zirkonzahn, Gais Italy)	• Control (C): No treatment • Diamond rubber polishing (R) • Coarse grit diamond bur abrasion (B) • Coarse grit diamond bur abrasion + diamond rubber polishing (BR)	Rubber polishing kit (Premium Compact kit, Dhpro, Paraná, Brazil) mounted to a handpiece and micromotor (500, Kavo, Joinville, SC, Brazil) at 12,000 rpm for 20 s per polisher until the thickness of the samples was equal to 0.5 mm	• 3-point flexural strength	• Flexural strengths were significantly different for all groups, with R > C > BR > B • Characteristic strength (σ0) of group R was significantly higher than other groups
Mohammadi-Bassir et al. (2017)	Pre-sintered Y-PSZ (Ceramill; Amman Girrbach GmbH)	• Control group (SP): No surface treatment • Grinding with a diamond rotary instrument (DRI) (Gr) • Grinding with a DRI + Glazing (Gl) • Grinding with a DRI + Polishing system 1 (BP) • Grinding with a DRI + Polishing system 2 (MP)	• BP: 2-step intraoral zirconia polishing kit (Busch & Co) by medium and fine rubber polisher with low-speed handpiece for 60 s • MP: 2-step intraoral polishing kit (DC A14&A13, Luster; Meisinger) by pre-polisher and fine high-shine polisher with low-speed handpiece for 60 s	• 3-point flexural strength	• Grinding groups had the highest value in flexural strength • Polishing groups had higher flexural strengths than the control group • No significant difference of mean flexural strength among the grinding and polishing groups

Table 3. *Cont.*

Authors (Year)	Material(s)	Experimental Group (s) (Group Code)	Polishing Protocol	Measured Mechanical Property	Results
Wang et al. (2020)	Pre-sintered 3Y-TZP (Lava Plus high translucency zirconia, LOT: 3343987 and 3706728; 3M ESPE, Neuss, Germany)	• Control (C): No treatment • Grinding with 6-blade round plain cut tungsten carbide burs (TC1) • Grinding with 8-blade finishing chamfer tungsten carbide burs (TC2) • Air particle (sandblast) abrasion (APA) • Rubber polishing (RP)	3-step StarGloss diamond porcelain polishers (Edenta AG, Switzerland) at 30,000 rpm for 2 min	• Biaxial flexural strength (BFS)	• Polishing had the highest BFS among the control group and all experimental groups • TC1 and TC2 had the lowest BFS, while grinding with polishing groups resulted in higher BFS than only ground samples
Khayat et al. (2018)	Y-TZP (Tizian Blank Translucent 98 mm Zirconium; Schütz)	• Control (C): No treatment • Grinding (G) • Grinding and polishing system 1 (GPB) • Grinding and polishing system 2 (GPK)	• GPB: 2-step Brasseler zirconia polishing kit (Dialite ZR polishing wheels; Brasseler USA) for 30 s • GPK: 2-step Komet polishing kit (Komet ZR Flash Polisher; Gebr. Brasseler) for 30 s	• Biaxial flexure strength (BFS)	• No significant difference on BFS among groups • The lowest value was in Group G and the highest value in Group GPK
Pittayachawan et al. (2009)	Y-TZP (Cercon® disc, DeguDent GmbH, Germany)	• Control: as received • Polishing	DP suspension (Struers, UK) containing polycrystalline diamond (Struers, UK) of size 9 µm particle size for 20 min and finally 3 µm for 10 min at 150 rpm	• Biaxial flexural strength • Vickers hardness	• Polishing showed a lower flexural strength than other reports • As-received specimens had slightly higher hardness than polished specimens • No significant difference in hardness between two groups • Fracture surface of polished samples had no detectable porosity or flaws
Hjerppe et al. (2016)	Y-TZP (Y_2O_3 3 mol%) (ICE Zirkon; Zirkonzahn GmbH)	• Control group: No treatment • Airborne-particle abrasion • Grinding dry with a micromotor • Grinding with turbine under water cooling • Grinding with silicon carbide paper • Polishing • Steam cleaning	Polishing brush (OptraFine; Ivoclar Vivadent AG) with diamond paste (Kohinoor)	• Biaxial flexural strength • 3-point bend strength	• Biaxial flexural and 3-point bend strengths of polishing group were slightly higher than the control group
Vila-Nova et al. (2020)	• TZP (Ice Zirkon Translucent, Zirkonzahn, Gais, Italy) • Y-TZP (Prettau Anterior, Zirkonzahn, Gais, Italy)	• Control (C): No treatment • Diamond rubber polishers (B) • Adjusting with cylindrical ultra-fine diamond burs (P) • Adjusting with burs + diamond polishers (PB) • Adjusting with burs + glaze (PG)	Abrasive rubber polishers of extra-hard diamond-impregnated polyurethane (Premium Compact, Dhpro, Paraná, Brazil) at 12,000 rpm for 20 s per disk	• 3-point flexural strength	• Flexural strength was influenced by finishing/polishing, with B > PB > C > P > PG

Table 3. *Cont.*

Authors (Year)	Material(s)	Experimental Group (s) (Group Code)	Polishing Protocol	Measured Mechanical Property	Results
Papanagiotou et al. (2006)	Pre-sintered Y-TZP (Vita In-Ceram YZ; Vita Zahnfabrik)	• Control (C): No treatment • Immersed in boiling water for 24 h/7 days (B24h/B7d) • Stored in humidified air at 250 °C for 6 h/24 h (H6h/H24h) • Polishing (P) • Airborne-particle abrasion (A) • Airborne-particle abrasion + Immersed in boiling water for 7 days (AB)	Pink wheel (stock #5000564U0 medium, grit size 30 mm) and a gray wheel (#5000748U0; fine, grit size 10 mm) (Dialite polishing wheels; Brasseler USA, Savannah, Ga) at 6500 rpm	• 3-point flexural strength	• The 3-point flexural strength and Weibull characteristic strength of the polishing group were slightly higher than the control group
Guazzato et al. (2005)	Fully sintered Y-TZP (5 wt% Y_2O_3) (DC- Zirkon, DCS Dental AG, Allschwil, Switzerland, Lot No 521)	• Heat treatment (H) • Sandblasted (S) • Grinding parallel along the length with diamond wheel (GPA) • Grinding perpendicular to the main axis with diamond wheel (GPE) • Polishing (P)	Diamond discs of nominal grit size 90, 70, 30, 15, 9, 3 and 1 µm at 800 rpm under water coolant	• 3-point flexural strength	• Both heat and surface treatments had significant influence on the strength of DC-Zirkon • Polished specimens showed lower Weibull modulus and flexural strength than other treatment groups
Traini et al. (2013)	Pre-sintered Y-TZP (Diazir, Diadem SAS, Louey, France)	• Control group (M): No treatment • Coarse polishing (CP) • Fine polishing (FP)	• CP: Silicone wells green-coarse polisher at 10,000 rpm • FP: Silicone wells yellow super-fine polisher (Edenta AG, Dental Rotary Instruments, AU/SG, Switzerland) at 10,000 rpm with InstaGlaze Diamond Paste (George Taub Products & Fusion Co., Inc., Jersey City, NJ, USA) without water cooling	• Fracture toughness (Ft) • Vickers Hardness (Hv) (Vickers indentation and SEM)	• Group CP had highest Ft, with CP > M > FP • Ft showed significant difference among both groups M and Cp vs. Fp, while no significant difference between M and CP • No significant different in Hv • Control group (M) had higher Hv than polishing groups
Buciumeanu et al. (2017)	Y-TZP (Zirkonzahn, Germany)	• Control (GC): No treatment • High speed tapered bur milling (GM) • High speed tapered bur milling + Polishing system 1 (GPK) • High speed tapered bur milling + Polishing system 2 (GPD)	• GPK: zirconia polishing kit Kenda (Kenda, Liechtenstein) • GPD: zirconia polishing kit Diacera (EVE Diacera, Germany)	• Wear resistance (pin-on-plate wear tests)	• Polished samples (GPK and GPD) had significantly higher wear resistances than rougher surfaces (GC and GM)
Lu et al. (2020)	Y-TZP (Blue Whale Ceramic Technology Co., Ltd., Zhengzhou, China)	Dual-axis wheel polishing with four different tool offsets and four different wheel speeds	Dual-axis wheel polishing (DAWP) with diamond micropower (Saint-Gobain corporation, France)	• Vickers hardness • Wear resistance	• Hardness was reduced by polishing • Wear resistance and tribological behavior was significantly improved by polishing

Table 3. *Cont.*

Authors (Year)	Material(s)	Experimental Group (s) (Group Code)	Polishing Protocol	Measured Mechanical Property	Results
Chong et al. (2015)	Unsintered Y-TZP (Vita Zahnfabrik, H. Rauter GmbH & Co. KG, Bad Säckingen, Germany, Material No. EC4YZ205, Batch No. 22410)	• Control ©: Enamel opposing enamel • Laboratory polished (LP) • Laboratory polished and glazed (G) • Clinically adjusted with diamond bur (CA) • Clinically adjusted with diamond bur and repolished (CAR)	• LP: MD 4-step polishing discs (Struers, Ballerup, Denmark) at 150 rpm for 8 min, 6 min, 1 min and 1 min for each step • CAR: 2-step zirconia-specific diamond polishing bur (Eve Ernst Vetter GmbH, Pforzheim, Germany)	• Wear resistance (masticatory simulator)	• The greatest wear of enamel antagonist was shown in CA, while the least volume was shown in CAR • Only polished surfaces (LP and CAR) and opposing enamel antagonists were smooth with minimal changes between pre- and post-testing
Preis et al. (2012)	Three different Y-TZP (Cercon HT, DeguDent, Hanau, G); (Cercon base, DeguDent, Hanau, G); (Lava, 3M Espe, Seefeld, G)	• Diamond bur grinding • Polishing/Repolishing (1) Polishing (2) Polishing–Grinding (3) Polishing–Grinding–Repolishing	Polishing set (Brasseler, 9545 C/M/F, Lemgo, G)	• Wear resistance (optical 3D profilometer; light microscope; SEM)	• No measurable wear was shown from polished, ground or repolished zirconia • Ground zirconia showed higher antagonistic wear • Ground and polished/repolished surfaces had significant differences of antagonistic wear area in groups Lava and Cercon HT

Table 4. Summary of measurements in surface roughness and phase transformation of included studies.

Authors (Year)	Roughness Measured (Yes/No)	Post-Test Analysis	Main Findings	Phase Transformation Measured (Yes/No)	Post-Test Analysis	Main Findings
Pfefferle et al. (2019)	Yes	• Profilometer (Mahr Perthometer SD 26, Mahr, Göttingen, Germany)	• Among one-step polishing groups, GB and FW had the highest SR, while PP had the lowest value • Among two-step polishing groups, NP had the highest SR • Two-step polishing showed significantly lower SR in all groups (except GBP) compared with one-step groups • Polishing paste furthermore reduced the surface roughness	No	Nil	Nil
Schatz et al. (2016)	Yes	• Profilometer • (MarSurf 400 SD26, Mahr, Göttingen, Germany) • Scanning electron microscopy (SEM)	• Dry polished specimens had higher surface roughness	Yes	X-ray diffraction (XRD)	• All specimens showed low volume fraction of monoclinic phase • No measurable difference in phase transformation among all groups

Table 4. *Cont.*

Authors (Year)	Roughness Measured (Yes/No)	Post-Test Analysis	Main Findings	Phase Transformation Measured (Yes/No)	Post-Test Analysis	Main Findings
Yin et al. (2019)	Yes	• Profilometer (SURFTEST SV-3000, Mitutoyo, Kawasaki, Japan)	• Roughness was reduced in all experimental groups compared with the control group • Group 4 showed the smoothest surface, while Groups 0 and 1 showed significantly higher roughness than the other three groups • No significant difference found among Groups 3, 4 and 5 • Polished specimen surfaces were significantly smoother and flatter and grains were homogenous	Yes	XRD	• Monoclinic phase was only detected in Groups 0, 1 and 2 • Group 4 showed the most stable phase
Bai et al. (2016)	Yes	• Confocal microscopy (LEXT OLS4000; Olympus) • SEM	• Polishing groups had markedly lower Ra than the control group • The mean surface roughness of the polishing kit group was significantly higher than brush polished groups • Polishing with K or B could remove the cracks from grinding	No	Nil	Nil
de Carvalho et al. (2021)	Yes	• Digital rugosimeter (Surftest, Model SJ-2010, Mitutoyo, Japan) • SEM	• Roughness was significantly different with B > C > R > BR • Superficial surfaces were changed in all groups • Polished specimens showed a greater uniform surface and some cracks or craters from grinding were removed by polishing	Yes	XRD	No notable tetragonal to monoclinic phase transformation induced by finishing/polishing
Mohammadi-Bassir et al. (2017)	Yes	• Profilometer (Hommel Tester T8000; Hommel- werke) • SEM	• Ground group (Gr) showed significantly higher roughness than other groups • No significant difference shown between two different polishing groups or the polishing and glazing groups • Polishing reduced the roughness of ground specimens but some ground grooves were still left	Yes	XRD	• Monoclinic phase was only observed in the grinding and two polishing groups • Compared to the grinding group, Group BP and MP had slightly lower percentages of monoclinic phase
Wang et al. (2020)	Yes	• Profilometer (Surtronic3+; Taylor Hobson, Leicester, United Kingdom)	• Rubber polishing significantly reduced the high Ra of the ground surface • Specimens from groups with the RP procedure had flat and smooth surfaces • Roughness of polished surface was higher than in the control group	Yes	XRD	No changes in crystalline phases after all treatments
Khayat et al. (2018)	Yes	• 3D optical interferometer • (Zygo New View 600; Zygo Corp)	• Group G had the significantly highest Ra, followed by group GPB • Groups GPK and control group showed the lowest Ra and were approximately equal to each other • Polishing resulted in smoother surface than glazing or grinding	No	Nil	Nil

Table 4. *Cont.*

Authors (Year)	Roughness Measured (Yes/No)	Post-Test Analysis	Main Findings	Phase Transformation Measured (Yes/No)	Post-Test Analysis	Main Findings
Pittayachawan et al. (2009)	No	Nil	Nil	Yes	XRD	Polishing resulted in phase transformation from one cubic phase (with larger lattice parameters) to the other cubic phase and tetragonal phase, and relieved some strain in cubic phase
Hjerppe et al. (2016)	Yes	• Surface roughness tester (601908; Leitz Wetzlar)	• Paste polished specimens had lower surface roughness than untreated, airborne-particle abraded and grinding groups	No	Nil	Nil
Vila-Nova et al. (2020)	Yes	• 3D optical profilometry • Atomic force microscopy (AFM) • SEM	• Roughness showed statistical differences between groups, with P > PG > C > PB > B • Rubber-polished group had more uniform surface	Yes	XRD	Monoclinic phase peaks were only observed in the conventional zirconia group with different finishing and polishing protocols
Guazzato et al. (2005)	No	Nil	Nil	Yes	XRD	A negligible amount of monoclinic phase was found on polished surface
Traini et al. (2013)	Yes	• Confocal scanning laser microscope (CSLM) (Carl Zeiss, Jena, Germany)	• Rs showed significant difference among both groups M and Cp vs. Fp, while no significant difference between M and CP • Fine polishing group (FP) showed significantly more flat surfaces	No	Nil	Nil
Buciumeanu et al. (2017)	Yes	• Profilometer • (Surftest SJ 201, Mitutoyo, Tokyo, Japan)	• Ground samples (GM) had the highest surface roughness • Group GPD had the lowest value among groups • Group GPK and control group showed similar roughness	Yes	XRD	• Group GPK and GPD showed similar phase transformation from tetragonal to monoclinic phase • Amounts of monoclinic phase in two polishing groups were lower than grinding group GM
Lu et al. (2020)	Yes	White-light interferometer (NewViewTM 7100, ZYGO, USA)SEM	Surface roughness of ground surface was reduced by polishingSurface roughnesses were proportional to the tool offset (polishing pressure) and wheel speed (polishing velocity)Polishing resulted in uniform and smooth surface topographies	Yes	XRD	No occurrence of phase transformations from DAWP process
Chong et al. (2015)	Yes	• Profilometer • (Mitutoyo SV600 Surftest; Mitutoyo America, Illinois, USA) • SEM	• CA zirconia showed the largest Ra and LP samples had the lowest Ra • Repolishing efficiently reduced the roughness of clinically ground specimens	No	Nil	Nil

Table 4. *Cont.*

Authors (Year)	Roughness Measured (Yes/No)	Post-Test Analysis	Main Findings	Phase Transformation Measured (Yes/No)	Post-Test Analysis	Main Findings
Preis et al. (2012)	Yes	• Profilometer (Perthometer SP6, Perthen–Feinprüf, G)	• Ra of zirconia was similar between polishing and repolishing, while the Ra of ground zirconia was the largest • Polished/repolished zirconia showed smoother surface than grinding group	No	Nil	Nil

3.4. Synthesis of Results

3.4.1. Experimental Groups

The testing approaches adopted by previous studies were grouped into three types. Six studies only had one or more polishing experimental groups in order to investigate the difference between the polished and untreated samples or among a variety of polishing systems [10,26,27,34,36,38]. In contrast, in other studies, diverse surface treatments were also introduced into the testing groups, for instance grinding, airborne-particle abrasion and glazing. This approach was employed within five studies and aimed to compare the results from various surface finishing procedures [20,21,35,40,41]. The other eight studies had a combination of two treatments within one group, where specimens were polished after adjustment [28–33,37,39]. Consequently, the impact of polishing the ground surfaces would be analyzed.

3.4.2. Polishing Systems

The polishing protocols for all studies were extremely diverse with various polishers, brands, speeds and polishing durations. Single diamond rubber bur or disc and polishing kit in a two-, three- or four-step polishing protocol were typically used by 14 studies [10,20,21,28–34,37–39,41]. A few studies used the same brand; however, the polishers were still not identical between the studies. Two studies utilized brush and paste as the polishing approach [10,35]. Some studies used novel polishing methods, such as a dual-axis wheel, polishing solution with polishing plate, rotating metallographic polishing device and DP-suspension containing polycrystalline diamond [26,27,36,40]. Only some authors reported the speeds and time used, which ranged from 150 to 30,000 rpm and 5 s to 15 min, respectively (Table 3).

3.4.3. Mechanical Properties

Flexural strength was the most common property measured in the studies [10,20,21,27–29,31,33,35,36,40,41]. There were three forms—biaxial, 3-point and 4-point flexural strengths—and some authors tested more than one type. Studies with rubber polishing bur, brush or novel polishing machines found higher flexural strengths of polished samples compared to the no treatment groups [10,20,28,29,35,36,41]. Polishing also resulted in a regain in strength of the ground samples [20,28,29,31,40]. However, the study by Mohammadi-Baassir et al. [33] that investigated two brands of intraoral zirconia polishing kits found that polishing procedures showed a reduction in flexural strength from grinding by a diamond bur. Moreover, the flexural strength was decreased after DP-suspension polishing of Cercon zirconia and diamond discs polishing of Y-TZP, as shown in studies from Pittayachawan et al. [27] and Guazzato et al. [21], respectively.

All three studies that analyzed hardness showed a decline from various polishing protocols [26,27,38]. By contrast, tribological behavior and wear resistance were improved by polishing resulting in less wear of the opposing enamel antagonist, which was demonstrated by five studies [26,32,34,37,39]. Only Yin et al. [30] measured the fracture strengths and found that they were enhanced by polishing or increasing the specimen thickness. For fracture toughness, Traini et al. [38] found that coarse polishers resulted in the highest toughness compared to fine polisher and untreated groups, while there was no significant difference ($p > 0.05$) between control and coarse polishing groups.

3.4.4. Roughness

More than half of the studies utilized profilometer for the post-test analysis of roughness and scanning electron microscopy to observe the superficial surfaces [10,20,29,30,32,33,36,37,39]. Others introduced various devices for roughness measurements, such as a digital rugosimeter, optical interferometer, confocal microscopy and specific surface roughness tester [26,28,31,34,35,38]. Almost all the studies, except that by Wang et al. [20], found that polishing was able to smooth the roughened surface from the control group without any surface treatment. This surface treatment led to more uniform and smoother surface topographies and could remove some cracks or craters caused by grinding.

Some polishing systems showed differences within the same study [10,30–32,34,36–38]. According to Pfefferle et al. [10] and Yin et al. [30], more polishing steps resulted in a much lower roughness with a smoother surface and the use of polishing paste further reduced the roughness. Finer polisher smoothed the surface more efficiently than a coarse one as expected, which was found by Traini et al. [38]. Furthermore, surface roughness was proportional to the applied pressure and velocity of polishing, as shown by Lu et al. [26].

3.4.5. Phase Transformation

X-ray diffraction was used by ten studies to analyze the phase transformation [20,21,26–30,32,33,36]. Among them, four did not observe any notable changes in crystalline phases induced by polishing [20,21,26,28]. Nevertheless, tetragonal to monoclinic phase peaks were found in YZP with diamond rubber polishers, as well as in monolithic zirconia when dry polishing with SiC disc or wet polishing with solutions [29,36]. DP-suspension also caused a conversion from the cubic to tetragonal phase and from larger to smaller lattice parameters [27]. Within the other three studies, the amounts of monoclinic phase from the grinding adjustment were reduced by further polishing [30,32,33].

4. Discussion

This systematic literature review investigated the changes in mechanical properties after polishing zirconia materials over the past 20 years. Nineteen of the reviewed studies evaluated five mechanical properties: flexural strength, hardness, fracture strength, fracture toughness and wear resistance. Seventeen of the nineteen studies also highlighted the effect of roughness and/or crystalline phase transformation, thus these two issues were also taken into consideration. Based on the review, the methodologies of the included studies showed heterogeneity. They utilized various polishing protocols and testing methods for mechanical properties. If they are standardized, it would be easier to perform meta-analysis for comparison among studies. However, most studies concluded similar influences from the polishing.

4.1. Mechanical Properties

Mechanical behavior is typically used to evaluate the clinical performance of dental materials. It reveals how the materials respond to external forces or loads, as well as the resultant deformation or transformation [14]. Sufficient mechanical integrity of dental materials is a necessity for them to function for long periods of time and ultimately for the patient's life [15]. Focusing on only one type of mechanical property is not sufficient to measure the overall material quality accurately [14]. It is vital to investigate the difference in the range of mechanical behaviors to give clear, scientifically proven guidelines to ensure suitable dental material selection.

The ability of a material to endure applied stress without fracture or irreversible deformation is measured by its strength [42]. However, simple axial loading is nearly never found in the oral cavity because of the structure of the teeth and the three-dimensional nature of jaw mechanics. Most external loads will evolve into stresses along different planes resulting in tensile and shear stresses. Therefore, flexure is a preferred measurement as the testing simultaneously generates compressive, tensile and shear stresses [15]. The test measures required strength to bend material until fracture [14]. A compression curl typically can present on the opposite side to the failure origin, and this could be identified on the bend surface. Further fractography in high magnification may help with characterization and assessment of the failure analysis [43].

Differences in strength values for identical specimens might be presented by various testing methods, such as biaxial, three- or four-point flexural strength tests. If the applied loads are placed in different directions or a larger area, the probability of flaws perpendicular to the stress axes can be increased, resulting in premature failure with a lower strength value [35,36]. This can explain the differences between various testing approaches for identical prepared materials. Hjerppe et al. [35] and Schatz et al. [36] conducted different flexural tests concurrently. Both of their results showed differences among testing methods but they had opposite results, with Hjerrpe et al. [35] finding a higher value from the three-point bend test while the biaxial test presented the highest strength in Schatz et al.'s research.

Rubber polished zirconia generally had a higher flexural strength but was similar to the untreated group. This may be due to zirconia grains on the surface being compressed during the polishing process and thus optimizing the material strength [28]. The utilization of an additional polishing step further improved the strength. Nevertheless, diamond or tungsten carbide bur abrasion would chip and dislodge the grains and propagate microcracks, resulting in deterioration of mechanical properties. Strength values could be restored by removing surface defects during the polishing treatment which could potentially contribute to the elimination of the stress concentration sites and release of the high stresses developed during grinding. Even though Pittayachawan et al. [27] and Guazzato et al. [21] observed a lower strength value after polishing, they utilized DP-suspension and diamond discs, respectively, as polishing protocols, which would not be commonly used in the dental field.

Another conjecture is that the polishing process induces a transformation toughening of zirconia from metastable tetragonal into monoclinic phase and the reduction of strength is concomitant of the decline of surface strains [10]. The opposite was found in Mohammadi-Bassir et al. [33]'s study that reported the greatest flexural strength of zirconia after grinding and subsequent polishing by rubber burs. The reason for this difference may be that fine polishing eliminated some transferred monoclinic phases from grinding, which removes the compressive stresses [44]. Furthermore, if cracks created by grinding are only on the superficial layer without extending deeper than the surface compressive layers, a significant difference in strength from polishing will most likely not be detected [31,45].

Hardness describes the ability to resist local deformation, which is an outcome of a defined measuring process instead of an inherent property of the material [15]. The surface degradation over time would be partly dictated by this mechanical property [43]. Among a variety of hardness tests, the Vickers test is normally performed to measure the resistance to scratching or indentation produced from an applied load in a small area [14]. Traini et al. [38] reported that coarse polishing resulted in a lower hardness value than a fine polished surface; however, there was no significant difference ($p > 0.05$) between treated and untreated zirconia.

Fracture strength is the value of maximum stress before a fracture will fail within a material, which reflects the ability of that material to resist failure [46]. The presence of surface defects critically reduces the fracture strength [47]. Therefore, surface imperfections from occlusal adjustment are recommended to be removed via polishing. Yin et al. [30] also discovered that the thicker the zirconia occlusal thickness, the higher the fracture strength recorded. Even though there are differences among varying surface finishings, all results were higher than the average bite force in the posterior region. Therefore, despite potentially poor handling of the material, this rarely leads to premature fractures.

Fracture toughness is an intrinsic property that shows the resistance of a material to cracks propagating from a pre-existing flaw. A reduced fracture toughness increases the likelihood of a failure when a load is applied. Materials with a high fracture toughness are more ductile. In other words, brittle materials are prone to fracture due to their poor fracture toughness [15]. Crack propagation and structural changes are supposed to be exacerbated in a moist environment, such as oral cavities [48]. The high fracture toughness of zirconia allows it to perform better than most ceramics. However, Traini et al. [38] found that fine polishing had a significantly ($p < 0.05$) lower stress value to resist fracture when compared to coarse polishing and non-polished groups. It has been found that different test methodologies for the same ceramic material may produce inconsistency in the fracture toughness [47]. Therefore, it is important to consider this issue when attempting to compare results among different studies with varying methodologies.

As an optimum dental material, the wear rate should be as close as possible to the physiological enamel wear rate to avoid excessive wear and damage to the natural tooth structure [18,49]. Increasing the strength and fracture toughness of dental restorative materials would enhance the wear resistance [18,50]. The wear resistance is generally indicated from the characteristics (width and depth) of generated wear track on the surface using the tribological test. A much shallower and less obvious wear groove was normally produced on the polished surface than non-polished surface, which means that the ultra-smooth surface improves tribological behavior.

High antagonistic wear was a concern within clinical studies due to the greater hardness of zirconia. However, it is difficult to predict the outcome simply based on hardness [51]. Even compared to veneering porcelain, zirconia with a higher hardness did not show high antagonistic wear. Buciumeanu et al. [32] also conducted the wear tests by opposing natural teeth and the average weight loss of zirconia was lower than natural enamel. Saliva, acting as an efficient lubricant, reduces the coefficient of friction (COF) and protects or slows down teeth surface wear during masticatory motion [52]. This would mean that zirconia dental restorations might cause less wear depending on the amount of opposing enamel during function. However, adjustment by diamond bur dramatically aggravates vertical enamel loss of zirconia. Chong et al. [37] and Peris et al. [39] indicated that repolishing could rebuild the wear resistance and reduce the weight loss of antagonistic enamel.

4.2. Roughness

Roughness is a parameter to evaluate outermost surface quality. Higher surface roughness mostly comes from the existence of textures and defects, which may influence the performance and lifespan of a dental material. It also intensifies the opacity and diminishes the translucency of zirconia because of the scattering effect [53]. The presence of grooves on the rougher surface increases the contact area, thus increases the likelihood of bacteria accumulation and plaque, which further causes caries and periodontal inflammation [54,55]. Moreover, superior hardness of zirconia combined with a rougher surface would exaggerate the wearing of opposing dentition. The correlation between surface smoothness and flexural strength was not always reflected in previous studies [31,33].

In terms of structural reliability, the rough stripe-like ground surface, as well as the pores and grain boundary cracks from sintering, weaken zirconia, thus it is necessary to eliminate cutting grooves and deeper valleys [56]. Currently, there is a wide variety of polishing instruments; however, sequential polishing by rubber polishers coated with diamond abrasive particles is indicated as the most valid and efficient approach for obtaining a uniform and mirror-like surface topography [44].

Several factors of polishing may affect the resultant roughness. According to Pfefferle et al. [10] and Yin et al. [30], an additional polishing step could result in a significantly smoother surface, thus a more desired surface quality is achieved. In addition, a fine polisher generates a flatter surface with lower roughness levels than a coarse polisher [38]. Lu et al. [26] states that the heavier the polishing pressure and the higher the velocity, the rougher the surface becomes. Lu et al. [26] explained that this increase in roughness was due to the increased pressure and cycles per unit of the abrasive particles increasing the cutting depth. Conversely, deeper cutting grooves from grinding cannot be guaranteed to be removed effectively if insufficient pressure is applied during polishing.

4.3. Phase Transformation

At ambient pressures, there are three crystallographic forms of pure zirconia that develop at certain temperature ranges: monoclinic occurs below 1170 °C, tetragonal occurs between 1170 °C and 2370 °C, and cubic occurs over 2370 °C [57]. The conversion between two phases is normally reversible. Partially stabilized zirconia (PSZ) involves varying levels of a dopant oxide for stabilizing the tetragonal or cubic phase [58]. To lower the tetragonal–monoclinic transformation temperature, Yttria (Y_2O_3) is commonly used at various levels. This enables the tetragonal phase to be stabilized at room temperature to a certain extent and therefore allows zirconia to be more easily used as a dental ceramic material [59].

Compared to 5Y-TZP, de Carvalho et al. [28] concluded that it is much easier to trigger the $T \rightarrow M$ phase transformation within 3Y-TZP by bur finishing. The high concentration of yttrium provides phase stability with the presence of the cubic phase which is more resistant to thermal transformation [60]. The monoclinic phase would have a detrimental influence on the mechanical properties of zirconia, which, unlike the metastable tetragonal phase, provides superior functional behavior [61]. Under cycling loads and thermocycling from the oral cavity, the $T \rightarrow M$ phase transformation spontaneously occurs around the grinding-induced surface defects due to the stress accumulated at the tip of the crack [62]. This might cause a decline in strength and increase in both roughness and opposing enamel wear. Ten of the nineteen reviewed studies included the evaluation on phase changes after surface treatments. Dental polishing, without other treatments, barely leads to the change in crystal phase composition of tetragonal zirconia. Even though Schatz et al. [36] and Pittayachawan et al. [27] detected phase transformation, the polishing methods from their studies are rarely used within the field of dentistry. While the monoclinic phase often exists on the surface after grinding, the amount of it can be reduced using a polishing kit. This was evident in the following three studies: Yin et al. [30], Buciumeanu et al. [32] and Mohammadi-Bassir et al. [33]. In addition, Yin et al. [30] stated that fine polishing can effectively eliminate monoclinic phase on the ground surface, while it is difficult to achieve this by coarse or medium polishing. The mechanism of monoclinic phase elimination by polishing is the removal of the grinding-transformed layer without any reversions of phase transformation, thus reducing the surface strains [33]. Normally, the removal amount from optimizing polishing is greater than the depth of the transformation zone [21,62].

4.4. Future Perspective

The critical analysis presented in this systematic review highlights that dental polishing of zirconia after grinding plays an important role in regaining the material's mechanical properties. Within this review, five properties were included and discussed; however, other physical and optical properties of zirconia could be assessed in future studies. There are also multiple groups of all-ceramic systems and brands of dental ceramics which still require investigation.

5. Conclusions

Within the limitations of this review, in general and to varying degrees polishing restores the mechanical properties of zirconia material. The reduction in mechanical properties and increased roughness of the zirconia surface from preliminary grinding can be restored through adequate polishing. It is concluded that:

- Roughness of the ground surface is decreased by all types of polishing.
- Fine polishing is not detrimental to flexural strength and can in fact result in a slight enhancement of flexural strength.
- Fracture strength, toughness and wear resistance improve after diamond rubber polishing, while hardness is reduced.
- Local temperature increase from dental polishing does not induce the $T \rightarrow M$ phase transformation of zirconia.
- M phase transformation induced by preliminary grinding of zirconia can be partially eliminated through adequate polishing of the affected surface.

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